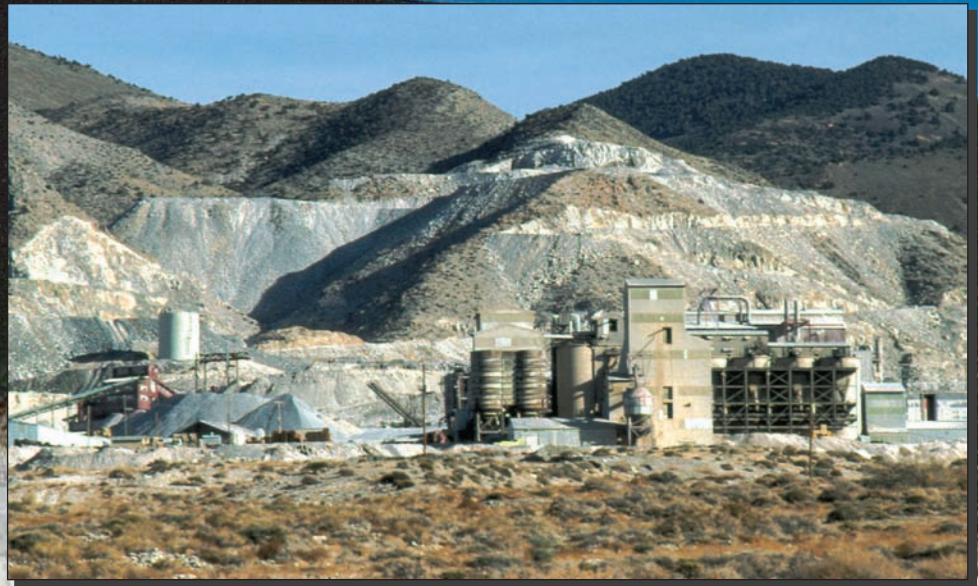


Premier Chemicals Mine and Plant, Gabbs, Nye County, Nevada. *S. Castor photo.*

Frehner Aggregate Operation at Sloan near Las Vegas. *D. Bryan photo.*

Huck Salt Operation, Sand Springs Marsh, Churchill County, Nevada. *S. Castor photo.*

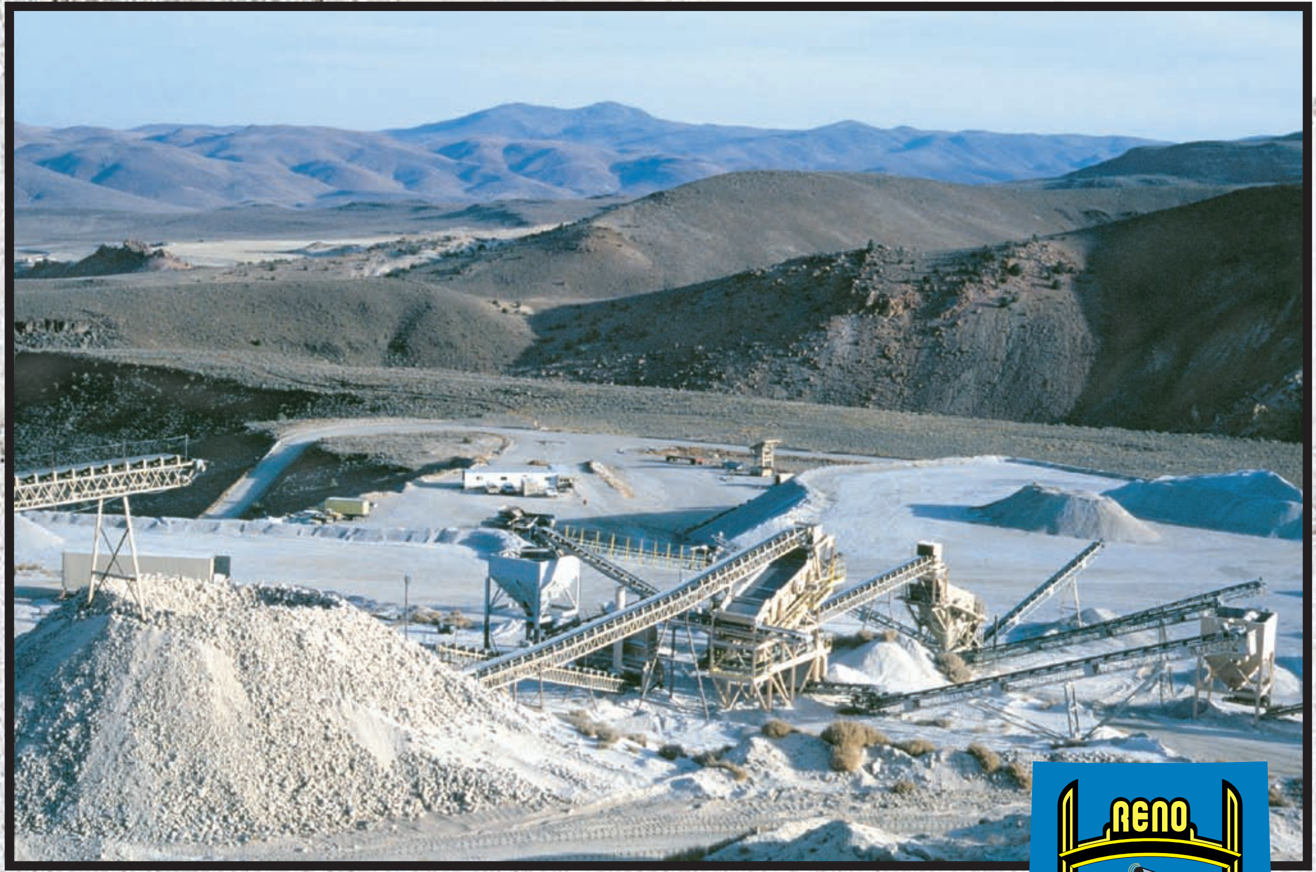
Proceedings of the 39th Forum on the Geology of Industrial Minerals

NBMG Special Publication 33

Proceedings of the

39th Forum on the Geology of Industrial Minerals

May 18–24, 2003



Nevada Bureau of Mines and Geology
Special Publication 33

Betting on Industrial Minerals

Reno, Nevada

J. Hursh photos

John Ascuaga's Nugget Hotel and Casino in Sparks, Nevada, venue for the 39th Forum.

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John Ascuaga's Nugget Hotel and Casino

Background photo: Adams Gypsum Mine field trip. *D. Bryan photo.*

Front cover photo: RMC All-Lite lightweight aggregate operation, Mount Washington, Storey County, Nevada; Truckee River Canyon and the Pah Rah Range in the background. *S. Castor photo.*

Front and back cover background photo: Eagle-Picher Clark diatomite deposit. *D. Bryan photo.*

The Nevada Bureau of Mines and Geology

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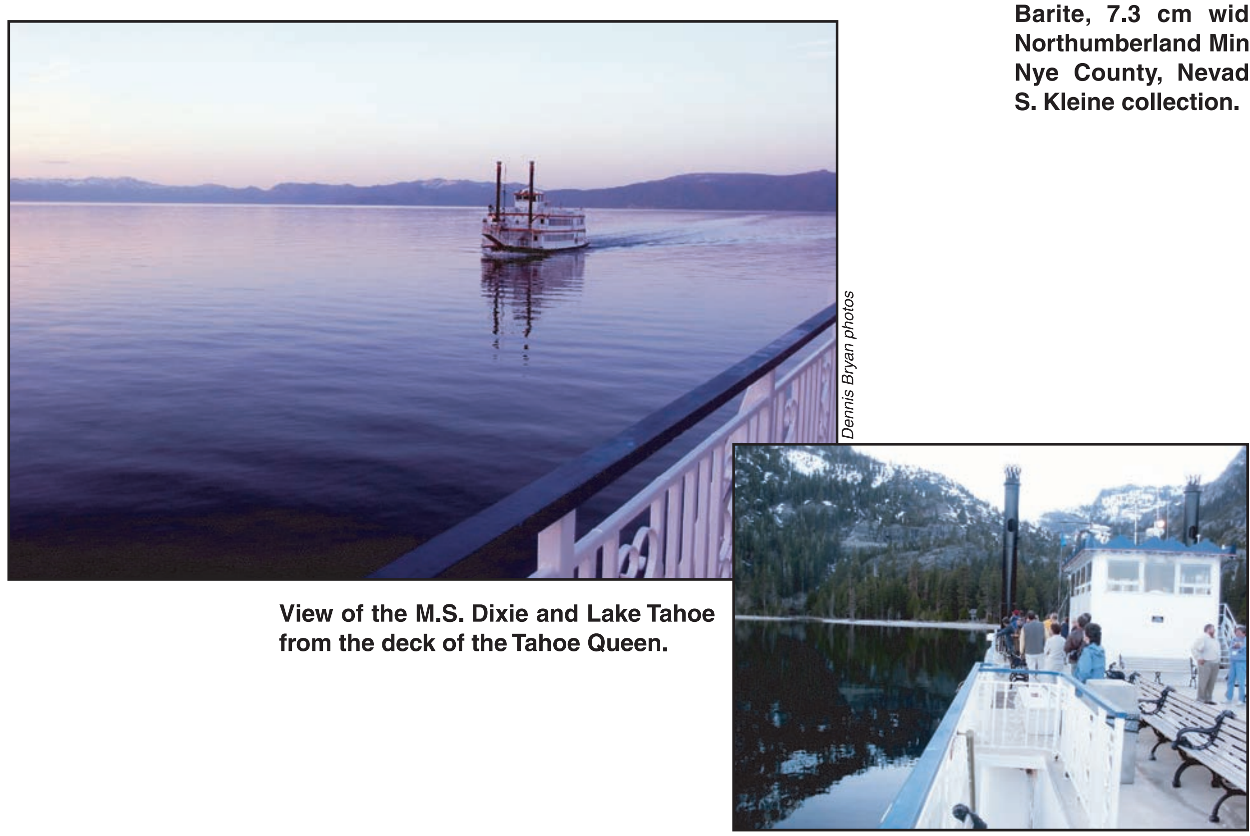
Barite, 7.3 cm wide, Northumberland Mine, Nye County, Nevada, S. Kleine collection.

Dennis Bryan photos



View of the M.S. Dixie and Lake Tahoe from the deck of the Tahoe Queen.

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Special Publication 33

Betting on Industrial Minerals

Proceedings of the 39th Forum on the Geology of Industrial Minerals

Reno/Sparks, Nevada
May 18–24, 2003

Edited by

Stephen B. Castor
Keith G. Papke
Richard O. Meeuwig

2004

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OF NEVADA
RENO

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Annual Meetings of the Forum on the Geology of Industrial Minerals

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario, Canada
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta, Canada
28th	1992	Martinsburg, West Virginia
29th	1993	Long Beach, California
30th	1994	Fredericton, New Brunswick/Halifax, Nova Scotia, Canada
31st	1995	El Paso, Texas
32nd	1996	Laramie, Wyoming
33rd	1997	Quebec City, Quebec, Canada
34th	1998	Norman, Oklahoma
35th	1999	Salt Lake City, Utah
36th	2000	Bath, England
37th	2001	Victoria, British Columbia, Canada
38th	2002	St. Louis, Missouri
39th	2003	Reno/Sparks, Nevada

Pyramid Lake, Nevada.
D. Bryan photo.

Preface and Acknowledgments

The Forum on the Geology of Industrial Minerals is an annual meeting that sponsors the exchange of information on industrial minerals and rocks. Attendees include industry personnel, consultants, government employees, and educators. The meeting provides a platform for presentations on the geology, production, uses, economics, and marketing of industrial mineral commodities, and political and environmental concerns with industrial mineral mining. It also includes field trips to local or regional industrial mineral operations and other points of interest. Each year the Forum is held in a different locality and is generally hosted by a state or provincial geologic survey or by an educational institution. The Forum was initially founded in 1965 by Professor Robert L. Bates of Ohio State University.

Forum attendees from our fair state have been pestered for many years with the question, “When are you going to host a Forum in Nevada?” At the 36th Forum on the Geology of Industrial Minerals in Bath, England, the Forum Steering Committee sequestered the Nevada delegation, threatening medieval torture unless Nevada recognized its inherent obligation to host a future Forum. Upon its return home, the delegation gingerly approached Jon Price, State Geologist and Director of the Nevada Bureau of Mines and Geology (NBMG), who immediately and delightedly committed formidable NBMG resources toward the 39th Forum on the Geology of Industrial Minerals. The Forum was held May 18–24, 2003, at John Ascuaga’s Nugget Hotel and Casino, Sparks, Nevada. NBMG served as host, along with the Nevada Division of Minerals and the Nevada Mining Association.

Nevada is a mining state, and we are proud of its past mining history and the unprecedented gold mining boom of today (see Fields, this volume). In total dollar value, gold mining produces nearly twenty times as much as industrial minerals; however, Nevada has a varied array of productive industrial mineral deposits (Castor, this volume), and some of the state’s industrial mineral mines have longevity records that surpass those of any of its metal mines. We hope that the attendees took advantage of the many attractions in Reno, “Biggest Little City in the World,” along with its sister city Sparks. In tune with the setting, the theme of the 39th Forum was “Betting on Industrial Minerals.”

Preparation for the 39th Forum began in 2000 with the following Organizing Committee: Dennis Bryan (Mactec Engineering), Alan Coyner and Walt Lombardo (Nevada Division of Minerals), Cami Prenn (Mine Development associates), Diane Bryan (Nevada Mining Association), Greg French (consultant), Bill Pennell (U.S. Borax), Keith Papke (consultant), Mario Desilets, Larry Garside, Terri Garside, D.D. LaPointe, Ron Hess, Beth Price, Jon Price, and Steve Castor (NBMG). In addition, Joe Tingley (NBMG), Ken Santini (Santini and Associates), Nathan Robison (University of Nevada), and Deborah Selig (Nevada Division of Minerals) joined the crew later to help with field trips.

The 39th Forum was attended by 251 participants from 31 U.S. states, seven countries, and four continents. Of the attendees, 68% were from industry (including support companies and consultants), 23% were from state and national government, and 9% from educational institutions. The Forum included three days of technical sessions that featured 46 talks and 11 posters. The presentations mainly focused on industrial mineral deposits, geology, and mining issues in Nevada and other western states, but talks and posters on worldwide industrial mineral resources and issues were included. A session on gemstones and collectable minerals was particularly well received.

In addition to the host and co-host organizations, the Forum would not have been possible without the help of the sponsors who are listed on the inside front cover of this volume. In addition, we thank the personnel of many mining companies that hosted field trip stops.

Field trips to industrial mineral deposits are an important and traditional part of the Forum on the Geology of Industrial Minerals, and eight field trips were offered to attendees of the 39th Forum. Two one-day pre-meeting trips provided visits to industrial mineral sites in the Reno/Sparks area. Trip 1, led by the 39th Forum’s co-chairmen, visited Eagle Picher’s diatomite mine at Clark Station, Nevada Cement at Fernley, Basalite’s lightweight aggregate operation near Dayton, and Art Wilson Company’s Adams gypsum mine near Mound House. The mine visits were followed by a short stop in the famous Virginia City mining camp. Trip 2, led by Keith Papke and Larry Garside, featured a tour of U.S. Gypsum’s Empire Mine and plant, followed by a ravioli lunch at Bruno’s Country Club, a well-known Nevada eatery, and a visit to Planet-X pottery. The trip then proceeded around the Smoke Creek Desert (a very large desert dry lake) to the halloysite mine of Nevada Cement Co., and returned to Sparks following a route along the west side of Pyramid Lake.

Four half-day field trips were available on the afternoon of the second day of technical sessions. Trip 3, led by Dennis Bryan, visited Reno area aggregate deposits, including All Lite Aggregate’s semi-lightweight aggregate quarry at Washington Hill, Granite Construction’s Lockwood andesite quarry, RMC’s Wadsworth sand and gravel operation, and Martin Marietta’s diorite quarry near Sparks (see Bryan and others, this volume). Trip 4, led by D.D. LaPointe and Jon Price, visited the Celite (World Minerals, Inc.) diatomite plant in Fernley, then traveled east of Fernley to one of Celite’s diatomite pits (see Houseman, this volume) where Miocene fish fossils were collected. Trip 5, led by Keith Papke and Larry Garside, traveled to Pyramid Lake for a presentation on the history of the lake and the genesis of tufa, followed by a visit to tufa outcrops. Stops were then made at a deposit of unconsolidated calcium carbonate previously mined for poultry feed and soil conditioner, and at the Nevada Cement clay pit. Field Trip 6, with Nathan Robison as leader, traveled into the Sierra Nevada near Truckee, California, to visit aggregate operations. The first stop was a Teichert Aggregate pit reclamation project at Donner Lake. Following this, visits were made to a Teichert pit in glacial gravels, a Martin Marietta cinder mine, and a Granite Construction basalt quarry.

Two three-day post meeting trips were available, one to industrial mineral deposits in northern Nevada, and one in southern and central Nevada along a route from Las Vegas to Sparks. Trip 7, the northern Nevada trip, was led by Keith Papke and Larry Garside. For the first two days the trip followed a route that includes the emigrant trail first used in 1841, the first transcontinental railroad, and modern Interstate 80. First day stops were a geothermal vegetable dehydration plant at Bradys Hot Springs, a perlite deposit near Lovelock owned by U.S. Gypsum Co., an Eagle-Picher diatomite mine, and a large zeolite deposit. Overnight accommodations were at Lovelock. Second day visits were to the Lone Tree Mine of Newmont Gold Co. and a barite deposit and mill operated by M-I Drilling Fluids. The second night was spent in surprisingly upscale accommodations at Battle Mountain, proclaimed “The Armpit of America” by the Washington Post in 2001, and site of “Festival in the Pit” sponsored by Old Spice. The last day included a visit to Austin, a historical 1860s mining camp, and travel along U.S. Highway 50, labeled “The Loneliest Road in America” by Life Magazine in the 1980s. Additional stops included an 1860s stage and telegraph station, a viewpoint for a Pony Express station and a large sand dune, and the Huck salt operation, a renewable playa mineral source.

Trip 8, with Ken Santini and Joe Tingley as leaders, included an early-morning flight to Las Vegas, where the intrepid attendees boarded a bus for the rest of the trek. The first day’s itinerary included the PABCO gypsum operation east of Las Vegas for tours of the mine and wallboard plant, a visit to the Chemical Lime pit and plant at Apex, a trip through the oasis-like Virgin River Valley to the Simplot Silica mine and plant at Overton, and travel through the scenic Valley of Fire State Park and back through Las Vegas to overnight accommodations in downtown Amargosa Valley, Nevada. Second day visits were to the IMV clay (Wahl and Papke, this volume), Badger Mining clinoptilolite, and American Borate Company operations. Following a presentation at Zabriski Point, California, by U.S. Borax, Inc. on historical borate mining (see Carpenter and others, this volume), the trip continued to Furnace Creek Ranch, then north through Death Valley, ending the day in historical Tonopah, Nevada. The third day included stops at the Silver Peak, Nevada, lithium brine operation (Zampirro, this volume), and at the Premier Chemical magnesite mine at Gabbs during the return to Sparks.

Guest activities included trips that were arranged and led by Diane Bryan and Beth Price. The first was a historical tour of the Virginia City silver-gold mining camp, now a tourist destination, led by Becky Purkey who provided anecdotes about the historical boomtown. The guests then had lunch at the Governor’s Mansion in Carson City, Nevada’s capital, where they met Mrs. Mary Louise Mackay, wife of Comstock millionaire and Mackay School of Mines namesake (actually Chautauqua performer Janet Bremer) and viewed the famous Mackay silver collection. The second day featured a morning visit to the W.M. Keck Museum of the Mackay School of Mines hosted by museum administrator Rachel Dolbier, along with a walking tour of old Reno. On the final day of technical sessions, a day-long trip to the Sierra Nevada included a visit to the Cal Neva Resort in Crystal Bay on the California/Nevada border on Lake Tahoe, playground of such 1950s and 1960s celebrities as Frank Sinatra, Marilyn Monroe, and J.F. Kennedy. Lunch and shopping in Truckee and a tour of Donner Lake State Park, made famous by a party of unfortunate wagon-train emigrants in 1846, completed the trip.

Evening social activities included a dinner cruise on Lake Tahoe, a pub night, and the traditional Forum banquet. These activities were arranged by Diane Bryan, Mario Desilets, Terri Garside, and D.D. LaPointe. The dinner cruise aboard the Tahoe Queen, a true paddle wheeler (although diesel powered), sailed from South Lake Tahoe, California, to Emerald Bay where a genuine California black bear was sighted near the lakeshore by sharp-eyed cruisers on the outside deck (we’re not sure how this was arranged—Diane’s not saying). Dinner was followed by dancing to the music of the Tahoe Queen’s dance band. The pub night was held at the Great Basin Brewing Company, purveyors of famous Nevada microbrews such as Ichthyosaur Pale Ale (named for the Nevada State Fossil and fondly known as “an Icky”). This brewpub is an example of geologists applying some of their nongeologic skills; the owners and the former brew master were trained in geology. The banquet, arranged by Mario Desilets, was held at the Nugget and featured Basque food and entertainers, and a silent auction where participants were able to acquire wine and food baskets, mineral specimens, and other mineral paraphernalia at bargain basement prices. More than $3,000 raised by the auction has been donated to the Bates Scholarship Fund to support student attendance at future Forums.

NBMG is pleased to present this proceedings volume for the 39th Forum. The papers and abstracts in this volume have been through a peer review and editing process similar to that used for other NBMG publications (two reviews for content along with editorial reviews). The reviewers were: George Austin, James Barker, Anthony Bauer, Dick Berg, Dennis Bryan, Jim Carr, Steve Castor, John Clatworthy, Al Coyner, Forrest Cureton, Peggy Dalheim, David Davis, Rich DeLong, John Dobra, Kelly Downing, Greg Ferdock, Richard Fox, Greg French, Larry Garside, Ray Harris, Tim Hall, Dan Hausel, William Hood, Michael Houseman, Matt Joeckel, Blair Jones, Bob Kellie, Stan Krukowski, Kim Lapakko, Bart Loudagin, James Mason, Lance Mead, Keith Papke, Don Peel, Bill Pennell, Jon Price, Randy Rice, Ian Scarr, Dale Siegford, Dan Thorne, Joe Tingley, Bryce Tripp, Joe Tingley, Peter Vikre, and Alan Wallace. The following NBMG personnel are thanked for their hard work during the publication of this volume: Dick Meeuwig (editing), Susan Tingley (illustrations), Jack Hursh (layout), and Kris Pizarro (illustrations).

Finally, the presenters at the 39th Forum on the Geology of Industrial Minerals are thanked for their efforts. Authors of full-length papers presented in this volume are especially thanked for taking the time to prepare and revise their manuscripts.

Steve Castor (NBMG)
Dennis Bryan (Mactec Engineering)
Co-chairmen, 39th Forum

Technical Sessions

Monday, May 19

Session 1, General Geology, 8:00–9:50AM, Chair J.G. Price

Welcome and annnouncements-D.P. Bryan

Faulds, J.E.	Geology of the western US Cordillera: a long-lived orogenic belt
Price, J.G.	Geology of Nevada
Fields, R.A.	Gold and the Nevada economy
Castor, S.B.	Industrial minerals in Nevada
Bon, R.L.	An overview of the minerals industry of Utah with an emphasis on industrial rocks and minerals

Session 2, Aggregate and Stone, 10:20AM–11:40AM, Chair D.P. Bryan

Bryan, D.P., Robison, N.E., and Castor, S.B.	The Nevada construction aggregate industry
Kohler, S.	Aggregate availability in California
Mead, L.	Dimension stone in North America
Harris, R.E.	The dimensional and decorative stone industry in Wyoming and the West

Session 3, Brines and Evaporites, 1:00–2:40PM, Chair W. Pennell

Zampirro, D.	Hydrogeology of the Clayton Valley brine deposits, Esmeralda County, Nevada
Barari, D., and Richardson, A.A.	Enhanced in situ recovery of soluble evaporite minerals using heat
White, W.W. III	Replenishment of salt to Bonneville Salt Flats: Results of the five-year experimental Salt Laydown Project (1997–2002)
Brown, N., Lamos, P., and Scarr I.	Present-day features relating to the deposition of trona at Owens Lake, Inyo County, California
Holmes, D.A., and Harben, P.W.	Pleistocene potash brine deposits: comparison of six world commercial sources

Session 4, Energy Efficiency and Mining, 3:10–4:10PM, Chair M. Canty

Cockrill, C.	Energy Efficiency Tools and Support for Industry
King, A.R., Edgerton, S., and Casada, D.	Hanson Aggregates East, cost savings through system optimization and efficiency
Swenson, R.J.	Proven energy cost reduction stategies-the US Magnesium LLC experience

Tuesday, May 20

Session 5, Clay and Rare Earths, 8:00-9:20AM, Chair S.B. Castor

Cowley, J. and Palmer, Q.	2000 years of history—what future for ball clay extraction in the UK?
Heivilin, F.G.	The road to Hungry Valley
Wahl, W. and Papke, K.	The IMV story—sepiolite and saponite
Castor, S.B., and Nason, G.W.	Mountain Pass rare earth deposit, California

Session 6, Marketing, Permitting, Valuation, and Environmental Concerns, 9:50–11:50AM Chair J.M. Brown

Clifford, P.R.	The future of the Florida phosphate industry
Van Gosen, B.S., Lowers, H.A., Sutley, S.I., and Gent, C.A.	Asbestos-bearing talc mines, southern Death Valley Region, California
DeLong, R.F.	Land-use conflicts/NIMBYs
Brown, J.M.	Environmental regulations and their effects on industrial minerals
Arbogast, B.F.	The need for new paradigms in mining reclamation and visual resource management
Parkinson, C.L.	Valuation of stone, aggregate, and industrial mineral properties

Wednesday, May 21

Session 7, Borates, Perlite, and Diatomite, 8:00–9:40AM, Chair G.M. French

Carpenter, S.B.	Borates in western North America
Barker, J.M. and Santini, K.N.	Turmoil in western US perlite markets in 2002
French, G.M.	The geology and development of the Tucker Hill perlite deposit, Cornerstone Industrial Minerals Inc., Lakeview, Oregon
Wallace, A.R.	Regional geologic setting of late Cenozoic diatomite deposits in the Great Basin
Houseman, M.D.	Late Miocene diatomite formation near Fernley, Nevada

Session 8, Soda Ash, Cement, and Limestone, 10:10–11:50AM, Chair A. Coyner

Santini, K.N.	U.S. soda ash producers
Hardy, S., Elgby, B., and Bryan, D.P.	Nevada Cement Company plant and raw materials, Fernley, Nevada

Technical Sessions *(continued)*

Wednesday, May 21

Session 8 continued

Tripp, B.T.	High-calcium limestone deposits and uses in Utah
Ahtola, T. and Reinikainen, J.P.	Paleoproterozoic marbles in the Svecofennian Domain, Finland
Itamar, A., and Mimran, Y.	Carbonate rock production in Israel

Session 9, Silica, Barite, and Garnet, 1:00–2:00PM Chair P. Vikre

Jahn, J.P.	Industrial sand in the U.S.
Koski, R.A. and Hein, J.R.	Sea-floor barite deposits at active continental margins: Analogues for stratiform deposits in Nevada?
Santini, K.N., and Barker, J.M.	Ruby garnet operation, Montana

Session 10, Gemstones and Mineral Collectables, 2:30–4:30PM, Chair G.C. Ferdock

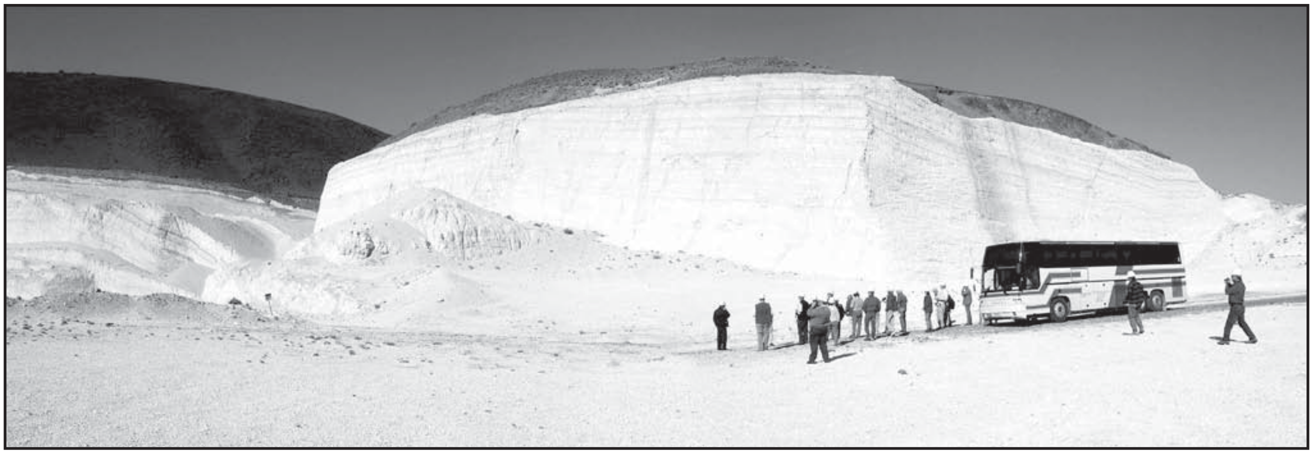
Berg, R.B.	Alluvial sapphire deposits in southwestern Montana
Cleary, J.G.	Discovery of jadeite in Guatemala
Ferdock, G.C.	World-class mineral specimens from Carlin-type gold deposits in the Great Basin of the western U.S.
Hausel, W.D.	Gem-quality cordierite (iolite) and corundum (sapphire, ruby) in Wyoming
Jones, C. and Jones, J.	Specimen recovery at the Meikle and Murray Mines in Elko County, Nevada

Closing session, 4:30–4:45PM

Shaffer, N.R.	Indiana welcome—40th Forum on the Geology of Industrial Minerals

Posters

Anderson, D.M.	Carrara Marble and Cement Company deposits, southern Nye County, Nevada
Edwards, W.A.D., and Budney, H.D.	Sand and gravel resource mapping in Alberta, Canada
Callicrate, T., and Griffin, L.	The Lincoln Hill dumortierite deposit, Rochester district, Pershing County, Nevada
Gedikoğlu, A., Uz, B., and Kumral, M.	Turkish magnesite deposits
Hegazy, H.A.	Crystal growth and formation of chemical zoning in some Egyptian red-brown garnets as gemstones, Eastern Desert, Egypt
Joeckel, R.M., Tucker, S.T., Clement, B.J.A., and Swigart, J.M.	The life, death, and resurrection of an underground diatomite mine in Nebraska
Kohler, J.F., and White, W.W.	Characteristics of the near-surface brine resources in the Newfoundland Basin, Tooele and Box Elder Counties, Utah
Papke, K., and Castor, S.	New industrial minerals of Nevada map
Peel, D., and Richards, J.	The application of sustainable development principles to the Alberta aggregates resource sector
Uz, B., Bacak, G., and Gedikoğlu, A.	Evaluation of granite and pegmatite occurrences of the Armutlu Peninsula (Ihsaniye, Karamursel, Kocaeli), Turkey, as ceramic raw material
Wolfe, M.E.	Hunting an elusive quarry: Geology and early stone architecture in Ohio



Field Trip 7 attendees, Eagle-Picher Clark diatomite deposit. *D. Bryan photo.*

Exhibitors

Rio Tinto - Borax
U.S. Geological Survey
Converse Consultants
Ruen Drilling
Geotemps, Inc.
Northwest Mining Association
Spectral International
Bell Marine Co.
Bureau of Indian Affairs
Industrial Minerals
Mine Development Assoc./Terrasource Software
Nevada Mining Association
Anadarko Petroleum Co.
Women's Mining Coalition
Granite Construction Co.
Mackay School of Mines
Society of Economic Geologists
Nevada Bureau of Mines and Geology
Nevada Division of Minerals
Geological Society of Nevada
Boart/Longyear-Lang Exploratory Drilling
Prosonic Corporation
Enviroscientists, Inc.
Geological Society of America
California Geological Survey

Field Trip 1 attendees at the Nevada Cement plant, Fernley, Nevada. *D. Bryan photo.*

Field Trip 7 attendees at Sand Mountain, Nevada. *H. Budney photo.*

Eagle-Picher Clark diatomite mine tour. *D. Bryan photo.*

Tertiary sediments at the Nevada Cement mine tour. *D. Bryan photo.*

Paleoproterozoic Marbles in the Svecofennian Domain, Finland

Timo Ahtola, Jukka Reinikainen, and Hannu Seppänen
Geological Survey of Finland

Introduction

The Geological Survey of Finland (GTK) has carried out calcite exploration for five years in the Uusimaa Belt, southwest Finland (fig. 1). The Uusimaa Belt forms a part of the Svecofennian Domain, and it belongs to an accretionary arc complex of southern Finland (1.90–1.82 Ma, Korsman and others, 1997). The aim was to find calcite marble deposits suitable for the production of ground calcium carbonate (GCC) for the paper industry. The main motive has been the significantly increased domestic use of paper pigments (fig. 2). The consumption of GCC has increased steadily throughout the 1990s. In 2002 the consumption of GCC was 1 Mt (million metric tons) of which 0.5 Mt was produced in Finland.

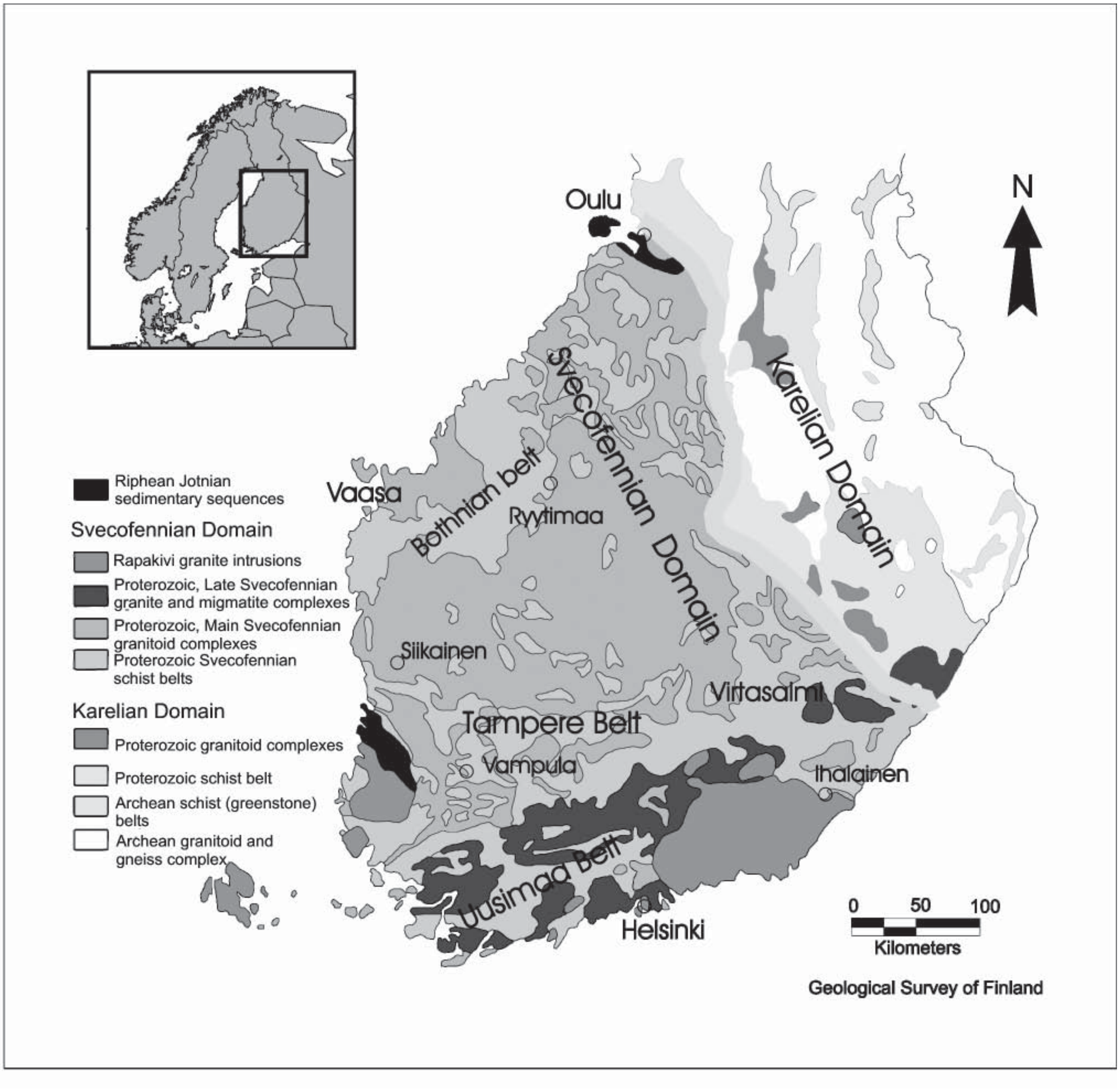


Figure 1. The Svecofennian Domain is a 1.9 Ga metamorphic terrain composed of volcanic-sedimentary schists and migmatite gneiss belts, intruded by granitoids.

New Paradigms are Needed in Mining Reclamation and Visual Resource Management

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Abstract

Historically, surface mining reclamation has been approached from various considerations: desired land use, regulatory requirements, and more recent societal values (including aesthetics, ecosystem diversity, and sustainability). It is time to break out of our current thinking regarding landscapes and mining reclamation. The form of our landscapes continually changes, yet traditional methods of visual resource methodology treat landscapes as framed-as if they were a landscape in static equilibrium. But landscapes are not framed because we exist in landscapes, not outside them. Rather than treating landscapes as objects, reclamation projects should recognize them as complex, continually changing, natural processes, by treating them as integrated systems.

Visual analysis experts argue over fundamental visual elements. Does aesthetic value revolve around form (fundamental earth landforms or vegetation), function (such as hazardous areas, ecological succession) or experience (within the context of culture or history)? Perhaps a computer program can be written to identify "natural design restoration" and "scenic attractiveness." The Internet may become a vehicle for relatively inexpensive and quick canvassing of public opinion to determine user values in landscape preference. Visual resource management must relate landform, biological, and cultural attributes to scenic beauty in an economical and practical manner that will better inform the public, mining industry, and planners. Utilizing an impartial, objective point of view in visual assessment remains a worthy goal in mining reclamation.

Visual Resource Management as an Essential Element of Mining Reclamation

The public and courts are demanding articulate design choices and objective standards in mining reclamation and visual landscape assessment. The visual landscape is considered a resource and perceived negative impacts generate much controversy in the mine permitting process. The mining process itself is also an important element to consider in a visual resource management program. The selection of data (direct observations) and its analysis involves more than sound science, it involves social and political perceptions. According to Klosterman "Philosophers now recognize that "social" facts and values are culturally defined and can both be defended and criticized in ways that parallel the "objective" methods of science" (Klosterman, 2001, p. 10). Yet, subjective decisions are still a varying portion of all human creative processes, whether scientific hypothesis or design approach (Hanna and Culpepper, 1998). Many methods in visual resource management, as they stand now, are more theoretical than practical and have conflicting definitions (Arbogast, 2002).

The application of aesthetic attributes in resource management in no way precludes the importance of other resources (such as vegetation associations, soil types, and geomorphology). Landscape assessment should include biological and physical elements as part of scenic attractiveness, along with public preference, genius loci (sense of place), and ecosystem diversity. It is the combination of science and art that is vital for a project's success. Eight design approaches to reclaiming mine sites were examined by Arbogast and others (2000). One of these, the integrated approach, combined science and art in a human-nature ecosystem.

This author began graduate school in landscape architecture with a bachelor of science degree in forensic chemistry having no idea (other than intuition) what was involved in the design process and planning. Students had to learn how to articulate their design choices and substantiate them. One of the earliest lessons learned in the studio was to be able to defend why any line or point was on a drawing. But what proof did one provide? "To use a legal analogy: scientists work to meet the standards set for criminal cases (which must be proven 'beyond a reasonable doubt'); journalists [or designers], because of deadline pressures, more often work at the level of civil cases (where preponderance of evidence is the standard of proof)" (Hartz and Chappell, 1997, p. 14). One could argue we (planners, industry, or government agencies) don't meet that standard as much as we should in visual resource management.

The Land Use Concept in Landscape Description

In attempting to deal with surface mining reclamation and visual resources, three general considerations emerge: 1) land use, 2) regulation, and 3) aesthetic value. Previously, land-use decisions were not based upon visual attributes and aesthetics because these factors were viewed as "non-scientific." That perception by government authorities may be slowly changing.

Most existing visual assessment methodologies deal with natural or rural landscapes. There is very little literature concerning visual aesthetics of urban areas yet that is where the majority of people live and where land use conflict frequently occurs (residential living versus mining versus agricultural or open space). Although many pits and quarries may initially be located outside city limits, with time and development, population centers encroach on existing mine sites generating the need for visual resource management in an urban setting. Population growth, suburban development, and political self-determination play a role in increased county government and services. Local governments in turn attempted to deal with the increasing need for mineral resources and visual impact mitigation in their zoning and land use regulations. Zoning in the United States dates back to the 1920s in an attempt to separate industry, commercial, and residential activity in urban areas. Public safety and health were the major public values, not aesthetics.

Extremely large mines with long life spans may not have a defined post-mining land use and can generate great vocal opposition due to the scale of visual impact. Some counties address this issue by restricting mineral resource development from lands defined as 1) wildlife habitat, 2) agricultural lands, and 3) natural landmarks and natural areas. Natural areas are landscapes recognized for one or more unique characteristics of natural beauty, geology, soils, vegetation, or historical significance. Natural landmarks can be specified as "* * * prominent landscape features that distinguish a specific locality * * * and are important because of the views they afford, their value as scenic vistas and backdrops, and the intrinsic value they hold* * *" (Boulder County, Colorado, 2000, p. 3). The landscapes may have additional cultural, ecological, or geological attributes.

The Jefferson County Mineral Extraction Policy Plan (Jefferson County, Colorado, 1977) went further and established a point system (between "0" and "100") for evaluating mine sites according to their ability to conform to County goals. Points are awarded for such characteristics as: visual impact, unique vegetation, wildlife habitat conditions, archaeological sites, historic sites, significant geologic features, geologic hazards, and quality of material resource. The ratings aren't used as final criteria in approval of mining cases but rather provide a reference point for review.

The Regulatory Concept in Landscape Description

Visual resource management advanced with the 1960s ecological movement to quantify land value. Federal laws ranging from the Surface Mining Control and Reclamation Act of 1977 (P.L. 95-87, 91 Stat. 445) to the Endangered Species Act and Wilderness Act deal with the aesthetic, ecological, historical, and economic value of landscapes. Thus the second consideration for landscape assessment is rooted in regulation. The National Environmental Policy Act of 1969 (42 USC£ 4321 et seq. in the United States Code) contains language requiring all practicable means to assure aesthetic and culturally pleasing surroundings, but the methodology of aesthetic resource evaluation is not specified. A landmark Supreme Court decision was made in Berman v. Parker, 1954, in which public values were broadened to include spiritual, physical, monetary, and aesthetic impact (Smardon and Karp, 1993). According to Smardon and Karp (1993) there is case law supporting aesthetics as meaning 1) visual beauty, 2) prevention of nuisance-type harms, 3) shared human values (i.e., aesthetics is a resource and interwoven with quality of life), or 4) environmental harmony (a broader concept that includes human and nonhuman values).

Most State and Federal considerations involve meeting regulatory requirements, tend to focus on impact mitigation, and may require an environmental impact statement. As in most regulations, there is a balancing act between being too general and ineffective versus too complex and restrictive.

The Concept of Aesthetics in Landscape Description

Western industrial society places a preeminent value on beauty. Just look at the appeal of entertainment and sports figures, plastic surgery, clothing, and decoration. The problem is in defining beauty. The public may not be able to define scenic landscapes or beauty, but they believe they know "ugly" when they see it, and to them any pit or quarry is ugly and thus a consideration in mine permitting and reclamation. In the European Union, the term "beauty" is used to establish a landscape aesthetic and there is more emphasis on a holistic approach to environmental and resource management. But the Europeans have not succeeded in defining "beauty" any better than we have. Attempts have been made to consider landscapes as works of art and place them in the context of the human and natural environment. It has been pointed out that landscapes are not framed works of art any more than a natural history diorama or botanical garden is the same thing as the natural landscape.

Immanuel Kant and Georg Hegel were two of the most important German philosophers of the 18th and 19th centuries. Kant's theory of aesthetic value concerns the notion of beauty, which he treats as applying primarily to natural objects and secondarily to works of art (Whewell, 2002). Kantian aesthetics focuses on aesthetic experience (observer or user perception) and on the contemplation of form (physical). Both perspectives are utilized in visual assessment studies when surveying public preferences and in site analysis. Hegel provided a more systematic and comprehensive aesthetic theory of the modern world (Shapiro, 2002). His approach to the arts was to understand them in terms of a meaningful succession of styles, or as expressions of the worldviews of culture or historical periods. Hegelian aesthetics emphasize the meaning and content of works of art (Shapiro, 2002). This philosophy is apparent in visual assessment methods that examine the sense of place and the observers' point of view.

The U.S. Forest Service (1995) "Landscape Aesthetics: A Handbook for Scenery Management" methodology is based upon a social and ecosystem paradigm, considered public oriented, and interdisciplinary. It combines user analysis (people's values and expectations), visual or site analysis, and ecology in a broad approach. This paradigm allows for changes in the natural landscape and accepts the cultural landscape. The physical, biological, and social components of ecosystems are inventoried and analyzed but professional judgment still comes into play. The U.S. Forest Service has a premise that scenic attractiveness is based upon human perceptions of beauty in landform, water, and vegetation. They, as most resource managers, recognize aesthetic value is not a stand-alone program but is one part of a larger environmental protection program.

From another federal perspective, the National Park Service (2001) refers to certain values perceived through the senses (such as scenic vistas, natural quiet, solitude, space, a sense of history, sounds of nature, and clear night skies) as "aesthetic." These aesthetic values are sometimes intangible but are to be protected along with tangible resources (such as animals, plants, water, geologic features, historic buildings and monuments, and archaeological sites).

The Relation of Natural Processes and Aesthetic Values

Physical scientists say geology and hydrology are vital to successful mining and reclamation. There are landscape architects who design landforms from the standpoint of aesthetics and function, claiming to combine art and science. Engineers design landforms from the standpoint of ground conditions, claiming civil engineering is a combination of science, art, and professional skill vital to project success (Waltham, 1996). The engineers are interested in ground subsidence, slope failure, rock strength etc. But a slope engineered for its own equilibrium angle may not be the best shape for the landform to fit into its surroundings.

A few geomorphologists and hydrologists have been involved in reclamation work wherein the goal is to work with natural processes. Trimble (1997) noted the up-front project costs of working with natural processes (including design work) may be greater but construction and maintenance costs are lowered. Geomorphologic designs yield a greater variety of slope aspects and lengths (providing greater diversity), long-term stability comparable with natural land, and greater visual harmony (at least in terms of blending in with the surrounding "natural" landscape) (Bugosh, 2002). One example: landscapes having eroded forms to begin with are proposed to include gullies, cut banks, and steep slopes in the reclamation plan. This approach may run contrary to existing reclamation regulations. How would one implement such a paradigm in the urban environment? Critics claim no landscape is truly sustainable and there are costs/tradeoffs involved somewhere. Geomorphologic impact assessments are also affected by a considerable degree of subjectivity with decision makers and planners still tending to consider the landscape in a static equilibrium rather than complex dynamic processes (Marchetti and Rivas, 2000).

Felleman, one of the main experts in visual analysis, states that the shapes of earth landforms are the fundamental visual elements, especially in mountainous and hilly areas, and they influence the parameters used to describe the visual sight (Brancucci and others, 2002). It is the amorphous nature of the parameters that become problematic to define.

Landform replication as a technique for reclamation of quarries is relatively new. Key factors in the construction (by "restoration" blasting) of varied slope sequences include rock screes, buttresses, and headwalls, which can be selectively vegetated to replicate natural limestone valley sides (Gunn and others, 1992). Practically speaking, Walton and Allington (1994) found landform replication significantly reduced recoverable reserves at a confined site and created problems in accommodating overburden and waste materials. They also found no guarantee that satisfactory revegetation will occur or that equivalent levels of slope stability can be established.

Another question is whether reclaimed sites resembling "natural" landforms are more beautiful than "sculptured" forms (earth art, where ecological values are expressed in a symbolic and visual mode) (Cole and others, 1976). There are examples where the reclaimed site is in contrast to the surrounding landscape but is not considered discordant. Giving people the information behind various design alternatives and the effect upon the Earth's environment builds understanding and may increase support for a project.

In the process of visual assessment and development, resource planners try to mitigate the negative impact of "human built" environments upon the natural landscape while at the same time protect humans from the natural landscape. Simultaneously, humans continue to build in areas that are known to be hazardous because of the powerful attraction for convenience, scenic views, esteem, and so on. How many times have homes been rebuilt along rivers following a flood? Despite the risk for natural disasters, we rebuild in floodplains or on unstable slopes, regardless of nature's power, but still complain of a proposed sand and gravel pit in the alluvium.

We ignore the natural change over time and complexity in whole systems that are a part of ecosystem aesthetics. In order for our natural (or built) systems to be sustainable we need to give more attention to evolutionary landscape. Planners and designers (and the public) work at keeping the landscape static, not wanting it to change, but it inevitably will change, both from a biological and cultural point of view. We remove mineral resources at a faster rate than we appear willing to allow the ecological healing process to occur. We want "natural landscapes" instantly. Can scientific attributes or sustainability yield exemplary visual aesthetics? Trimble (1997) points out one is still faced with the dilemma of measuring attributes such as integrity, health, stability, climax, production level, and so on.

Human beings are very much a part of the biologic landscape and natural landscapes are an idealized concept. "In fact there is no single moment in time that we can point to and say, this is the state of nature * * *" (Pollan, 1991, p. 186). If natural excludes anything human-made, when does an abandoned sand and gravel pit, farmland left fallow, logged forest, or reclaimed quarry as lake become natural? Many people consider urban street trees, their front yards, botanical gardens, agricultural fields, and grazing lands as natural.

Jordan's (1994) paradigm for a healthy relationship between humans and the natural landscape involves the ecosystems, an economic relationship with these systems, our cultural evolution (including physical, mental, emotional, and spiritual abilities), a sense of history, flexibility (because nature continues to change), and a way to articulate the terms of that relationship. He gives the example of 1960s national park restoration-as far as the public is concerned, the emphasis is on the creation of the "finished" ecosystem vignette (more like painting or sculpture) than on the ecologic process and relationship. Our environmental preferences (positive or negative) are "psychological" and reflect our experience, culture, and history.

Surveys and public meetings for determining landscape preference can aid in planning future mining sites and alternatives. The Internet has been used as a medium for landscape preference surveys and one study (Wherrett, 2001) had a response rate comparable with traditional postal mail surveys. It allowed a large region and number of respondents to be examined, was less time consuming to run than traditional surveys, although pages can take some time to load if there are many graphics, and the population sampling may be biased.

New computer software and methodologies may help planners and industry reclaim and heal the mined landscape in a more aesthetic, economic, and sustainable manner with public input. Geographic information systems and CADD have already speeded our design and scientific work. Some researchers have looked at fractal geometry as a way to approach the complex nature of landscape analysis. Others are investigating fuzzy logic in which spatial features may be vague and are expressed with degrees rather than a binary yes/no classification. Healthy landscapes and the processes of nature have been compared to "Chaotic" systems (dissipative, nonlinear feedback systems that are unpredictable and self-organizing) and exhibit self-similarity (patterns are repeated, with variations, at an infinite variety of scales) that is recognized as beautiful in our inherited sense of aesthetics (Turner, 1994).

Summary

There is a need for Western society to acknowledge that humans are an integral component of landscapes and to recognize the difficulty in distinguishing human from natural landscapes or ugly from beautiful scenes. Natural processes and human activities spatially interact to produce a continually changing landform. Traditional considerations of land use and zoning regulations (including the specification of landscape features and environmental impact statements) and scenery management tools that treat landscapes as pieces of art play an important role, but, do not provide a universally accepted methodology for assessing the visual impact of mining and reclamation, especially in rural or urban areas. Newer visual assessment paradigms may aid us in appreciating landforms more fully and to treat landscapes as a complex system rather than a simple object. Combining site ecology (including the hydrologic, geologic, and biologic processes), long-term landscape impact (i.e. ecosystem sustainability and biodiversity), and public opinion will strengthen visual resource surveys. It is important to share visual impact information, landscape alternatives, and mining's effect upon the earth up-front with the public to help integrate divergent opinions regarding the mining process.

One can report that 1,598 million tones of stone were consumed in the United States during the year 2000 (A.F. Barsotti and D.E. Morse, U.S. Geological Survey, written commun., 2003). It is a statement of fact that is used for forecasting resource needs or economic growth but does not convey the value of the resource in terms of human lives or the impact upon the environment. The more information we gather on complex systems the more difficult and confusing it may seem to understand and decide how to be in aesthetic harmony with the natural world. There is still a need for standards that meet a higher burden of proof in the various disciplines undertaking visual resource management. Enormous effort is also needed to make an effortless visual assessment methodology for mining landscapes that is practical, economical, and objectively valid.

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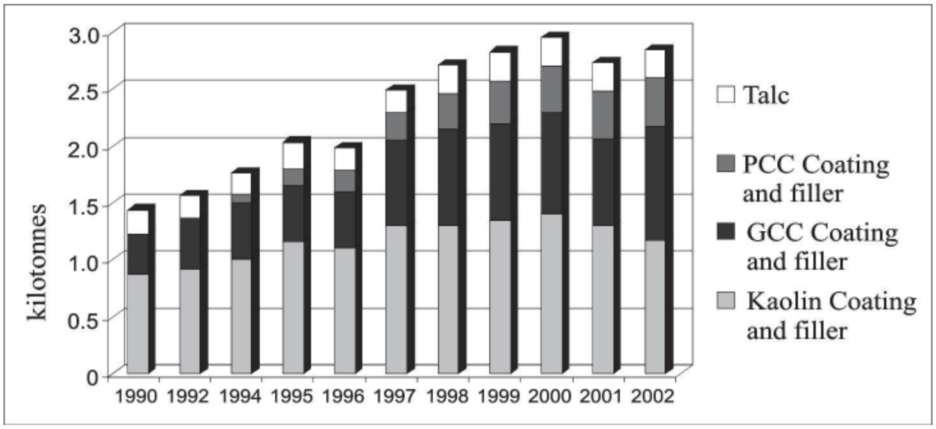

Figure 2. Consumption of paper pigments in Finland (1990–2002) in thousands of metric tons. The increasing demand for paper pigment minerals is the main reason for the prospecting of calcite marbles in southwest Finland.

Table 1. Mineral resources of the marble deposits studied in southern Finland (Sarapää and others, 2003).

Deposit	Resources	Depth	Ore content	ISO-Brightness < 20 µm	Stage	Owner
Norrlammala	7.1 Mt	75 m	78.2% calcite	91.5–92.1%	Under evaluation	Omya Oy
Calcite marble					for open-pit mine	
Genböle	5.3 Mt	100 m	87.1% calcite	90.0–91.7%		GTK
Calcite marble						
Illo	5.8 Mt	80 m	77.4% calcite	89.5–95%	Open for tender	GTK
Calcite marble	9.4 Mt	120 m	“			
	12.9 Mt	160 m	“			
Järvenkylä	1.9 Mt	75 m	80.3% calcite	91.2–94.7%		Nordkalk Co.
Calcite marble	3.2 Mt	125 m	82.4% calcite			
	7.7 Mt	300 m	“			
Kalkkimäki						
Calcite marble	2.0 Mt	75 m	81.6% calcite	91.1–92.9%	Open for tender	GTK
Calc-dolo marble	3.7 Mt	75 m	70.1% carbonate	88.2–90.4%	in 2003	
Woll-calc marble	2.0 Mt	75 m	14.7% wollastonite,			
			57.5% calcite			
Iso-Sorro						Nordkalk Co
Calcite marble	2 Mt	75 m	70% calcite	91.3–92.1%		
Dolomite marble	6 Mt	100 m	55% dolomite,			
			30% calcite			
Hyypiämäki	17 Mt	100 m	76% calcite	90.4–94.2%	Feasibility studies	Omya Oy
Calcite marble	or 7.2 Mt		86.7% calcite			
Kuovila	39 Mt	125 m	75% calcite		Open for tender	GTK
Calcite marble	or 20.2 Mt		81.8% calcite	90.4–95.9%	in 2003	
Woll-calc marble	9 Mt	125 m	54% calcite,			
			15% wollastonite			
Hakala	1.3 Mt	125 m	84% calcite	94.5–94.8%	Open for tender	GTK
Calcite marble					in 2003	

Calcite Exploration in Southwest Finland

During last five years, GTK has located and studied nine economically interesting calcite marble deposits in southwest Finland by mapping and drilling (table 1). Deposits are submitted to the Ministry of Trade and Industry, which sells the claim rights to mining companies. Six of the marble deposits studied have been sold to domestic and international industrial-mineral enterprises.

Geology of Svecofennian Calcite Marbles in Finland

Conclusions based on Jukka Reinikainen´s study (2001)

1. The Svecofennian carbonate rocks are for the most part calcite marbles; dolomite marbles are fewer and dolostones are minor. The marbles of the western part of the Uusimaa Belt (fig. 1) are calcitic in composition, whereas in the eastern part of the Uusimaa Belt they are composed of alternating calcite and dolomite marble layers. Based on evidence from the Virtasalmi district, the marbles in the Savo Belt are mainly dolomitic in composition, with a few marbles of calcitic composition.

2. The studied Svecofennian marbles are mostly interbedded with felsic volcanoclastic rocks and chemically precipitated cherts. During the precipitation of the Svecofennian carbonate rocks the volume of terrigenous clastic material (clay, silt, sand) was low. In the Uusimaa Belt the primary silicate interlayers of the marbles originated as cherts and volcaniclastic material. The latter were obviously deposited as ash-cloud tuffs and water-laid tuffites. In the Virtasalmi district the primary silicate interlayers are composed of cherts; the volume of volcaniclastic material was minor. At Norrlammala, based on U-Pb determination of zircons from a felsic volcanic rock, minimum age of the carbonate precipitation is 1.888±11 Ga. The precipitation of carbonates could have been chemical or organic. Primary organic structures, if such existed, may have been largely destroyed during the intense deformation and metamorphism. Thus, the absence of stromatolite structures in the Svecofennian marbles in Finland is not a quite unequivocal evidence of the absence of stromatolites in the original carbonate sediments. Anyway, the lack of stromatolite structures is compatible with the model that most of the Svecofennian carbonate sediments in Finland were deposited in deeper environments than the Karelian ones. However, the abundant chert layers suggest that the precipitation of the carbonate rocks was affected by organic activity.

3. The compositional layering in the Svecofennian marbles can be used as an indicator of internal stratigraphy (fig. 3). It is proposed to have formed at the time of precipitation as autochthonous cycles, in which the beds with variable composition form a characteristic carbonate succession. Calcite-chert assemblage forms the bottom and dolomite rock occurs in uppermost part of the succession. The precipitation of carbonates seems to have taken place intermittently; it may have ceased for a while. During the hiatus the topmost layers were dolomitized more easily because there was sufficient time for seawater to react with the original calcium carbonate. Intervals in the carbonate sedimentation, therefore, probably favor the formation of dolomite. The middle part of the carbonate succession, calcite rock, retained the primary composition possibly due to its rapid burial by the following carbonate cycle.

4. The granoblastic texture and regularly low Mn and Sr contents of the Svecofennian dolomite marbles suggest that they were dolomitized during or soon after deposition, by circulating Mg-rich seawater. As indicated by the low (13CPDB (-2 to -4‰) and Sr values, thin dolomite marble layers at Norrlammala were formed after deposition. Minor porous dolostone bodies were produced at Norrlammala and Nummi-Pusula after metamorphism along fracture zones in calcite marble. Very low Sr (below 30 ppm) values and extremely high Mn (2,000–6,000 ppm) contents further indicate the post-depositional origin of the dolostones.

5. During metamorphism most primary silicates and a great part of dolomite of the studied marbles were consumed to produce calcite, tremolite, diopside, phlogopite, forsterite and chondrodite. Most of the calcite of the calcite-dolomite and dolomite marbles was formed in metamorphism along with abundant Mg-rich calc-silicate minerals. The higher the metamorphic grade in the silicate-bearing dolomite marble, the higher the calcite content. Post-metamorphic dedolomitization occurred along cleavage planes in dolomite crystals and produced Mg-poor secondary calcite at Ukonkangas and Rummukka.

6. On the basis of metamorphic mineral assemblages in the marbles, peak metamorphic temperatures at 5 kbar pressure were 620–680°C at Rummukka and 670–720°C at Ukonkangas. The mineral paragenesis at Nummi-Pusula indicates high-grade metamorphic temperature, 725–760°C, which corresponds to a 735ºC peak-temperature estimate based on the calcite-graphite thermometer. The peak-temperature for metamorphism is about 650°C at Norrlammala. The calcite-dolomite thermometer, with exsolutions of dolomite reintegrated to $MgCO_3$ content in the host calcite, gave temperatures that are 120–150°C lower than the ones based on the metamorphic mineral assemblages. Therefore, the $MgCO_3$ content of calcite provides minimum temperature estimates for peak metamorphism of 615°C at Norrlammala, 625°C at Nummi-Pusula, 580°C at Ukonkangas, and 595°C at Rummukka.

7. The studied Svecofennian marbles in Finland are interpreted to have deposited as autochthonous sediments in quite deep water of basin margin to pelagic environments (fig. 4). The dolomite rocks are believed

to have formed closest to the shoreline, in shallower water, whereas the chert-interlayered calcite rocks were precipitated in the deepest water. The Tutunen calcite-chert assemblage at Virtasalmi resembles Paleozoic chalk-chert associations, and may have been deposited originally as a pelagic succession.

8. The Svecofennian carbonate rocks formed originally rather thin layers, which are now impressively thickened in many places owing to multistage deformation. Svecofennian marbles form stratabound deposits that were significantly purified during metamorphism and have good potential as high-quality raw material for paper pigment, dimensional stone, and agricultural use.

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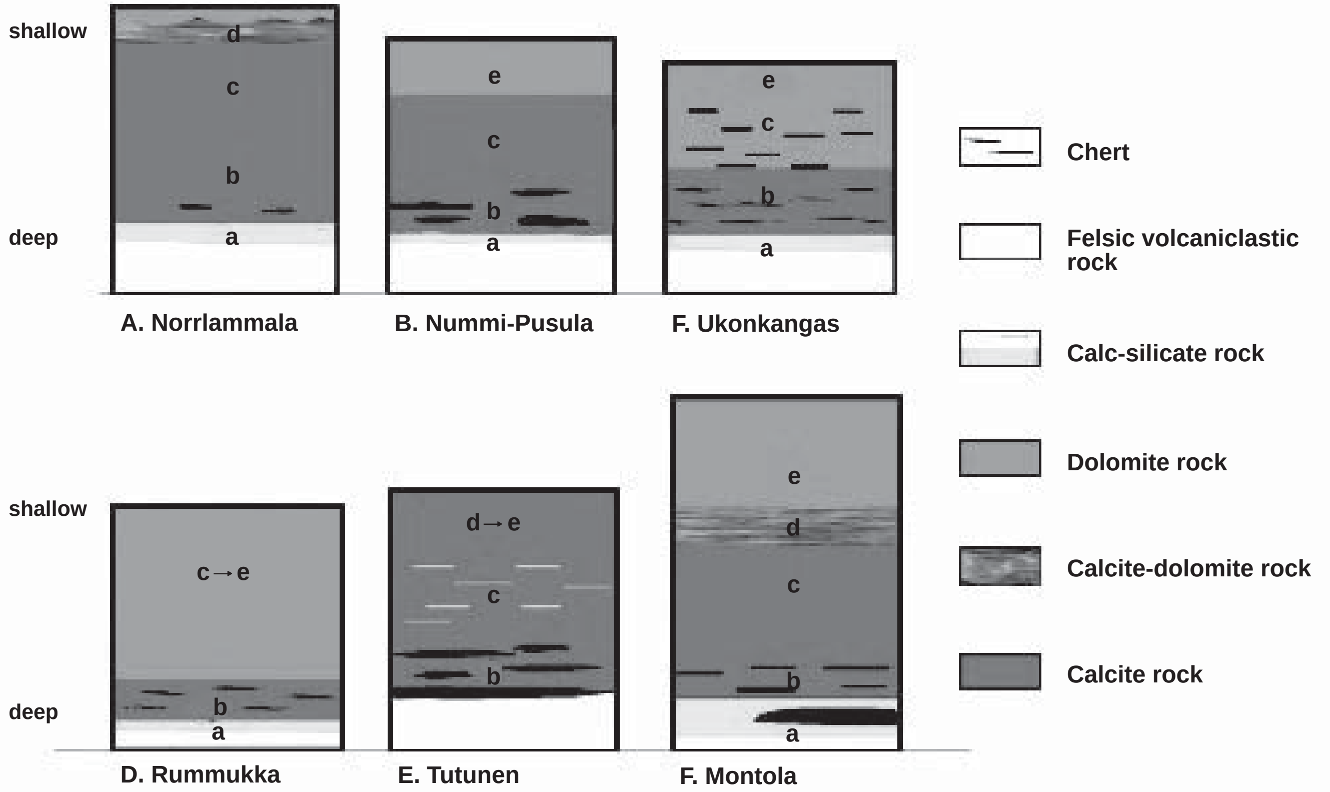

Figure 3. Svecofennian carbonate successions from the Uusimaa and Savo Belts. A) Norrlammala, B) Nummi-Pusula, C) Ukonkangas; D) Rummukka; E) Tutunen; F) Montola. Five cycles of differing composition are from bottom to top: a) calc-silicate rock and chert; b) chert-rich calcite rock; c) calcite rock, includes generally thin dolomite interlayers; d) calcite-dolomite rock; e) calcite or dolomite rock. The latter represents possibly the deposition from the shallowest water, whereas the lowermost cycle, calcite-chert rock, is interpreted to have precipitated in the deepest water (Reinikainen. 2001).

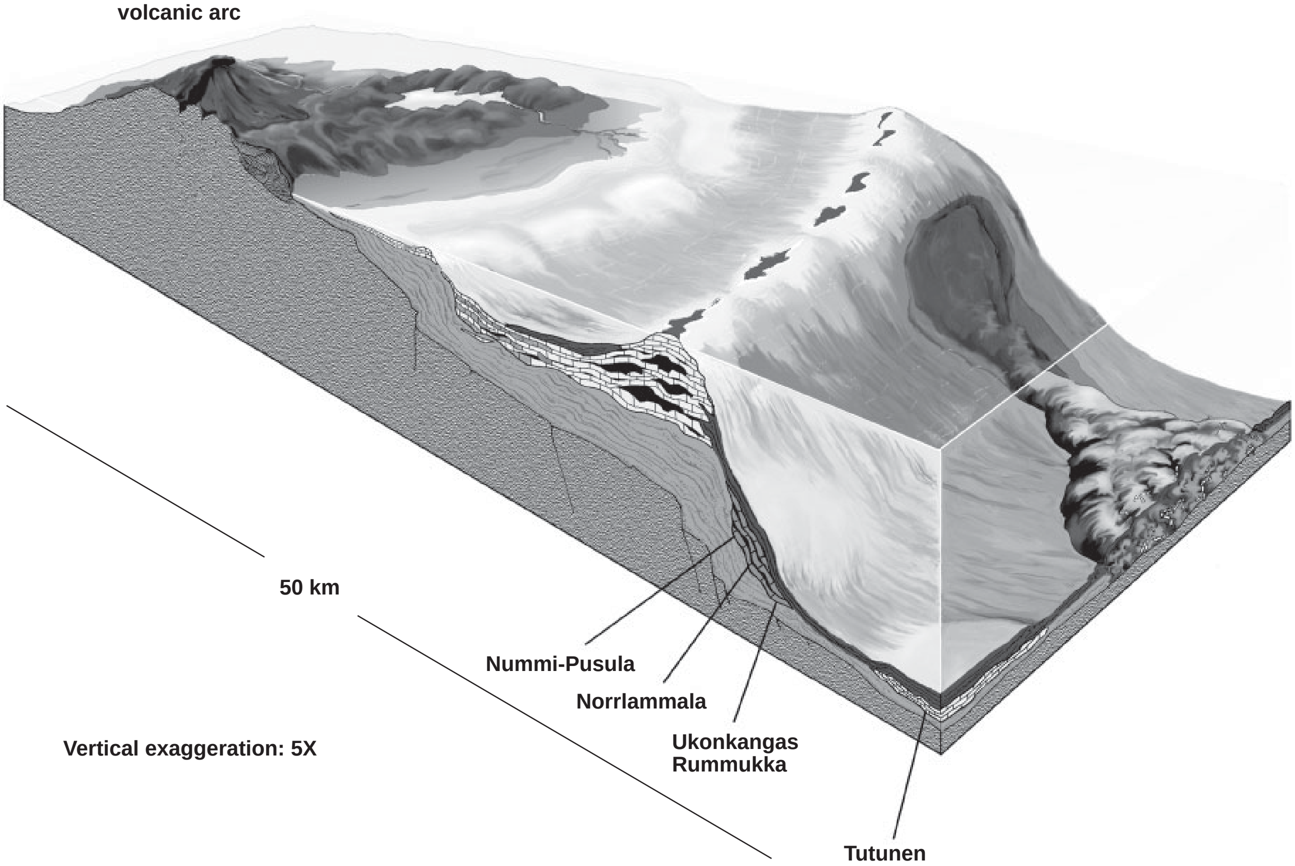

Figure 4. Schematic model for depositional environments of the studied carbonate rocks. Each of the studied marbles may have been formed in separated basins, i.e., they are not necessarily linked to each other (Reinikainen, 2001).

Turmoil in Western United States Perlite Markets in 2002

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Abstract

The perlite industry in the United States is undergoing rapid change, and competition between producers remains intense. Total production has retreated from the high of 711,000 metric tons reached in 1999. This is due in large part to the economic downturn coupled with severe competition from perlite imported into the eastern and gulf coasts of the U.S. from Greece, whose imports reached a record 210,000 metric tons in 2002. Two sales bright spots are evident: microspheres and horticultural perlite. The highly value-added microsphere market shows strong growth and is a significant profit center at prices of $350–500/metric tons, for most of those in on the largely proprietary furnace technology. The horticultural perlite market is strong, with prices reaching $80–85/metric ton, but supplies are limited due to the wasting of other perlite grades in low demand unavoidably produced during horticultural perlite production. These wasted grades, often more than half of total perlite production, are a cost that may be limited by producers by reducing horticultural production. Rumors abounded in 2002 about the sale of most perlite operations but no transactions were completed; expect one or more in 2003. Several former producing perlite operations were expected back on line but remained inactive. Many deposits are known that have never been exploited so long-term perlite supply is assured. A slow consolidation of the industry into a few larger players may be the end result of the state of flux evident among U.S. perlite producers.

Introduction

Commercial perlite is high-silica (71–75% SiO_2) volcanic glass that is usually perlite (2–5% water) but may include obsidian ((2% water) and pitchstone (>5% water). These glasses contain enough water from hydration during weathering to expand into rock foam particles when flash heated in a controlled process in special furnaces. Perlitic volcanic glasses occur within volcanic domes, lava flows, and welded ash-flows. Perlite is usually geologically young (<60 million years) because glassy volcanic rocks are readily altered by weathering.

Current Market

Total domestic perlite production in 2002 was 548,000 metric tons compared to 711,000 metric tons (all-time high) in 1999 (table 1). Perlite production by end-use was construction 67%, horticultural 12%, filteraid 8%, fillers 8%, other 5%. The filteraid market is declining, the horticultural market is growing, and construction end-use sales remain steady. Filler markets are growing and include perlite microspheres—a trendy, value-added product.

Decline in domestic perlite production was caused by the downturn in the economy over the last three years and competition from imports. Imports reached a record 210,000 metric tons in 2002. Imports are almost exclusively from Greece with minor tonnages from Mexico. Silver & Baryte imports perlite from Milos Island, a tidewater deposit, by maritime shipments to the Eastern and Gulf coasts of the U.S. at costs that are far below the cost of rail from western U.S. perlite producers. These imports are shipped into the St. Lawrence (Canada), Baltimore (Maryland), Brunswick (Georgia), and Mobile (Alabama) areas. The latter site represents a recent step closer to western perlite producers that may peel off more of their eastern contracts. It is not hard to imagine pushing a perlite-laden ship through the Panama Canal to the west coast of the U.S. The main deterrent to this scenario is the large number of low-volume perlite end users scattered throughout the region. Distribution of shiploads after delivery to Los Angeles or other ports would be costly, therefore, western producers are protected...so far.

Perlite Microspheres and Horticultural Perlite

Two sales bright spots are perlite microspheres and horticultural perlite. The horticultural market is strong but supplies are limited so prices reached about $80–85/metric ton for horticultural-grade processed ore. The highly value-added microsphere market shows strong growth and interest. Microspheres are a profit center for most of the producers that have this largely proprietary (but we suspect relatively simple) technology at $350–500/metric ton. Don't expect the producers to help you get into the microsphere market, but buying a furnace from Silbrico or Incon would not hurt.

Horticultural-grade perlite production yields other perlite grades as well. These unavoidably produced non-horticulture grades are partly unsaleable due to weak demand. They often comprise more than 50% of total perlite production. They are eventually sent to waste at a cost when available storage is filled. Thus, horticultural production has been limited by producers, to minimize these losses, by balancing horticultural profits with the costs of excessive waste of some processed perlite grades. For example, the Dicaperl No Agua operation in New Mexico is on a reduced production schedule. The result of all this is that customers are on allocation, and several projects to bring more horticultural to market are underway.

Divestiture

Rumors abounded in 2002 about the sale of most perlite operations. Some due diligence was performed, but no transactions were completed. Expect some divestiture(s) in 2003. We expect Dicaperl to stay out of the market, World Industries to buy, and Basin and/or Cornerstone to sell.

Development Continues

The Frenier deposit in British Columbia may reopen and a permit was granted to BBF Resources with horticultural production proposed for 2004. The severe transport constraints that sunk Frenier last time still exist; limiting haulage to horticultural-grade perlite only may overcome this. Exploration was active at the perlite deposit on the Gaspé Peninsula of Quebec by at least two groups. Gaspé would be well placed on the east coast if it can be developed but the perlite is not yet of proven marketability.

Production in Mexico from two mines, down from four, reached more than 80,000 metric tons in 2001 and perhaps 90,000 metric ton in 2002 (Armando Allatore, Fideicomiso De Fomento Minero, Monterrey, NL, Mexico, verbal commun., 2003). This represents a rapid increase over the last few years. The closure of two marginal mines represents a strengthening of the Mexican perlite industry.

Former domestic operations expected back on line, such as Malad City in Idaho, remained inactive. The U.S. Gypsum operation at Grants, New Mexico, which has been on the market for several years, is being decommissioned. The rail-siding lease expired in January. The plant at the rail siding will be demolished after asbestos removal and burial at the mine, which will be lightly reclaimed, bermed, and gated.

Long-term domestic supply is assured because many undeveloped perlite deposits are known in New Mexico and other western states. Minor exploration activity for horticultural continues in New Mexico. Exploration and perhaps development of deposits for horticultural-grade perlite is ramping up in the Black Rock Desert of Utah. Ana Steffen (University of New Mexico) is studying perlite and obsidian expansion by forest fires in northern New Mexico-a potential exploration tool.

Turmoil or ... What to do?

The perlite market in the western U.S. is undergoing rapid change and increased competition. Western perlite producers are beginning to be oriented westward rather than eastward because in general markets are opening to the west (including the Pacific Rim) and are closing to the east.

Silver & Baryte projects are underway in Asia for local use and for export. So perlite may be imported directly to the U.S. west coast from Asia or perhaps Greece. This would increase perlite-industry turmoil by further constraining western U.S. producers. Fewer domestic players may be the end result of the current turmoil among U.S. perlite producers.

Table 1. U.S. perlite production, imports, exports, and consumption in thousands of metric tons from 1998 to 2002. Perlite data, compiled by Wallace Bolen of the U.S. Geological Survey, are available at http://minerals.usgs.gov/minerals/ and include production statistics 1946–2000 (by Carl DiFrancesco and Wallace Bolen) for the domestic industry since startup. Data for 2002 are estimated. Parenthetical data are subtracted.

	1998	1999	2000	2001	2002
Production	685	711	672	588	548
Imports	150	144	180	175	210
Exports	(42)	(47)	(43)	(43)	(45)
Consumption	793	808	809	720	713

Probable Bedrock Source of Sapphires in Alluvial Deposits North of Butte, Montana

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Abstract

Alluvial sapphire deposits north of Butte were studied in an effort to determine the bedrock sources of the more than 55 tons of sapphires recovered from alluvial deposits in southwestern Montana. These deposits north of Butte along the South Fork of Dry Cottonwood Creek and along Lowland Creek are surrounded by the Eocene Lowland Creek Volcanics that range in composition from rhyolite to dacite. Volcanic rock adhering to three sapphires from the Dry Cottonwood Creek deposit is similar in mineralogy to lava flows in the Lowland Creek Volcanics. I attribute surface etching of sapphires from these deposits to partial resorption during transport in a magma undersaturated in Al_2O_3. Preservation of delicate projections and general lack of prominent abrasion features imply a short distance of fluvial transport. These observations indicate that the Lowland Creek Volcanics are the most likely bedrock source of these sapphires.

Lack of discovery of the bedrock sapphire source can be attributed in part to the dense forest and lack of bedrock outcrops, particularly at the head of the Dry Cottonwood Creek drainage. Rarity of adhering rock on these sapphires may indicate that they were derived from a friable or altered bedrock source that is not well exposed. Another possible explanation is that sapphires occur in the bedrock in very low concentration and have been significantly concentrated by fluvial action to form a mineable deposit. Crude estimates of the quantity of sapphires in the Dry Cottonwood Creek deposit and volume of volcanic bedrock eroded from the head of this drainage indicate a bedrock concentration of sapphires of only one carat in over 400 cubic yards of rock.

Introduction

Sapphires were first discovered in Montana in 1865 by gold miners working gravel deposits along the Missouri River northeast of Helena. Within the next 30 years gold miners discovered three other major sapphire deposits. At Yogo Creek sapphires were first discovered in placer deposits and subsequently traced back to their bedrock source, a Tertiary monchiquite dike (fig. 1). This dike yielded 18.2 million carats (3.96 short tons) of uncut sapphires that are famous for their generally uniform blue color (Mychaluk, 1995). The Yogo deposit is the only Montana deposit where sapphires are mined from bedrock; all others are placer deposits where sapphires are recovered from alluvium.

Sapphires have been mined from alluvial deposits in three general areas: ancient river terraces or bars as they are called, along a 22-mile stretch of the Missouri River northeast of Helena, the South Fork of Dry Cottonwood Creek and Lowland Creek north of Butte, and the large Rock Creek (Gem Mountain) district west of Philipsburg (figs. 1 and 2). Cumulative production from the Missouri River deposits is estimated to exceed 100,000 oz, possibly as much as 500,000 oz (3 to 15 tons) (Clabaugh, 1952). Production from the Dry Cottonwood Creek deposit is substantially less than this, probably less than 6,000 oz and the Lowland Creek deposit has produced even less.

The largest concentration of sapphires in Montana is in the Rock Creek district where sapphires have been recovered from at least six gulches that radiate from low mountains north and west of Rock Creek and occupy an area of approximately 25 square miles. During a 10-year period between 1906 and 1923, 41.8 tons of sapphires were shipped from the Rock Creek district (Emmett and Douthit, 1993). I estimate that production of sapphires since 1923 brings total production to at least 50 tons with an additional 5.5 tons of proven reserves in part of this district (Emmett and Douthit, 1993). Total estimated production of sapphires from all alluvial deposits in southwestern Montana certainly exceeds 55 tons with an unknown quantity of sapphires remaining. Most production from Montana deposits preceded 1943 when synthetic sapphires replaced natural sapphires for watch and instrument bearings. Sapphires are now mined commercially at the Yogo deposit by Yogo Creek Mining (Freeman, 2002, 2003) and there are operations along the Missouri River and in the Rock Creek district (Gem Mountain) where individuals can sieve gravel for sapphires.

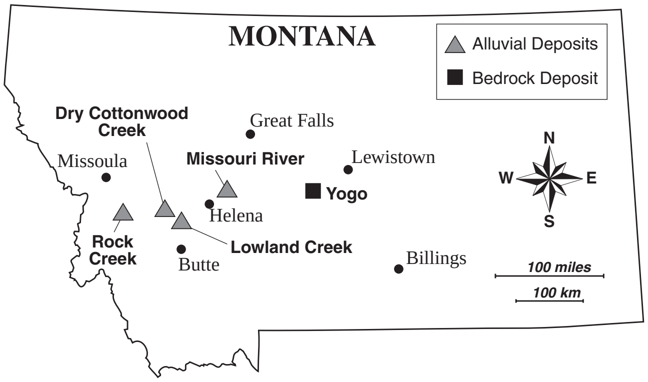

Figure 1. Principal sapphire deposits in Montana.

In spite of this large quantity of sapphires recovered from alluvial deposits in southwestern Montana, the bedrock sources have not been recognized. Prospectors have searched unsuccessfully for a bedrock source for more than 100 years. With no specific evidence individuals have suggested that these alluvial sapphires were derived from dikes, diatremes, and contact metamorphic aureoles. In her extensive study of sapphires, Garland (2002) suggested the possibility that the alluvial sapphires in southwestern Montana were derived from metamorphic rocks adjacent to the Bitterroot lobe of the Idaho batholith that are exposed in the Bitterroot Range 25 miles west of the Rock Creek district (also Garland and Gorton, 2002). Berg and Dahy (2002) speculated that sapphires were transported from a deep metamorphic source rock to the surface by Tertiary magmatism.

I investigated the sapphire deposits north of Butte (South Fork of Dry Cottonwood Creek and Lowland Creek) in an effort to determine the source of sapphires in these alluvial deposits. I selected these deposits because of their small areal extent. Sapphires are concentrated along a 1.5-mile stretch of the South Fork of Dry Cottonwood Creek and along the lower 3.3 miles of Lowland Creek (figs. 3 and 4).

The complex geologic history of erosion and redeposition of sapphires concentrated in the Rock Creek district as well as the large areal extent of this and the Missouri River deposits eliminated these deposits from consideration for detailed study. These sapphire deposits will be described in a report on Montana sapphires now in preparation to be published by the Montana Bureau of Mines and Geology.

Methods

Most of the sapphires that I studied from the deposits north of Butte were provided by individuals who either mined or bought them. I screened gravel from several tributaries to Lowland Creek, but no sapphires were found. Likewise I tested gravels from several localities in the Whiskey Gulch drainage (fig. 2), also with negative results.

In addition to sapphires from deposits north of Butte, I examined more than 2,500 sapphires from all major Montana alluvial deposits in transmitted light under a binocular microscope to identify those with mineral inclusions, adhering rock, and surface features. I examined surfaces of selected sapphires in more detail by scanning electron microscopy (SEM) at the Image and Chemical Analysis Laboratory at Montana State University, using a Jeol scanning electron microscope. Specimens were rinsed in acetone and blown with nitrogen to remove dust before coating with Au and Pd. Nancy Equall performed all the analyses and took all the photographs. Thin sections were made of sapphires with adhering rock or mineral inclusions. Discussion of the mineralogy of inclusions is beyond the scope of this paper.

Geology

Sapphire deposits north of Butte along the South Fork of Dry Cottonwood Creek and Lowland Creek are surrounded by the Eocene Lowland Creek Volcanics. (fig. 2). The estimated composite stratigraphic thickness of this sequence of volcanic rocks is nearly 6,000 feet and the extent of the original volcanic field is estimated to exceed

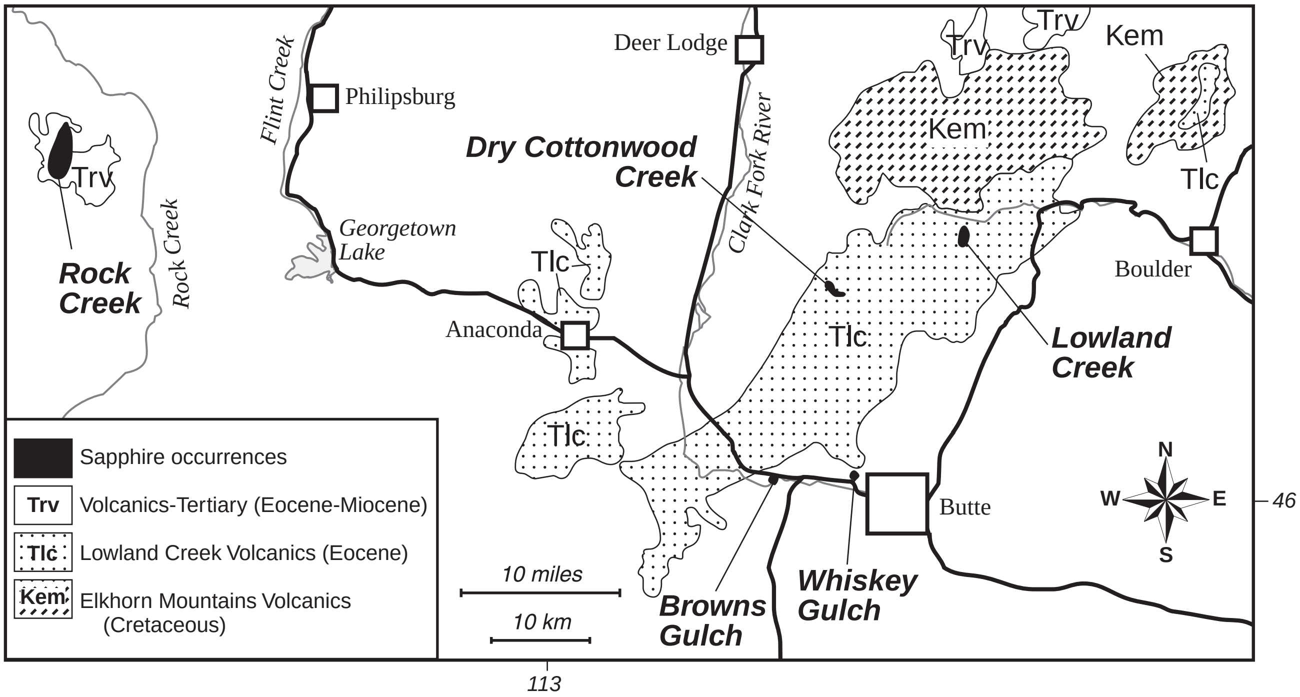

Figure 2. Sapphire deposits and occurrences in southwestern Montana. Geology simplified from Lewis (1998).

800 square miles (Smedes, 1962; Smedes and Thomas, 1965). Smedes (1962) described the Lowland Creek Volcanics as quartz latite. Derkey and Bartholomew (1988) in their detailed map of the Ramsay quadrangle west of Butte described a compositional range from rhyolite to dacite for these volcanic rocks. This complex sequence includes welded tuffs and other pyroclastic rocks, lava, and breccia that contains both volcanic clasts and clasts of granitic rock derived from the underlying Cretaceous Boulder batholith. The Lowland Creek Volcanics have been divided into five mappable units (Smedes and others, 1962; Smedes, 1968). The welded tuff unit and a lava unit are the major units exposed along the South Fork of Dry Cottonwood Creek and along Lowland Creek. Remnants of the very large Cretaceous Elkhorn Mountains Volcanics field are exposed in the area northeast and northwest of Butte (fig. 2).

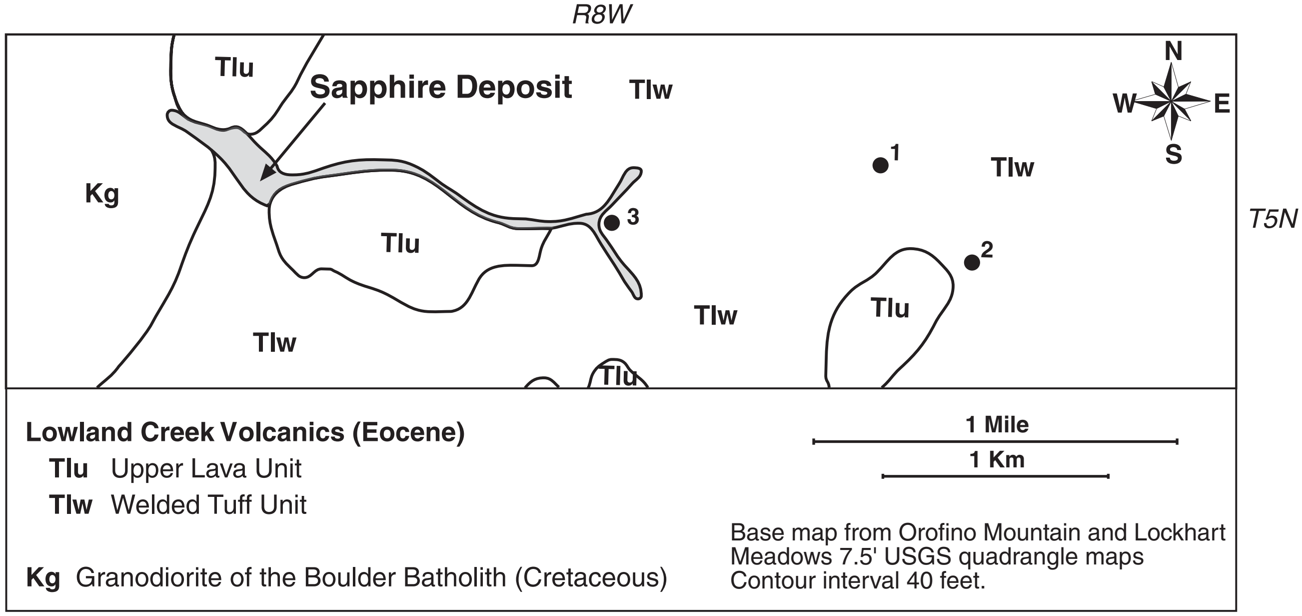

Figure 3. Bedrock geologic map of the South Fork of Dry Cottonwood Creek showing extent of sapphires and distribution of Lowland Creek Volcanics. Locality 1 is meadow where sapphires were recovered. Locality 2 is approximate location of spring where sapphires were found (Clabaugh, 1952). The calculation of the bedrock eroded to yield the sapphires in this deposit was based on the volume of bedrock from locality 3 to the head of the drainage. Bedrock geology modified after Smedes (1968).

Figure 4. The upper part of the South Fork of Dry Cottonwood Creek drainage. View is to the south with the meadow (locality 1 in figure 3) in the middle foreground.

Sapphire Deposits

Sapphires were commercially mined from deposits on the South Fork of Dry Cottonwood Creek between 1907 and 1911 and more recently from 1995 into 1998. They have been found in mineable concentration along a 1.5-mile stretch of the South Fork, but not along the North Fork of Dry Cottonwood Creek or other unnamed tributaries. Sapphires have also been recovered from a small meadow near the head of the South Fork (locality 1, fig. 3). Clabaugh (1952) reported panning sapphires at the highest spring on the South Fork of Dry Cottonwood Creek at an elevation of 6,950 feet, only 450 feet below the highest point on the ridge at the head of this drainage, and less than 1,000 feet from this drainage divide (inferred site locality 2, fig, 3). At the time of writing I have not been successful in finding this spring. Garland (2002) provided excellent detailed information obtained by trenching on the distribution and grade of the sapphire deposits along the South Fork of Dry Cottonwood Creek.

Sapphires were also recovered during placer mining for gold along the lower 3.3 miles of Lowland Creek(fig. 2). In addition to these deposits along Dry Cottonwood and Lowland Creeks, sapphires have been found near the mouth of Browns Gulch and one large (1.3 g) sapphire was recovered near the mouth of Whiskey Gulch (fig. 2). There are also several unconfirmed reports of sapphires having been found northwest of Butte in several tributaries to Browns Gulch.

Sapphires

Shapes and Surfaces

Sapphires from the South Fork of Dry Cottonwood Creek and from Lowland Creek are indistinguishable; they are similar in color, shape, surface features, and mineral inclusions suggesting that they had a similar history and were derived from a similar source rock. They differ from those recovered from the Missouri River and Rock Creek deposits in all of these characteristics except color, in which they resemble the Missouri River sapphires but not the more deeply colored Rock Creek sapphires. Colors of sapphires from Dry Cottonwood Creek and Lowland Creek range from very pale blue to very pale green to colorless and rarely pink to purple pink.

Shapes of sapphires from Dry Cottonwood Creek and Lowland Creek include irregular forms, slightly rounded hexagonal prisms, hexagonal tablets, and small, nearly spherical forms (fig. 5).

Surfaces of many sapphires, particularly those with somewhat rounded form, have a frosted appearance. Grooves, developed where surfaces intersect either basal or rhombohedral parting planes, are the most characteristic feature of sapphires from the deposits north of Butte (fig. 6).

Such grooves are rare on sapphires from the Rock Creek district or from the Missouri River deposits. A few sapphires from the deposits north of Butte have glassy conchoidal fractures that cut cleanly across the specimen, where they fractured either in the trommel during recovery, or more likely, during fluvial transport. Even those sapphires that appear unabraded are seen to have small conchoidal fractures or small chips when examined by optical microscopy or SEM. Glassy conchoidal fractures contrast sharply with the frosted surfaces seen on most of these sapphires (figs. 7A and 7B).

Figure 5. Sapphires from Dry Cottonwood Creek selected to show variety of shapes and surfaces typical of sapphires from this locality. Forms shown are hexagonal tablets, hexagonal prisms, irregular smooth surfaces, fractured grain, and small, almost spherical grains, many with straight grooves. Scale is in millimeters.

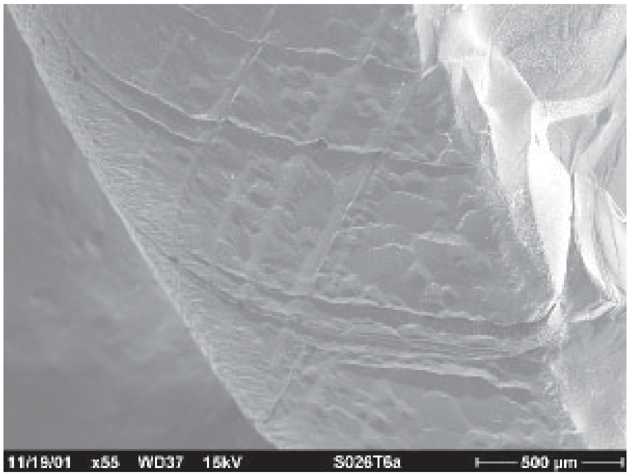

Figure 6. Scanning electron micrograph of sapphire from Dry Cottonwood Creek showing development of grooves.

In addition to grooves, the most distinctive feature of sapphires from the deposits north of Butte are irregular projections, usually on the basal pinacoid (fig.8). The external forms of these projections appear randomly oriented, but the projections are in optical continuity (i.e. the same crystallographic orientation) with the sapphire crystal. Projections are also found on some of the small, almost spherical sapphires. Preservation of these projections indicates limited abrasion in the fluvial environment that suggests short distance of transport.

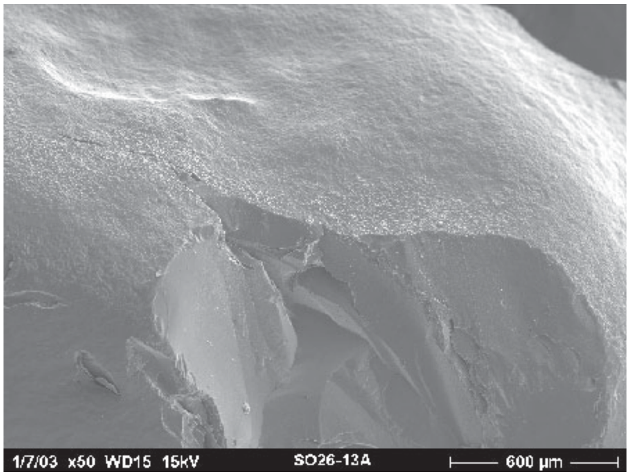

Figure 7A. Scanning electron micrograph of sapphire from Dry Cottonwood Creek showing older frosted surface and smooth conchoidal fracture.

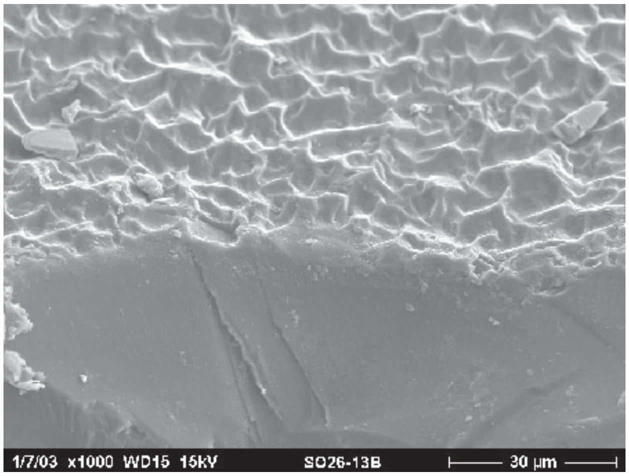

Figure 7B. Enlargement of part of figure 7A showing in detail the difference between the frosted surface and the conchoidal fracture.

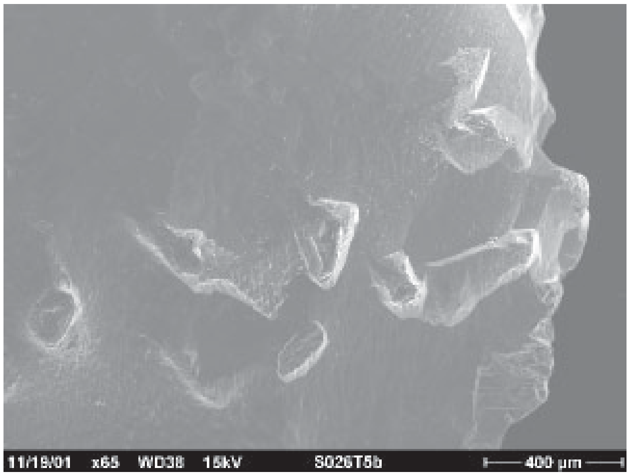

Figure 8. Scanning electron micrograph of sapphire from Dry Cottonwood Creek showing projections on basal surface.

The smallest sapphires (2 mm) recovered from these deposits are almost spherical (fig. 9A). An enlarged image of the surface of one of them shows small trihedral depressions but no indication of abrasion (fig. 9B). By comparison a stream - worn corundum pebble from Alder Gulch shows an entirely different surface characterized by many small sharp fractures (fig. 10). Purplish gray corundum and rarely rubies, but no sapphires, are found in dredge tailings remaining from gold mining along Alder Gulch 55 miles southwest of Butte.

I compared the surface features of alluvial sapphires with those of a sapphire recovered from the trachybasalt sill at French Bar along the Missouri River (fig. 11A). This sill near Canyon Ferry Dam on the Missouri River contains sparse small, pale colored sapphires (Berg, 2002; Berg and Dahy, 2002). Careful removal of surrounding igneous rock from this sapphire reveals that it is somewhat rounded and has surface pits and irregularities similar to those seen on sapphires from the alluvial deposits north of Butte (fig. 11B).

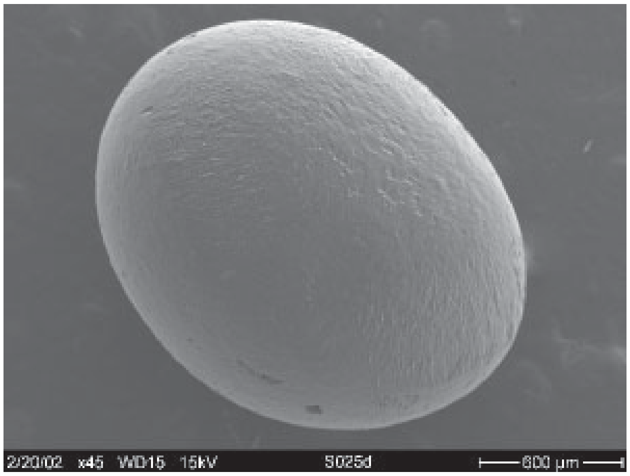

Figure 9A. Scanning electron micrograph of almost spherical sapphire from Dry Cottonwood Creek.

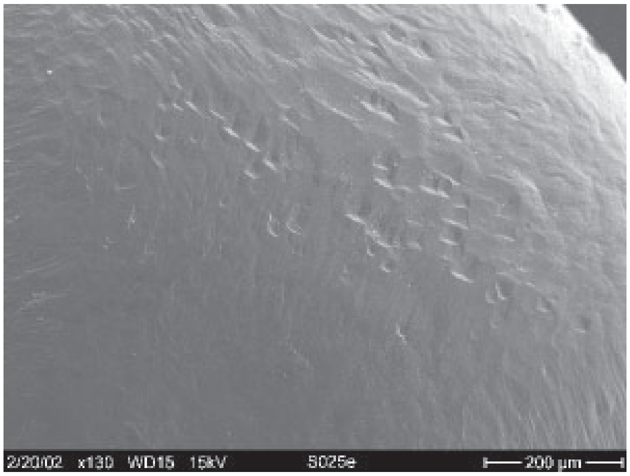

Figure 9B. Enlargement of the surface of the sapphire shown in figure 9A showing small trihedral depressions.

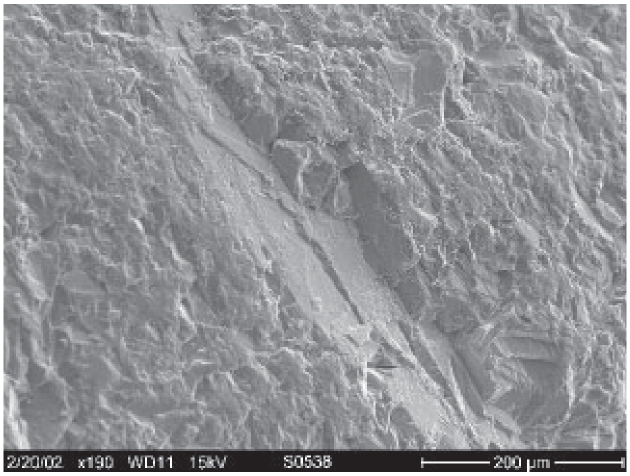

Figure 10. Scanning electron micrograph of surface of stream-worn corundum pebble from Alder Gulch showing microfractures developed during stream transport.

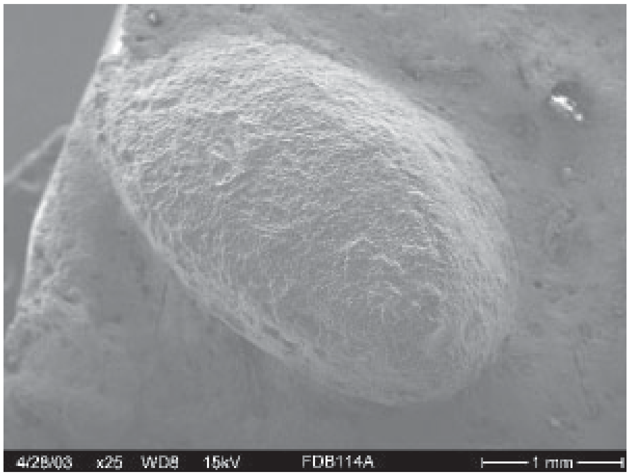

Figure 11A. Scanning electron micrograph showing pitted surface of sapphire partly exposed by removal of surrounding rock. Specimen is from trachybasalt sill exposed at French Bar near Helena (Berg and Dahy, 2002).

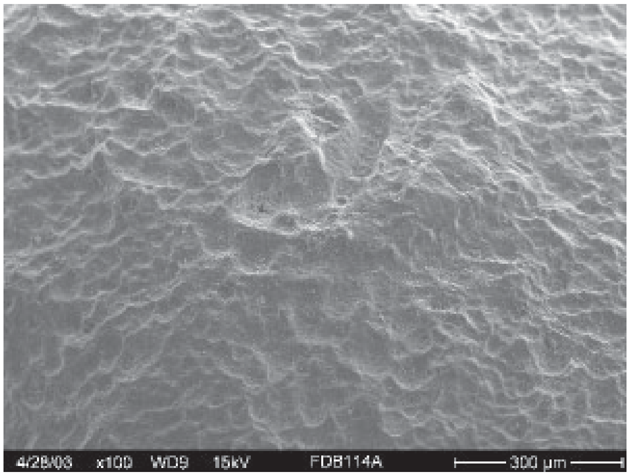

Figure 11B. Enlargement of part of the sapphire shown in figure 11A, showing irregular surface.

Adhering Rock

Rock found adhering to alluvial sapphires is an important clue in the search for bedrock sources. Because of the irregular surfaces of many of these sapphires and limited evidence of abrasion, I expected that small remnants of rock would commonly be preserved. However, this is not the case; preserved matrix rock is exceedingly rare. I have seen only six alluvial sapphires, three from the Rock Creek district and three from Dry Cottonwood Creek, with adhering rock.

Determination of adhering rock composition is questionable because of the small amount of rock remaining, usually less than 3 mm^2 in thin section. However examination in thin section shows that all adhering rock is volcanic. The adhering rock of one specimen from Dry Cottonwood Creek contains K-spar and biotite phenocrysts in a matrix composed mainly of plagioclase microlites and is possibly rhyodacite (fig. 12). Another specimen from the same area contains plagioclase, biotite, and quartz phenocrysts in a groundmass of plagioclase microlites; this rock is probably in the rhyodacite compositional field. A third specimen from the Dry Cottonwood Creek contains altered hornblende(?) phenocrysts in a fine-grained groundmass of plagioclase microlites, Mineralogy of this specimen is similar to that of porphyritic dacite in the Lowland Creek Volcanics described by Derkey and Bartholomew (1988). Aside from the caution that these are only inferred compositions based on very small rock fragments, this rock may not be typical of the source bedrock. It is likely that the preserved rock is atypically durable and that sapphires with no adhering rock were derived from a less durable rock that was completely removed during weathering or stream action.

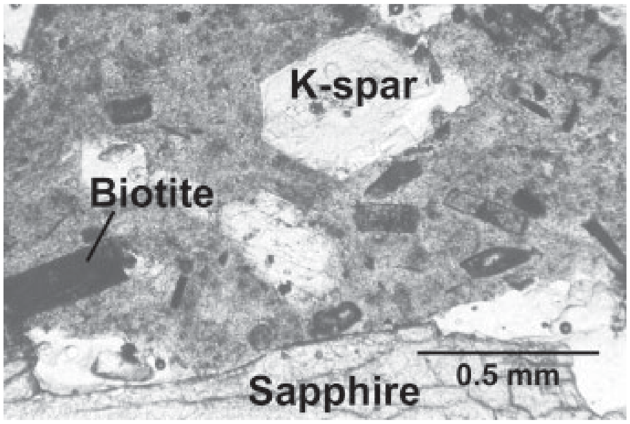

Figure 12. Photomicrograph with crossed polars of thin section of a sapphire from Dry Cottonwood Creek with adhering volcanic rock in which a K-spar and biotite phenocrysts are surrounded by a groundmass with abundant plagioclase microlites.

Associated Garnets

The abundance of garnets with sapphires in both the Dry Cottonwood Creek and Lowland Creek deposits may have a bearing on the sources of these sapphires. Garnets in these deposits are much more abundant in the heavy mineral assemblage than sapphires. They are 5.5 times (by weight) more abundant than sapphires recovered by screening gravel in a small meadow near the head of the South Fork of Dry Cottonwood Creek (locality 1, fig. 3). Garnets are predominately orange red, pale pink, and less commonly bright red. One sapphire from Dry Cottonwood Creek contains two pale pink included garnets, and a large (1.3 g) sapphire from the mouth of Whiskey Gulch (fig. 2) contains four small garnets, also pale pink.

Both pale pink and orange-red garnets are locally abundant in the upper lava unit of the Lowland Creek Volcanics exposed along Lowland Creek and also exposed near the head of the South Fork of Dry Cottonwood Creek. They are generally smaller than 3 mm and are surrounded by a thin rim of biotite, generally with radial orientation. I interpret the surrounding biotite to be a reaction rim that indicates that these garnets are xenocrysts, derived from a metamorphic rock largely assimilated by magma.

Discussion

Distribution of sapphires, exposed bedrock, rock adhering to the sapphires, and surface features all suggest that sapphires in the Dry Cottonwood Creek and Lowland Creek deposits were derived from the Eocene Lowland Creek Volcanics. Significant concentrations of sapphires in this area north of Butte are restricted to the South Fork of Dry Cottonwood Creek and the lower part of Lowland Creek. Rock adhering to three sapphires from the Dry Cottonwood deposit is similar in composition to that in the Lowland Creek Volcanics that surround this drainage basin. The most reasonable explanation for grooves and frosted surfaces of the sapphires is that sapphires were partly resorbed while in a magma undersaturated in Al_2O_3, a magma from which corundum could not crystallize and with which corundum would be in disequilibrium. Preservation of delicate projections on some sapphires indicates short transport distance in the fluvial environment.

If these interpretations are correct, it is surprising that the bedrock source of this large quantity of sapphires has not been recognized in at least one of these alluvial deposits in southwestern Montana. As pointed out previously, the Dry Cottonwood deposit was selected for detailed study because this deposit is of small areal extent and in a restricted drainage basin. Experienced prospectors are persistent and observant and would be expected to have found the source of the sapphires in this deposit. However, there are several possible explanations for the bedrock source remaining elusive.

1. Dense forest and lack of outcrops at the head of the drainage of the South Fork of Dry Cottonwood Creek (fig. 4).
2. The Sapphires weathered out of a poorly lithified or friable rock such as volcanic ash that is simply not exposed.
3. Hydrothermal alteration or deep weathering has caused the source rock to be easily eroded and thus not exposed.
4. Sapphires are sparsely distributed in the source rock and have been extensively concentrated in the deposit along the South Fork of Dry Cottonwood Creek. Because of a low concentration in the volcanic rock that contains abundant quartz phenocrysts easily confused with small sapphires, sapphires have not been recognized.

In an effort to evaluate the last possibility, I made an estimate of the concentration of sapphires in bedrock eroded from the head of the south Fork of Dry Cottonwood Creek necessary to yield the sapphires in this deposit. Clabaugh (1952, p. 54) estimated that the Dry Cottonwood Creek deposit had “ * * * yielded several thousand ounces of industrial sapphires and a few thousand carats of gem materials during the periods of active mining, 1907–1908 and 1910–1911.” I arbitrarily assumed that more recent mining and unmined sapphires increase this estimate ten times to 30,000 oz (4.2 million carats) and also that the volcanic rocks were the only source of sapphires in this deposit; specifically the volume of volcanic rock that has been eroded from the head of the drainage of the South Fork of Dry Cottonwood Creek above locality 3, figure 3. Furthermore, I assumed that sapphires are uniformly distributed within these volcanic rocks. This assumption in this first approximation is probably invalid because xenocrystic garnets that presumably were derived from a source similar to the ultimate source of sapphires are not uniformly distributed in this volcanic rock. However, based on these assumptions, the concentration of sapphires in this volcanic rock is extremely low; 480 cubic yards of bedrock would yield only one carat of sapphire. A spherical, one carat sapphire is about 5 mm in diameter. If the total quantity of sapphires initially in this deposit is 100 times that mined in the early years of production, the concentration would still be only 48 cubic yards of bedrock per carat. Concentration of sapphires in gravel along the South Fork of Dry Cottonwood Creek locally reaches 30 g (150 carats) per bank cubic yard (Garland, 2002). Because of the chemical and physical durability of the mineral corundum, this concentration seems possible. Geologic processes can be very efficient in milling and concentrating durable minerals such as corundum.

Conclusions

Sapphire-bearing rock included in rhyolitic to dacitic magma was partly assimilated to yield the more refractory minerals, garnet and sapphire (fig. 13).

Between the incorporation of sapphire-bearing rock in this magma and its extrusion to form the Lowland Creek Volcanics, sapphires were partly resorbed by this magma undersaturated in Al_2O_3. The small, almost spherical sapphires may be the last remnants of sapphires that were almost completely dissolved; other sapphires may have been completely dissolved. Extended weathering of these volcanic rocks yielded sapphires that were then concentrated by fluvial processes to produce mineable deposits in Lowland Creek and in the South Fork of Dry Cottonwood Creek. The Missouri River and Rock Creek sapphire deposits may also have been derived from Tertiary volcanic rocks by similar processes.

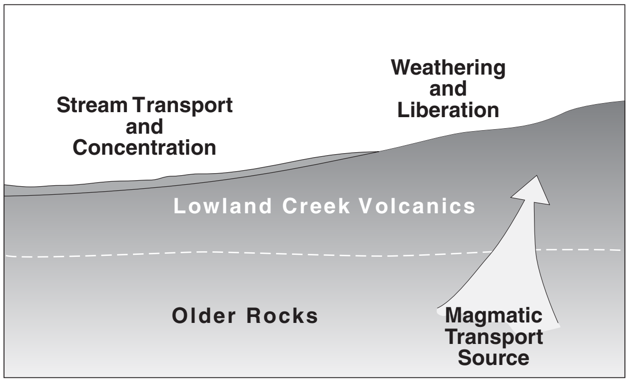

Figure 13. Diagram depicting probable evolution of alluvial sapphires in deposits north of Butte.

Acknowledgments

This work was made possible by the generosity of many individuals who not only provided sapphires, but also freely shared their knowledge of sapphire deposits. I especially thank Dale Siegford of the Sapphire Gallery in Philipsburg, Jim Rex who together with his father mined sapphires on the South Fork of Dry Cottonwood Creek, Chris Cooney of Gem Mountain, and Ben Duffey of Helena. Also I thank Mary Garland, who by challenging my ideas, has forced me to dig deeper in support of my hypotheses. Most of all I thank Katie McDonald of the Montana Bureau of Mines and Geology who by asking me a question about the source of alluvial sapphires in Montana, started me on this fascinating quest. The support from the Montana Bureau of Mines and Geology for this continuing investigation has made it possible and is appreciated. Reviews by Camela Carstarphen, Mike Stickney, Larry Smith, Katie McDonald, Wayne Van Voast, and Ed Deal improved this paper substantially.

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Environmental Regulations and Their Effects on Industrial Minerals

Jonathan M. Brown

Abstract

Although few will argue the benefits that prudent cost-effective regulations provide to society, the economic growth in this country is being shackled by the unchecked proliferation of regulations. Everyone in business knows this, but few recognize the enormity of the cost that businesses, especially those involved with the development of our country's natural resources, are incurring.

Under the Congressional Review Act of 1996, Congress has the authority to repeal any and all regulations that it deems counterproductive and of little benefit to society. Furthermore, housed within the Office of Management and Budget, which is part of the Executive Office of the President, is the Office of Information and Regulatory Affairs (OIRA). This office's primary responsibility is to review regulations and recommend to Congress those that should be repealed. Nevertheless, the number of times Congress has done so is astonishingly few.

Because Congress is supposed to vote the will of the people, perhaps affected industries need to reassess the effectiveness of their outreach programs and focus on how they can influence the will of the people and in turn its effect on Congress and the Administration.

Would a grassroots effort that supports and complements our traditional legislative approach provide a more immediate result in stemming the seemingly unstoppable tide of regulations? Is the American public aware of the added costs this plethora of red tape adds to the quality of life they currently enjoy, and are they willing to take action once informed?

This paper provides some sobering statistics on the growth of regulations and suggests an actionable approach that might help turn this tide.

Introduction

In spite of the passage of well-intended legislation, such as the Unfunded Mandates Reform Act of 1995, the Small Business Regulatory Enforcement Fairness Act, and the Congressional Review Act, Congress has done little to stem the ever-rising tide of regulations.

As far back as 1971 Richard Nixon and later both Gerald Ford and Jimmy Carter used the Office of Management and Budget to try to regain control of the regulatory process. Yet, it was Ronald Regan in 1981 who established the modern structure for the review of regulations by requiring agencies to prepare a cost-benefit analyses of their proposed regulations (Gattuso, 2002a). These analyses were then reviewed by the Office of Information and Regulatory Affairs and if approved moved forward unless appealed at the Cabinet level.

The Nevada Bureau of Mines and Geology takes no position on the opinions expressed in this paper.

Nevertheless, much of the regulation proliferation problem appears to lie in the fact that Congress employs only a handful of people to monitor the federal regulatory activities of more than 50 federal agencies employing more than 126,000 workers (Antonelli, 1998). Although required by statute to provide cost-benefit analyses for each proposed regulation, most of these analyses result in a broad range in values. For instance, benefits for rules adopted between 1995 and 2002 ranged from $81 to $121 billion, a range of some 50%. This broad variance clearly decreases the usefulness of the final results (Gattuso, 2002a). Further adding to the problem is the fact that Congress must rely on the information provided to it by the very agencies that are trying to get regulations instituted, agencies that over the years seem to have been taken over by staff who are preservation minded and are often at odds with language in the enabling legislation and charter of their own agencies. Since they are protected from dismissal by civil service regulations, these bureaucrats are not easily accountable for their actions. Therefore, it is no wonder that in just the three years (1996–1998) since the General Accounting Office started tracking final rules issued by federal agencies, not a single regulation, out of 8,675 reviewed, was rejected (Antonelli, 1998).

Making matters worse is the fact that OIRA is part of the Office of Management and Budget that in turn is part of the Executive Office of the President. Therefore, it is not surprising to see, as shown in table 1, the rise and fall of OIRA's aggressiveness towards regulatory review depends on what political party controls the Presidency.

Table 1. Number of rules returned per year to agencies for further work; data from Gattuso (2002a)

Years	1981–1992	1993–1997	1998–2000	2001–2002
President	Republican	Democrat	Democrat	Republican
Number	31	20	0	20

It is interesting to note that the 20 rules returned between July 2001 to March 2002 were more than during the entire previous administration. Nevertheless, the system is not flawless because political pressures can be, and often are, brought to bear in order to bypass or overrule the review process. The effect of this imperfect review process can be seen in many different ways, but one is by the growth in the number of Federal Register pages over the years as shown in table 2, even though such growth may not be wholly dependent on regulation proliferation.

Table 2. Number of pages in the Federal Register, data from Crews (2002)

Year	Number of Pages
1992	57003
1993	61166
1994	64914
1995	62645
1996	64591
1997	64549
1998	68571
1999	71161
2000	74258
2001	64431

Although the overall increase during this time period was 13%, a closer inspection of these numbers indicates an increase of 21.4% in pages during the two-term Democratic Clinton Presidency. The number would most likely have been much higher had it not been for an influx of Republican congressional reformers in 1995 that kept pressuring the President by keeping a watchful eye on the number of pages in the Federal Register. The partial shutdown of the federal government that same year also helped reduce the promulgation of new regulations. The graphic effect of which party controls the Presidency and Congress on the number of new regulations can be seen in figure 1. Accompanying this tide of new regulations is a corresponding growth in the size of government needed to administer and enforce these rules.

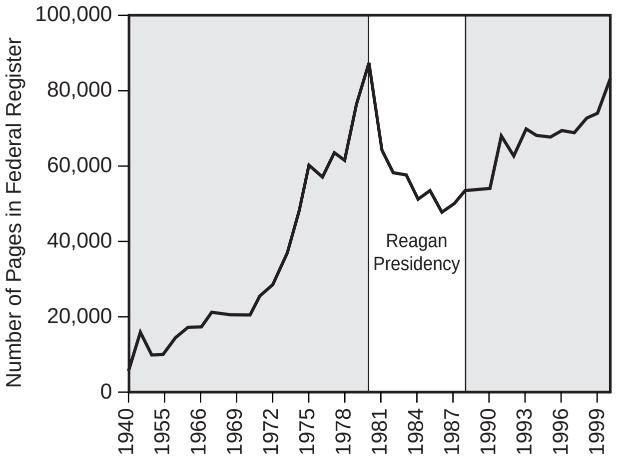

Figure 1. Growth in federal regulations on the basis of pages in the Federal Register, from Covington (2002). Data from 1966 to 2000 are more detailed than those from 1940 to 1966.

Implications

More important than the number of new trees that have to be sacrificed to print this tide of new pages in the Federal Register are the impacts on society from this plethora of promulgated regulations. Chief among these is the economic impact.

According to the Cato Institute, regulatory costs for 2001, including paperwork costs, have been estimated at $854 billion (Crews, 2002). Figure 2 shows another way to think about the magnitude of regulatory costs in the United States by comparing it to the 2000 gross domestic product (GDP) of Canada and Mexico. Figure 3 shows that regulatory cost rivaled all corporate pre-tax profits in 2000.

Regulatory costs are primarily a tax on corporations that eventually are passed on to individuals through price increases. Therefore, it is no wonder that the $854 billion of regulatory cost, a figure that is about the same as the entire federal discretionary budget for 2001, translated to about $2,500 per American (Gattuso, 2002a). Details of how hidden regulatory costs in 1998 (the last year for which information is available) ate up 18% of the annual after-tax income of a median two-earner family (Crews, 2002) can be seen in figure 4.

The growth in regulations has also caused an increase in the outlay of federal money to administer and enforce these regulations. Since 1992 this outlay has increased by 28.2% and in 2001 stood at $21 billion. When added to the cost of regulations, it is easy to see in figure 5 that there appears to be a second "off the books" budgetary expense that is approximately 47% of the total Federal outlay of funds.

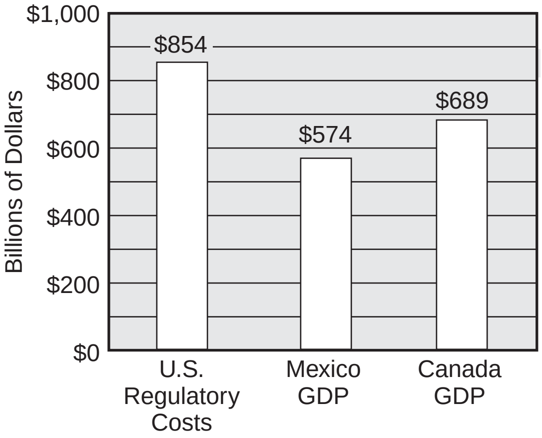

Figure 2. U.S. regulatory costs compared with Mexico's and Canada's GDP (from Crews, 2002). Sources: W. Mark Crain and Thomas D. Hopkins, " The Impact of Regulatory Costs on Small Firms," report prepared for Small Business Administration, Office of Advocacy, RFP no. SBAHQ-00-R-0027, October 2001, www.sba.gov/advo/research/rs207tot.pdf. GDP figures for Canada and Mexico are from U.S. Census Bureau, Statistical Abstract of the United States: 2001, Table 1340, p. 841, www.census.gobv/prod2002pubs/01statab/intlstat.pdf .

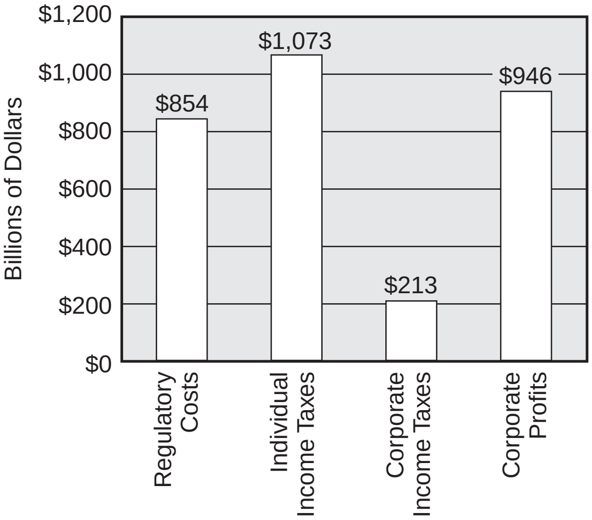

Figure 3. Regulatory costs compared with individual income taxes, corporate income taxes, and corporate pretax profits (from Crews, 2002). Source for taxes and profits: U.S. Census Bureau, Statistical Abstract of the United States: 2001, Table 459, p. 305, and Table 758, p. 501.

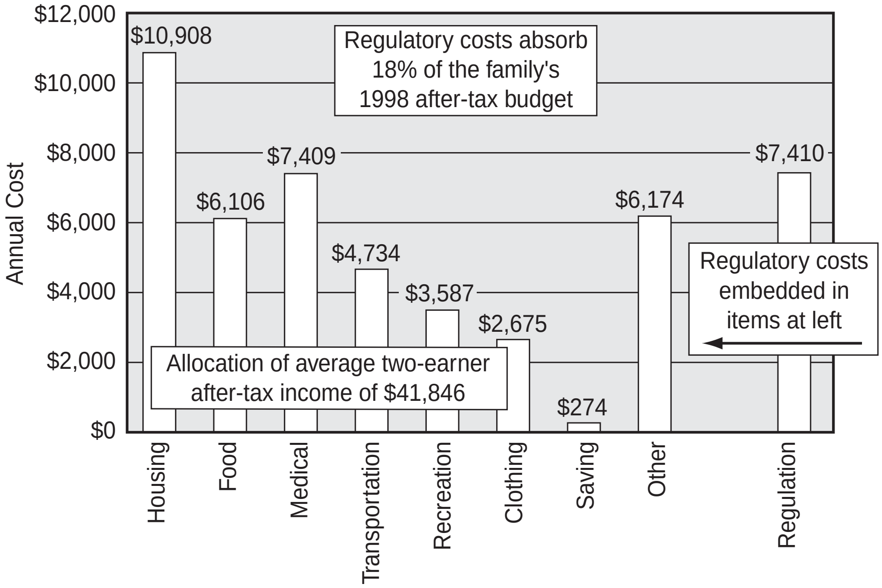

Figure 4. After-tax budget of two-earner family (from Crews, 2002). Sources: calculations based pm Tax Foundation data and Thomas D. Hopkins, "Profiles of Regulatory Costs: Report to the Small Business Administration, U.S. Department of Commerce," NTIS PB96128038, November 1995, www.sbs.gov/ADVO/research/rs1995hoptot.pdf.

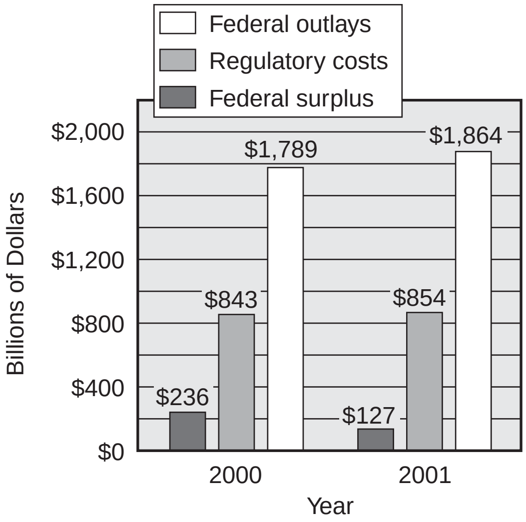

Figure 5. Off-budget regulatory costs compared with projected Federal spending and surplus (2000–01 dollars) (from Crews, 2002). Sources: Congressional Budget Office, The Budget and Economic Outlook: Fiscal Years 2003–2112, January 2002, www.cbo.gov/showdoc.cfm?index=3277&sequence=2; and W. Mark Crain and Thomas D. Hopkins, "The Impact of Regulatory Costs on Small Firms," report prepared for Small Business Administration, Office of Advocacy, RFP no. SBAHQ-00-R-0027, October 2001, www.sba.gov/advo/research/rs207tot.pdf. Notes: Regulatory costs for 2001 are projected on the basis of average annual increases in regulatory costs between 1995 and 2000 in Crain and Hopkins. Federal surplus and outlay numbers are by fiscal year; regulatory costs are by calendar year.

Impacts on the Mining Industry

Figures 6 through 8 show the dramatic impact that the flood of regulations has had on various parameters that record the vitality of the mining industry. Mining claim decline is a case in point. Although declines in metal prices and in the general state of the world economy have had a negative effect on the number of claims recorded (fig. 6) and held (fig. 7), the imposition of annual holding fees in 1993 by the federal government was clearly the most important factor. Mining claims recorded fell from nearly 150,000 in 1989 to less than 20,000 in 2001, and claims held declined from 1,010,003 in 1992 to 207,757 in 2001 (fig. 7).

Declining exploration spending in the U.S. (fig. 8) is another measure of the health of the domestic mining industry. Although economic decline since 1998 is certainly a factor in this decline, overseas competition for exploration funding is also important. Increased regulatory burdens on mining in the U.S. have caused some companies to curtail U.S. exploration programs in favor of overseas ventures.

According to the Bureau of Labor Statistics, government civilian employment has risen 13.8% since 1991 while mining employment has dropped 23.7% during the same period. Government employment is now greater than the combined total of manufacturing and mining. Furthermore, compensation of government employees grew by 47.4% from 1991 to 2001, while compensation for mining

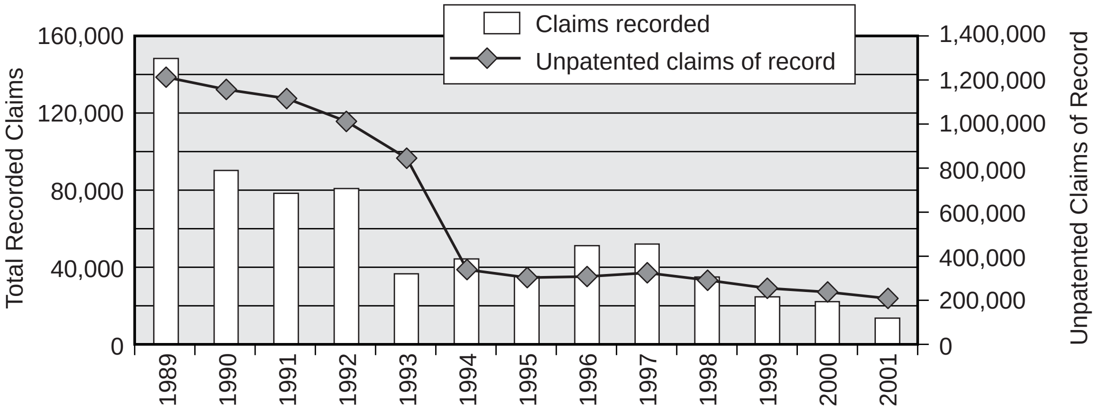

Figure 6. Decline in recorded mining claims, 1989 through 2001. Data are from the U.S. Bureau of Land Management.

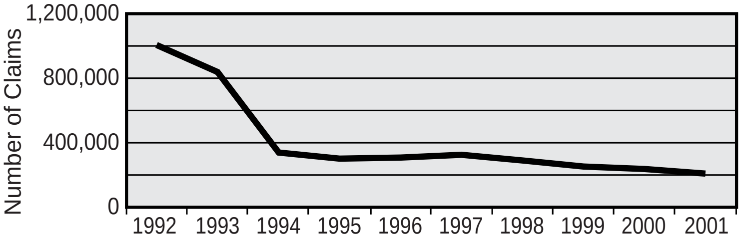

Figure 7. Decline in the number of active mining claims, 1992 through 2001. Data are from the U.S. Bureau of Land Management.

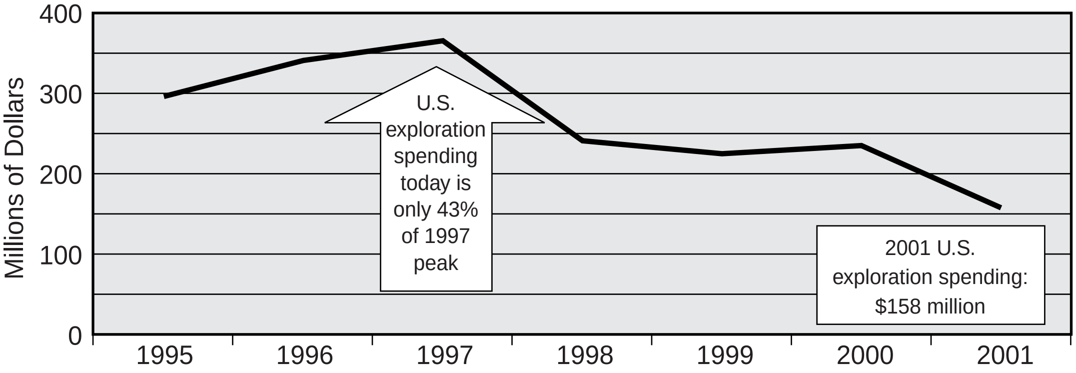

Figure 8. Decline in estimated mineral exploration spending in the United States. Data from Mining Engineering Magazine, May 2002, p. 26–36.

employees only grew by less than half, 20.4%. Average annual increases in compensation rates were 4.3 and 1.85% respectively, which is slightly better than inflation for government employees, and much worse for those in mining.

As long as Congress is not held accountable for this ever-rising tide of costly regulations, the wealth building mechanisms of society will continue to erode, and government's share of the nations total employment will grow. Once federal regulations are enacted, it is the common practice of most states and many local governments to adopt these federal regulations by reference into their administrative programs, thereby duplicating them. This duplication of regulations causes mirror-like duplication in program staffs. Unchecked, this growth in government employment, especially at the state and local level, will generate additional increases in regulatory fees to help pay for these new employees.

Many examples exist of fee-based regulatory programs that are not subject to the check and balance system of the legislative budgetary process. The time has come to change the system that fosters this duplication and in some cases triplication of federal regulations, and curb the growth of government.

Possible Solutions

Ask our Congressional representatives to do the following:

- Take the Office of Information and Regulatory Affairs (OIRA) out of the Executive Office of the President and make it a stand-alone organization, like the General Accounting Office, reporting to Congress.
    - Improve the cost-benefit analysis capabilities of OIRA and stop depending on the information provided by regulatory agencies.
    - Require explicit consideration of the employment effects of all new regulations (Laffer, 1993).
    - As proposed by Gattuso (2002b), require annual reporting by agency of:
        - Number of major and minor rules proposed or promulgated
        - How many were supported by analyses.
        - How many had quantified and/or monetized costs and benefits.
        - To what extent did each adhere to Office of Management and Budget guidelines for analyses
    - Provide an annual summary of the number of regulations reviewed, the number accepted, and the reasoning behind it.
    - Publish the annual cost of regulations, including enforcement, on individuals and businesses
    - Adopt the following table for cost analysis reporting:

Proposed Breakdown of "Economically Significant" Rules

Category 1	>	$100 million	<	$500 million
Category 2	>	$500 million	<	$1 billion
Category 3	>	$1 billion		
Category 4	>	$5 billion		
Category 5	>	$10 billion		

- Demand that Congress reject any and all regulations it deems counterproductive and of little benefit to society.
- Reduce the number of regulatory rule writers in those regulatory agencies writing the greatest number of regulations having low cost-benefits analyses.

Finally, the addition of a grassroots effort would help to supplement the mining industry's traditional lobbying effort by developing active constituents willing to support legislators regarding regulatory reform. At the state level such a grassroots program would facilitate the reform of the "me too" duplication of regulations and staffs at the state and local levels of government.

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Present-Day Features Related to the Deposition of Trona at Owens Lake, California, and a Comparison with the Trona Deposits of the Green River Basin

Neil Brown, Anadarko Petroleum
Paul Lamos, U.S. Borax
Iain Scarr, Rio Tinto Exploration

Introduction

The history of the Owens Lake trona deposit has been well documented, starting with studies conducted before the inflow to the lake was diverted and the lake desiccated. Upon the decision to divert the Owens River into the Los Angeles Aqueduct, Hoyt Gale was dispatched in 1912 by the U.S. Geological Survey (Gale, 1917) to measure the composition of the water of Owens Lake and determine the content of the various salts in that brine. Following diversion of the inflow, the sequence of mineralization was observed and documented, as were flooding events in 1938–39 and 1968–69 and the subsequent mineral redeposition. Alderman (1983) reported on drilling through a large portion of the post-1968 deposit, and calculated the tonnage of salts in the salt body and contained brine. His findings that some salts were depleted in comparison to the original brine, while others actually increased, came as quite a surprise, but apparently can be explained by several mechanisms, the most important being loss of some of the heavier brine derivatives by seepage into the pre-lake sediments.

The entire history of the of the extensive Owens Lake trona deposit seen today (except for the relatively insignificant shorelines crusts that existed prior to 1912) took place in modern times. The sequence of events leading to the present-day deposits are known, have been documented, and are indeed represented in the beds exposed by mining at the U.S. Borax Inc. Owens Lake operation. In essence, Owens Lake was a controlled experiment demonstrating the events resulting in the deposition of a trona body, and displaying clearly the features associated with those events.

This paper explores the similarities and dissimilarities between the modern deposit of Owens Lake and the older trona deposits in the Green River basin in Wyoming, opening for discussion and further research the conclusions to be drawn concerning the genesis of the Wyoming deposits.

Features of the Owens Lake Deposit

Significant events in the deposition of the Owens Lake salt body are reflected in the textures and features visible in a vertical section of the upper 4 feet of the deposits as exposed by modern-day mining (fig.1).

The pre-1938 strata, as measured in the central portion of the trona deposit today being mined by U.S. Borax Inc., consists of a sequence of alternately banded pale-tan to white and tan to dark brown trona (fig. 2), containing alternating crystalline and massive, “ice cream” trona. Similar to the features described by Boni and Atkinson (1998) for bed 17 in the Green River basin, the dark colors are due to insoluble algal remnants. Cyclic banding of the Owens Lake trona is the result of seasonal changes during the 3 years it took for Owens Lake to become completely desiccated, and for all of the trona to be deposited. A layer of burkeite and an overlying mixed salt and detrital insoluble layer represent the final stages of deposition. The burkeite is often easy to distinguish at Owens Lake by its pink color, imparted by halobacteria, microorganisms that that thrive in very saline environments. The mixed salts and insoluble sediment layer is similar to the rough surface seen on the present-day surface, where salts are constantly broken, dissolved, re-precipitated and mixed with insoluble dust and silt.

A major flooding event in 1938, the result of excessive runoff that exceeded the capacity of the Los Angeles Aqueduct, is represented by a 3-inch layer of insoluble clay and silt, mixed with small crystals and fragments of trona. This dark-brown layer includes not only the sediments and fragments of mineral washed in from the margins of the trona deposit, but also the crystalline trona deposited as the initial “winter salt,” similar to that described by Smith and others (1987) for the initial mineralization following a similar flooding event in the winter of 1968–69.

A thick, nearly white layer of “ice-cream” type trona deposited after 1939 is characteristic of a period of constant evapotranspiration that took place within one season. As with the lowermost beds, the “ice cream” trona is capped by a dirty, brecciated surface salt layer (at 30 inches, fig. 1) that formed from weathering and recrystallization between 1939 and 1968.

The 1968–69 insoluble material/mixed layer was formed in a short period following the last major flooding event before the capacity of the aqueduct was increased. The overlying thin layer of “crystal mush,” fairly clean, crystalline trona, with distinguishable crystals of 1–2 mm (see fig. 3) is most probably evidence of the first stage of crystallization described by Smith and others (1987), when an assemblage of salts, including natron, was crystallized as the result of cooling nighttime temperatures. As Smith and his co-authors noted, most of the other, more soluble salts redissolved as the temperatures increased, but the natron was in all likelihood converted to, or replaced by, trona. Immediately above the “crystal mush” zone is another layer of “ice cream” trona, again deposited during one warm season of excess evaporation, followed by the most recent brecciated surface salts.

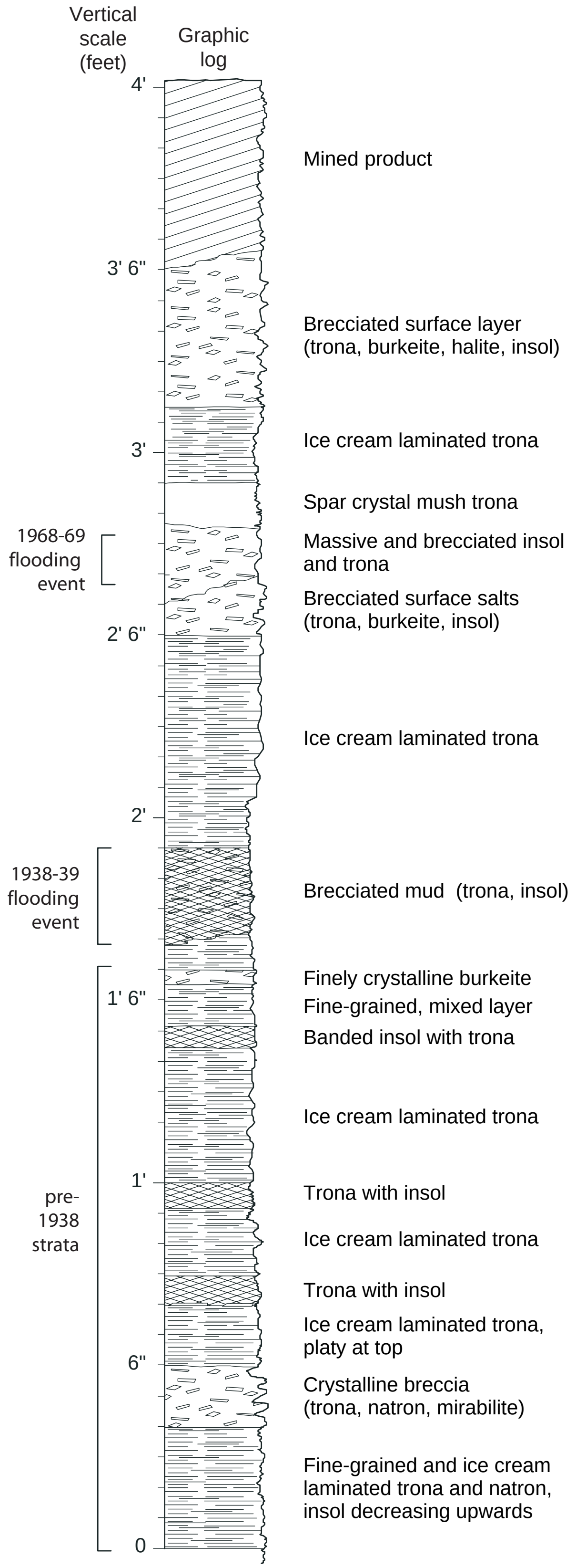

Figure 1. Vertical section of the top 4 feet of the Owens Lake salt deposit.

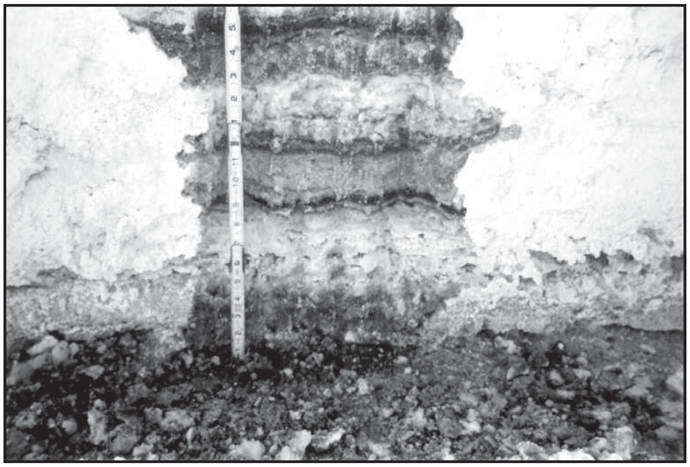

Figure 2. Banded trona of the pre-1938 deposition at Owens Lake. Section shown is about 16 inches thick.

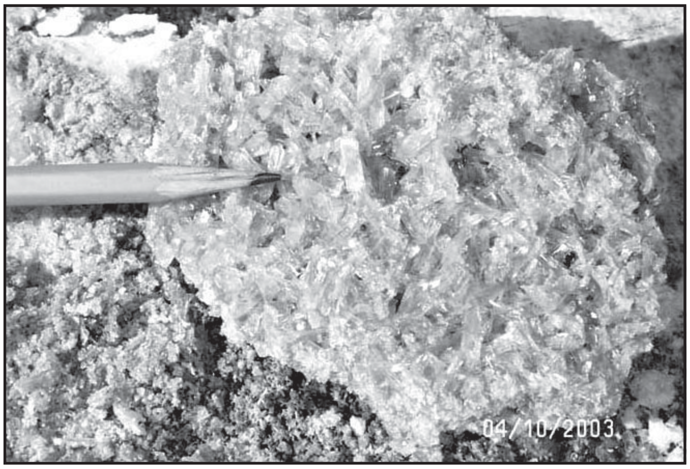

Figure 3. Crystalline trona, deposited following the 1968–69 flooding at Owens Lake.

Mineralogy

Based on a compilation of results from several thousand drill holes, Alderman (1983) provided the most accurate inventory of the present-day salt deposit. Trona is the most common individual mineral species, followed in order of abundance by burkeite, thermonatrite, halite, and insoluble matter. Brine comprises approximately 30% of the deposit. Table 1 shows Alderman's inventory of the Owens Lake salts.

Table 1. Owens Lake components.

	From Alderman, 1983
Trona $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_20$	46%
Burkeite $2Na_2SO_4 \cdot Na_2CO_3$	11.6%
Thermonatrite $Na_2CO_3 \cdot H_2O$	4.4%
Halite NaCl	1.8%
Insol	6.2%
Brine	30%
Na_2CO_3 (8.9%)	
$NaHCO_3$ (0.2%)	
NaCl (18.0%)	
Na_2SO_4 (4.5%)	
H_2O (68.4%)	

Alderman's conclusions regarding changes to the Owens Lake salt content over time and the resultant mineralogy may be relevant in more fully understanding the origin of the mineralogy of the Green River basin trona deposits.

Table 2 shows a comparison of Alderman's calculated salt contents with those of Gale from 1912 (Gale, 1915) prior to diversion of the Owens River.

Table 2. Salt content, Owens Lake (millions of tons).

	From Gale, 1917	*From Alderman, 1983*
	Pre-1917 Lake	Present evaporite deposit
Na_2CO_3	53.6	38.6
$NaHCO_3$	10.1	21.8
NaCl	64.5	9.6
Na_2SO_4	24.3	10.7
Totals	152.5	80.7

Alderman suggested that the removal of brine by seepage into the sub-lake basin sediments is a possible explanation for the large loss of sodium chloride and overall loss of salts. The greater density of the late-phase brine and porosity of the sediments beneath the lake, both measured by Alderman, are the key contributing factors.

Comparison of Owens Lake with the Green River Basin Deposits

Observations made at Owens Lake since 1913 provide us with an excellent record of what processes took place and how the trona was deposited. Textures and features of the Wyoming deposits, similar to those observed at Owens Lake, implies that similar processes may have occurred, and that examination of the well-documented depositional record of the Owens Lake deposit might provide clues to the depositional processes that occurred in the Green River basin.

The Green River basin trona deposits contain the world's largest reserve of trona. It is estimated that more than 127 billion tons of soda ash equivalent are present in the Wilkins Peak Member of the Green River Formation (Dyni, 1997). More than 2 billion tons of economically mineable trona remains in the beds currently being mined in the basin and 12.1 billion tons of mineable trona in all beds. This represents a reserve life of about 80 years for the mined beds at current rates of mining; and well in excess of 200 years for all of the conventional mineable beds in the basin.

A comparison of the dimensions of the two basins is shown in table 3. The Green River deposits obviously contain significantly larger reserves of trona derived from a considerably larger basin (Lake Gosuite). The Owens Lake deposit was created by a single major event; the diversion of Owens River water. The Green River basin trona deposits were created by hundreds of such precipitation and evaporation cycles.

Table 3. A comparison of Owens Lake and Lake Gosuite basin and deposit size.

	Owens Lake	Lake Gosuite
Size of original lake (sq. miles)	100	8,100
Extent of trona deposition (sq. miles)	34	1,300
Trona resources (tons)	50 million	12.1 billion

Rates of deposition for the Green River deposits have been estimated at 2 to 4 inches per year. (Bradley and Eugster, 1969) At Owens Lake, it would appear that most of the original deposition of about 4 feet thickness occurred during 1917 to 1923, when all of the Owens River waters were diverted from the valley. Lake Gosuite, the Eocene lake in which the Wyoming deposits formed, was receiving higher rates of input from annual precipitation and runoff than was Owens Lake and therefore depositional rates should be lower due to seasonal dissolution and reprecipitation.

Textures

The trona beds in the Green River basin display three major textures referred to by Leigh (1991) as "maple sugar" (light brown to white, fine-grained 1 mm to microcrystalline aggregated masses), "root beer" (amber, light to very dark, translucent coarse crystalline, 5 mm to 30 mm fibrous masses with random radiating bladelike euhedral crystals), and "spar" (vertically oriented, clear crystalline, columnar vein-filling trona).

At Owens Lake, one of the most common textures is referred to as "ice cream." Figures 4 and 5 show typical samples of maple sugar and ice cream trona textures. The two textures appear to be very similar. The major difference is in density of the rock, as the Green River trona has been strongly compacted and dewatered due to burial, while the Owens Lake material still contains up to 30% intergranular brines. When the material is dewatered and mined it has a considerably lower density than the maple sugar trona type. Both maple sugar and ice cream trona can be white to dark yellow to brown depending on the amount of organic material present.

Garrett (1998) postulated that the maple sugar trona of the Green River basin deposits formed when the lake became shallow enough to be affected by daily temperature fluctuations, with the trona forming on the surface and sinking to form "sucrosic" textured beds of trona. At higher lake levels, radiating crystal type beds (root beer texture) were formed by evening cooling and settling to the lake bottom.

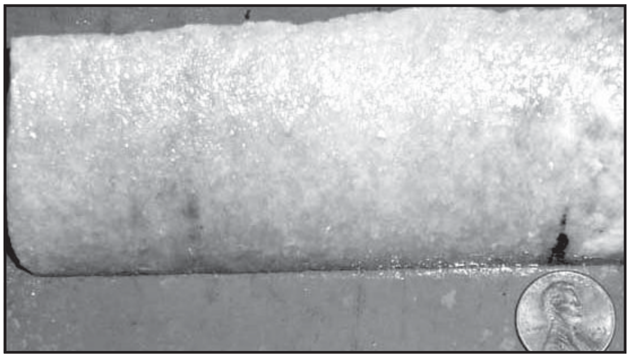

Figure 4. Maple sugar texture in trona core from bed 17, Green River basin, Wyoming.

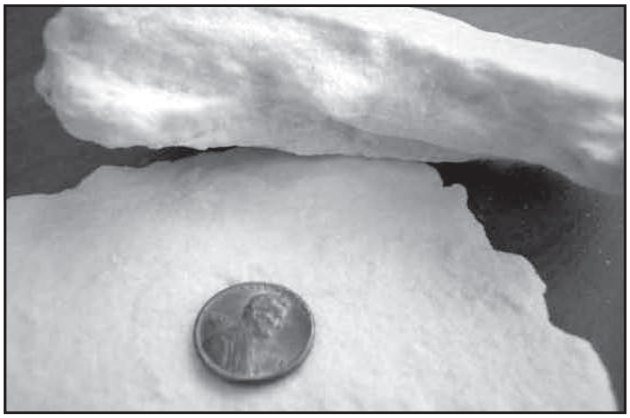

Figure 5. Ice cream texture in trona ore sample from surface of Owens Lake, California.

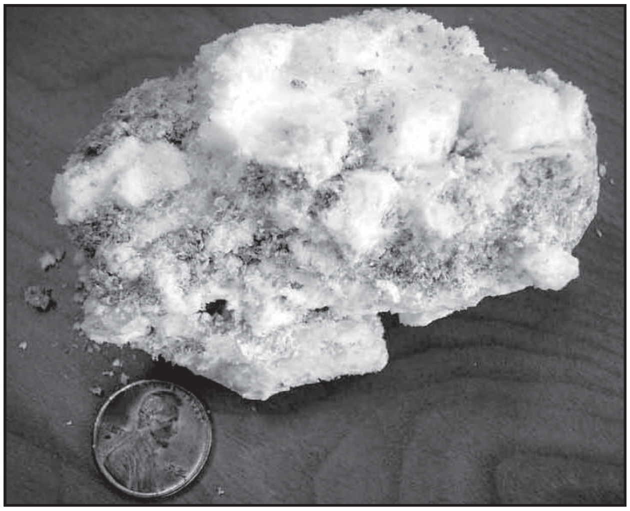

Figure 6. Ice cream and coarsely crystalline trona from the Owens Lake deposit.

A similar process was observed at Owens Lake, where a "crystal mush" textured trona appeared to be the result of crystal rafts forming on the water surface, then sinking to the lake bottom when disturbed by rippling caused by wind gusts. Large open voids between the crystals are commonly filled with ice cream textured trona. Similar relationships are seen in Green River bed 17 core. Figures 6 and 7 show ice cream and maple sugar trona with coarsely crystalline trona. The crystalline trona at Owens Lake is thought to have formed on the dry lake surface and then washed to the center of the depression where it accumulated.

Insoluble clay, marlstone, shale, and silts occur in both deposits. At Green River, these layers were due to increased precipitation that washed sediments into the ancient Lake Gosuite. These bands of insoluble material can generally be traced several miles across the entire deposit (fig. 8). At Owens Lake, distinct bands of insoluble material were formed by the two major flooding events in 1938 and 1968.

Halite occurs in several of the Green River trona beds, but generally only in the deeper portions of the each particular bed's depositional basin. We believe that the halite precipitated late, after the trona, and was redissolved with each precipitation event and transported to the lowest parts

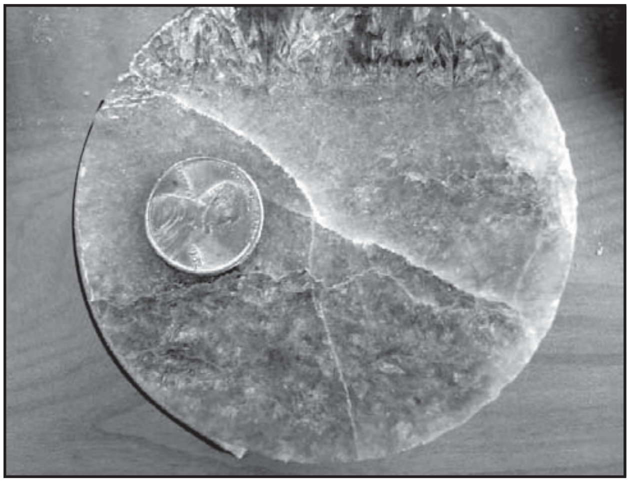

Figure 7. Maple sugar and coarsely crystalline trona from Green River basin.

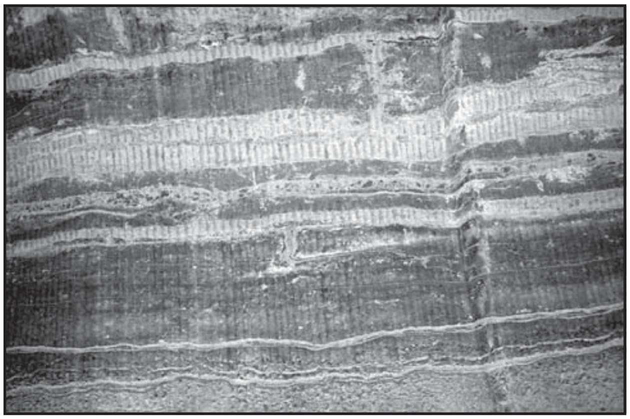

Figure 8. Thin dark bands of oil shale and marlstone in trona bed 17, Green River basin, Wyoming.

of the basin. As described above, the larger precipitation events would also commonly deposit thin impermeable silt or clay layers on top of the trona, forming a seal that isolated the salt that was still in solution. At Owens Lake the halite precipitated last as a white crust on the surface of the dry lake, and a great deal of halite remains in solution as interstitial brine within the trona deposit (fig. 9). When the material is mined and the brines drained from the bed, the halite content of the mineral product is generally less than 2%.

In the Green River basin, trona is the predominant mineral seen in the beds and is 85 to 95% of the mined material. Nahcolite and halite occur in several (but not all) of the beds and appear to be common in the deeper parts of the depositional basins. At Owens Lake, trona is the predominant mineral, but burkeite, thermontrite, and halite occur in significant amounts also (table 4). Natron and mirabilite occur in minor amounts.

The contrasting mineral assemblages indicate a difference in the composition of the original waters entering the closed basins. At Owens Lake, there are records documenting the composition of the original waters before desiccation. In the Green River basin, the composition of the original lake water is unknown, but apparently contained less SO_4 and Cl than the Owens Lake brines. It is also important to note that the Owens Lake deposit is still evolving. It is currently composed of 30% brines. Many of the mineral assemblages seen there today would not survive burial and diagenesis in their current state.

Figure 9. Late white halite crust precipitated from brine at Owens Lake.

Table 4. Mineralogical comparisons between Owens Lake and Green River basin deposits.

	Owens Lake	Green River basin
Trona	46%	85–95%
Burkeite	11.6%	none
Insoluble	6.2%	5–15%
Thermonatrite	4.4%	trace
Halite	1.8%	<1%e
Brine	30%	none
Shortite	none	<1%
Nahcolite	none	trace
Natron	trace	none
Mirabilite	trace	none

Conclusion

Although a much smaller deposit, the single trona bed formed by the man-caused desiccation of Owens Lake appears similar in some respects to the Green River basin (former Lake Gosuite) deposits. Transformation of the salt contents of Owens Lake after the lake was isolated and dried out offer a model for the genesis of the largely monomineralic Green River basin deposits. In addition, some textures of the Owens Lake trona remain in the otherwise compacted and recrystallized minerals of the Green River basin deposits. More work remains to be done, but it appears that Owens Lake deposit is somewhat analogous to the Wyoming deposits and offers some clues regarding their genesis.

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The Nevada Construction Aggregate Industry 2003

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Abstract

The Nevada construction aggregate industry, one of the fastest growing in the U.S., is changing rapidly because of competing land use, social impacts, environmental issues, and concerns about material quality. We present data that are based on personal interviews and estimates of production from more than 80 suppliers of construction aggregate. More than 150 aggregate production sites are shown on a map of Nevada with insets for the Reno-Sparks-Carson City and Las Vegas areas (fig. 1).

Estimated total production of construction aggregate in Nevada in 2002 was about 35 million short tons. This equates to consumption of approximately 15 tons per person per year, considerably higher than the national rate of 10 tons per capita.

The Las Vegas area, the fastest growing metropolitan area in the United States, consumes most of the aggregate in Nevada; approximately 26 million tons in 2002. Sand and gravel has historically dominated production, but quarry operations in Paleozoic carbonates at the city fringes produce increasing amounts of higher quality aggregate used in concrete and asphalt. Sand and gravel in alluvial fan deposits, mined from large established pits and by portable operations at local construction sites, provides most of the aggregate base.

The Reno-Sparks-Carson City area, the second largest population center in the state, consumed an estimated 6 million tons of construction aggregate in 2002. The geology and dynamics of operations that serve this area are much different from those in the Las Vegas area. They are generally quarry operations in volcanic and intrusive rocks and they produce aggregate for use in concrete, asphalt, and aggregate base. Production from portable operations is minimal.

The outlying communities in the state are predominantly served by intermittent operations in sand and gravel from alluvial fans, riverbeds, and paleo beach deposits, with a minor component of crushed stone.

Introduction

The construction aggregate industry in Nevada is greatly influenced by fundamental factors that are unique to the state. When combined, these factors help define the industry in the state. The factors are:

- Nevada is mainly in the Great Basin physiographic province, a geomorphic unit characterized by internal drainage basins and intervening mountain ranges. The Great Basin has unique geologic characteristics that distinguish it in many ways from other areas of the country, especially when considering recent sand and gravel deposition.
- Nevada has a cool high desert environment in the north and a hot low desert environment in the south.
- Nevada is the seventh largest state, by area, in the U.S.; 87% of this area is federal land.
- Nevada is the fastest growing state, percentage wise, in the U.S. Current population is approximately 2.3 million. Nevada is also the leading state in percentage of people living in an urban environment; 90% of Nevadans live in the Las Vegas and Reno-Sparks-Carson City metropolitan areas.

Nevada's growth is led by Las Vegas, the fastest growing metropolitan area in the country. In 2003, there were approximately 900,000 more people in Nevada than in 1990. The Las Vegas area is clearly the population center of the state with nearly 1.6 million people and approximately 5,000 new residents per month moving into the metropolitan area.

Because of Nevada's quickly growing population, its construction aggregate industry is one of the most rapidly growing in the U.S. As in most areas of the country, the character of the state's aggregate industry is changing. Competing land uses, social impacts, and environmental issues are putting constraints on an industry that as recently as 25 years ago had little regulation or opposition. Larger companies with extensive regional or national presence in the construction aggregate industry are acquiring and consolidating the independently owned local aggregate sources and bringing a higher level of experience and sophistication to the industry.

Overview of Production

The Nevada Bureau of Mines and Geology estimates that the total production of construction aggregate in Nevada was about 35 million short tons in 2002, with a value of approximately $160 million. By contrast, total 2002 U.S. production is estimated by the U.S. Geological Survey at about 3.0 billion tons. Aggregates are the second most valuable mineral commodity in the state, after gold (valued at $2.3 billion in 2002). Nevada's aggregate consumption equates to approximately 15 tons per person per year, considerably higher than the national average of approximately 10 tons per year. Nevada's production includes both sand and gravel and crushed rock with the crushed rock production increasing as lands containing sand

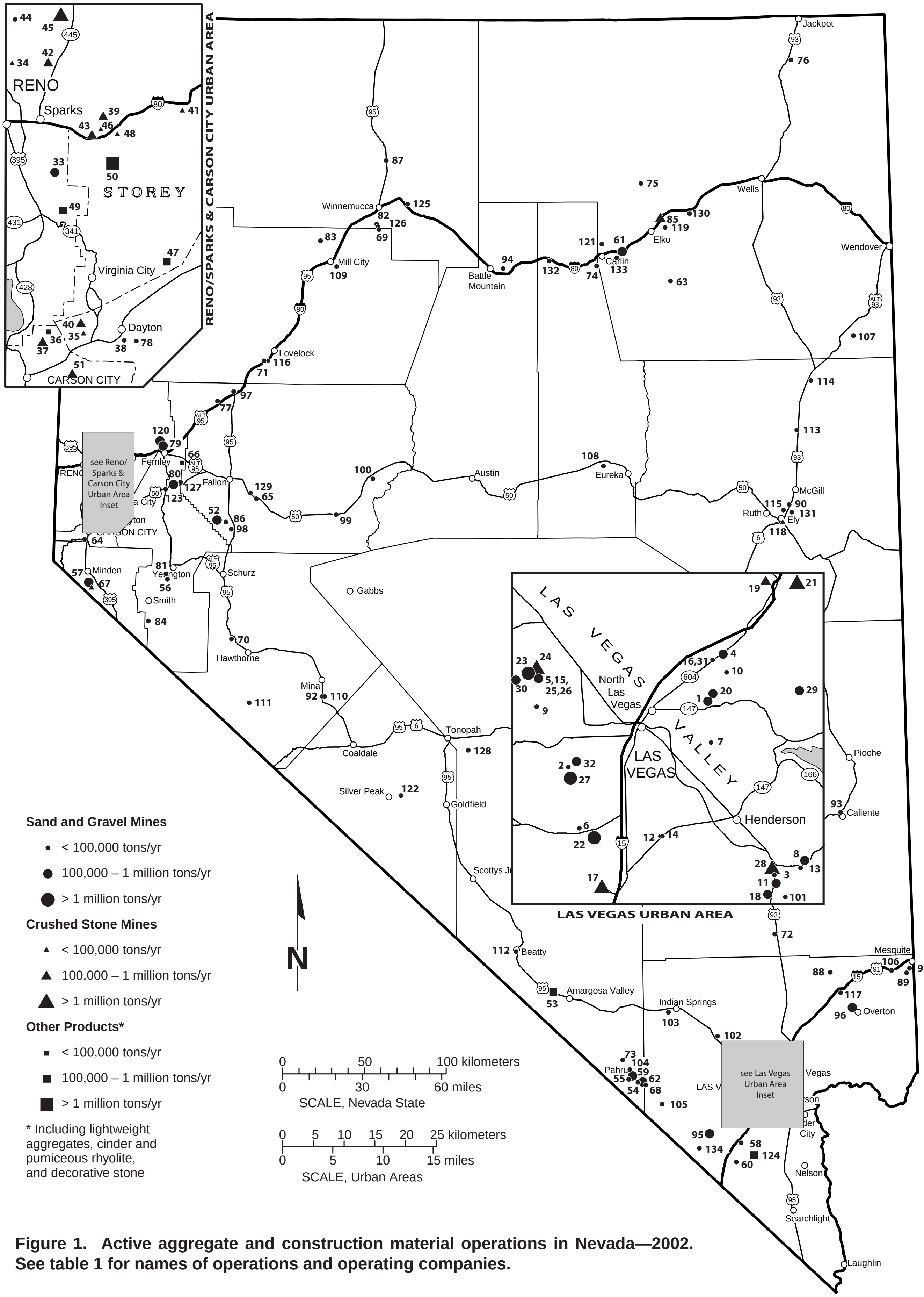


Figure 1. Active aggregate and construction material operations in Nevada—2002. See table 1 for names of operations and operating companies.

Las Vegas Urban Area Mines

No.	Operating Company	Operation
1	Airway Rock Products	Airway Pit
2	Allstate Sand and Gravel	Sunrise Pit
3	American Asphalt & Grading	Eldorado Rock Products Pit
4	American Sand and Gravel	Salt Lake Highway BLM Pit
5	American Sand and Gravel	Lone Mountain BLM Pit
6	Bird Springs Materials	Bird Springs Pit
7	Bob's Sand and Gravel	Eldorado Valley Pit
8	Boulder Sand & Gravel	Bootleg Canyon Pit
9	Charlie Brown Construction Co.	Charlie Brown Pit (Ft. Apache & Maule)
10	Charlie Brown Construction Co.	Nellis Pit
11	Construx (Silver State)	El Dorado Pit
12	CTC Crushing, LLC	Cactus Pit
13	DBE Excavating	Boulder City Operation
14	Diamond Construction	Eastern & Lake Mead
15	Diamond Construction	Lone Mountain BLM Pit
16	DL Denman Corporation	DL Denman Pit
17	Frehner Construction (Sloan)	Sloan
18	Gornowich Sand & Gravel	Gornowich Pit
19	Granite Construction	Apex (Chemical Lime overburden)
20	Hollywood Gravel	various, incl. Hollywood Pit
21	Las Vegas Paving Corp.	Apex Landfill Pit
22	Las Vegas Paving Corp.	Blue Diamond (Jones) Pit
23	Las Vegas Paving Corp.	Mendenhall Pit (BLM)
24	Nevada Ready Mix Corp.	Lone Mountain Pit
25	Pipes Paving	Lone Mountain BLM Pit
26	Quality Sand and Gravel	Lone Mountain BLM Pit
27	Rinker Materials	Buffalo Road Pit
28	Rinker Materials	El Dorado Pit
29	Sandia	Pabco Pit
30	Southern Nevada Paving	Far Hills & 215
31	Southwest Paving & Grading	Southwest Paving & Grading
32	Wells Cargo Inc.	Spring Mountain Pit
101	NDOT	CL11-01

Reno/Sparks and Carson City Urban Area Mines

No.	Operating Company	Operation
33	A & K Earthmovers, Inc.	Bella Vista Pit
34	A & K Earthmovers, Inc.	Golden Valley
35	Canyon Creek Construction	Canyon Creek Pit
36	Cinderlite Trucking Corp.	Cinder Pit
37	Cinderlite Trucking Corp.	Goni Pit
38	Dayton Ready Mix and Hughes	Pit name unknown
39	Frehner Construction	Mustang
40	Frehner Construction	Moundhouse
41	Gopher Constr.	Tracy/Clark
42	Granite Construction	Hidden Canyon
43	Granite Construction	Lockwood
44	Martin Marietta Materials	Lemmon Valley
45	Martin Marietta Materials	Spanish Springs Quarry
46	Martin Marietta Materials	Mustang
47	Naturalite Aggregates - Basalite	Lower Naturalite Plant
48	Nevada Hydrocarbon (Gopher)	Mustang Pit
49	Rilite Aggregate Company	Rilite Pit
50	RMC Nevada	All-Lite Pit
51	T.E. Bertagnoli	Bertagnolli Pit
78	Granite Construction	Dayton

Rural Nevada Mines

No.	Operating Company	Operation
52	A & K Earthmovers	Desert Mountain
53	Cind-R-Lite	Cinder Cone Mine
54	Andrew Barasky Excavating	Andrew Barasky Pit (Pahrump)
55	Basin Sand and Gravel	Basin Sand and Gravel Pit
56	Bedrock Products	Tibbles Pit
57	Bing Materials Co.	Bing Materials Pit
58	BLM	North Jean Lake BLM Pit
59	BLM	Pahrump BLM Community Pit
60	BLM (Sheep Mtn.)	Sheep Mountain
61	Boehler Construction Co.	Boehler Pit
62	Bolling Construction	Bolling Construction
63	Canyon Construction	pit name unknown
64	Carson City DOT	Voltaire Canyon Pit
65	Churchill County	Salt Wells Pit (BLM)
66	Churchill County	Hazen Pit
67	Cinderlite Trucking Corp.	Dresslerville Pit
68	Concrete Systems	Pahrump Operation
69	Curtis Machinery	Curtis Pit
70	Day Zimmerman	Hawthorne Army Depot/Beach Pit
71	DeBraga	Lovelock/DeBraga Pit
72	Earl Williams (BLM)	Coyote Springs Pit
73	Elite Concrete	pit name unknown
74	Elko Sand and Gravel	Carlin Division Pit
75	FNF Mining Construction	Dinner Station Pit
76	FNF Mining Construction	Jackpot Operation
77	Gopher Construction	Jessup Aggregates
79	Granite Construction	Wade Sand Pit
80	Granite Construction	pit name unknown
81	Grant Smith Aggregates	Grant Smith Aggregates
82	HE Hunewill Construction	Sonoma Gravel Pit
83	HE Hunewill Construction	Thomas Creek Pit
84	HE Hunewill Construction	Desert Creek Pit
85	Harney Rock and Paving	Pardo Pit
86	Hiskett & Sons	Russel Pass
87	Humboldt County	Paradise Hill Pit
88	Infiniton Sand & Gravel	Meadow Valley Wash
89	J & J Mill and Lumber	Lee Brothers Pit
90	J & M Trucking	Isbell Pit
91	Jensen Construction	Mesquite BLM Pit
92	Jim Wilkin Trucking	Mina Pit
93	Jim Wilkin Trucking	Wilkins Pit
94	John Davis Trucking Co.	3D pit
95	Las Vegas Rock	Rainbow Quarries
96	Leavitt Ready Mix	Kaalin Pit
97	Makedon	Pit name unknown
98	NDOT	CH08-03
99	NDOT	CH27-02
100	NDOT	CH36-02
102	NDOT	CL18-02
103	NDOT	CL19-01
104	NDOT	CL47-03
105	NDOT	CL47-04
106	NDOT	CL88-03
107	NDOT	EL09-01
108	NDOT	EU02-06
109	NDOT	HU83-08
110	NDOT	MI01-03
111	NDOT	MI12-02
112	NDOT	NY08-06
113	NDOT	WP05-02
114	NDOT	WP06-02
115	NDOT	WP28-01
116	Pershing Co. Water Conserv. Dist.	Perth Pit
117	Ready Mix Inc. (RMI)	Glendale Quarry
118	Reck Brothers	HiLine Quarry
119	Rees' Enterprises	Stitzel Pit
120	RMC Nevada	Paiute Pit
121	Ruby Dome, Inc.	Jones Pit
122	SANROC	Foote Mineral Pit
123	Silver Springs Aggregates	Silver Springs Pit
124	Southern Nevada LW	Money Pit
125	Sweeney Construction	Stall Ranch Pit
126	TG Shepard	Grass Valley Pit
127	Tedford	Lahontan Pit
128	Tonopah Sand and Gravel	Tonopah Sand and Gravel Pit
129	Truckee-Carson Irrigation District	Truckee-Carson Irrigation District Pit
130	Vega Construction Trucking	Elburtz Pit, Elko
131	White Pine County	White Pine County Pit
132	WMC Co., Inc.	Dunphy Pit
133	WMC Co., Inc.	pit name unknown
134	Unknown Operator	Sandy Valley Pit

Table 1. Nevada aggregate producers—2002.

and gravel near the major market areas are developed. In addition, natural lightweight aggregates in the form of pumiceous rhyolite and volcanic cinder are utilized in concrete masonry units and in semi-lightweight concrete applications in both the Reno and Las Vegas areas.

Figure 1 is a map of Nevada showing the locations of the producing construction aggregate deposits in the state, their general level of production, and the type of material mined (sand and gravel or quarried rock). Companies operating at these locations are listed in table 1.

Las Vegas Area

The Las Vegas area produces and consumes most of the construction aggregate in the state, about 26 million tons. There are five companies that produce more than 1 million tons of aggregate yearly. The major aggregate producers and their major operations are:

- Frehner Construction - Sloan Quarry
- Las Vegas Paving - Apex Landfill, Blue Diamond Pit, and Mendenhall Pit
- Nevada Ready Mix - Lone Mountain Pit
- Rinker Materials - Buffalo Road Pit and El Dorado Quarry
- Southern Nevada Paving - Far Hills and 215 Pit (Lone Mountain area)

Reno and Northern Nevada Area

The Reno-Sparks-Carson City area produces approximately 6 million tons of aggregate per year. The major aggregate producers and their major operations are:

- Granite Construction - Lockwood Quarry and Hidden Canyon Quarry
- Martin Marietta Materials - Spanish Springs Quarry
- RMC - All-Lite Quarry and Paiute Pit

The remainder of the state, with only 10% of the population, produces an estimated 3 million tons per year. Much of this production is in Nye, Lincoln, and Churchill Counties, and some of this is trucked into the two major metropolitan areas.

Methodology in Map Compilation

Figure 1 shows approximately 130 aggregate producers. Insets for the Las Vegas and Reno-Sparks-Carson City areas show the locations of the producers in these areas in more detail. The map was compiled based on information from the U.S. Geological Survey, the Nevada Bureau of Mines and Geology, and the Nevada Division of Minerals. In addition, some information came from the personal files of the authors and from several individuals recognized in the acknowledgments. Producers who make materials for the higher end of the aggregate market are included. These higher end products primarily include concrete aggregate, asphalt aggregate, and aggregate base. Deposits where the primary product is used only for fill material are not included.

The aggregate deposits shown on figure 1 are those which are currently or recently active. They are divided into production amounts of less than 100,000 tons per year, 100,000 to 1,000,000 tons per year, and more than 1 million tons per year.

Many small operators in the state that produce less than 10,000 tons per year are not included in our summary. These producers generally make aggregate base. In addition, there are sources that produce small amounts of concrete aggregate for use in ready-mix concrete in some of the small communities in Nevada.

Other sources include numerous pits utilized for rural highway contracts put out by the Nevada Department of Transportation (NDOT). These sources, which are used for base aggregate and asphalt aggregate, mostly exploit local sand and gravel deposits, and are generally located on public lands administered by the U.S. Bureau of Land Management (BLM) along major highways at intervals of every 10 to 20 miles. Such pits tend to be small and located in alluvial fans, which are ubiquitous in the Great Basin geological environment. They also tend to be intermittent and are utilized every few years when there is a highway contract in the area. Other rural sources include Pleistocene beach sands, dry wash deposits, or recent river gravels.

Uses of Nevada Construction Aggregate and the Impacts of Aggregate Quality on Those Uses

The three major uses of construction aggregates are for concrete, asphalt, and aggregate base. Because Nevada is the fastest growing state, much of the construction aggregate is going into highways and other infrastructures that are necessary for the rapid growth. For such uses quality is an important issue in determining the suitability of a given rock or sand and gravel deposit, and it is important that the material meets the appropriate specifications. Much of the material that is used in ordinary fill applications for various construction projects cannot meet such specifications and will not be discussed further. Fill comes from “borrow” pits in various materials that range from good to low quality. It should also be noted that ordinary fill material is often supplied by producers of high-quality aggregate from overburden or less desirable areas of their properties.

Concrete Aggregate

The highest and most demanding use of construction aggregate, from a quality perspective, is for portland cement concrete aggregate. The specifications for aggregate used in concrete are more rigorous than for that used in other applications. Durability, soundness, cleanliness, and the absence of chemical reactivity are very important. Concrete is used in the construction of many kinds of structures: pavements for highways and streets; structural concrete in buildings; foundations for almost all structures; and general flatwork, including floors, driveways, and sidewalks. The aggregate component of concrete is essentially filler that comprises about 75% by volume of the freshly mixed concrete.

Sand and gravel is generally the aggregate of choice for use in concrete by finishing and placement contractors because its rounded particle shape lends to superior workability. Natural sand is especially desired in concrete. Crushed rock aggregates are more angular and often provide less workability in fresh concrete mixes; in many cases, crushed rock makes it harder to place, compact, finish, and pump concrete. Nonetheless, most portland cement concrete produced in southern Nevada contains crushed rock aggregate.

Aggregate quality impacts the properties of finished concrete in many ways (e.g., strength, durability, freeze-thaw resistance, and weight). Higher quality aggregates are needed for most concrete applications, and the universally accepted standard for concrete aggregates is ASTM C33, Standard Specification for Concrete Aggregates. This specification spells out testing for abrasion, soundness and deleterious constituents. In addition, the specification details requirements for gradation requirements on the coarse and fine aggregate fractions, which are factors controlled in the processing plant. Processing of the aggregate prior to use in the concrete is important to assure the material is clean, free of deleterious fine material, and of the right gradation to assure a dense mix with minimal voids.

Asphalt Aggregate

Asphalt aggregate qualities are also important to assure that the end product, asphalt, is strong and durable. Because asphalt is a flexible pavement the aggregate used as the filler (approximately 90% by volume) must be an angular or crushed product to assure higher flexural strength by particle interlock. Sand and gravel is rounded and not suitable unless it is crushed, and there are specifications for the percentage of fractured faces in asphalt aggregate. Most of the asphalt aggregate used in the metropolitan Reno-Sparks-Carson City area of northern Nevada is from rock quarries, but crushed sand and gravel is still used extensively in southern and rural Nevada.

Most asphalt applications are for highways, roads, driveways and parking lots. Therefore the specifications are generally developed by state highway departments and/or local government public works agencies. Aggregate specifications are more stringent for federal highways with heavy truck traffic than they are for local streets and parking lots with relatively less intense traffic. The quality and specifications for asphalt aggregate are similar to those for concrete aggregate except gradations are different and asphalt stripping characteristics (ability of the oil to adhere to the aggregate) must be taken into account. Also, an ideal asphalt aggregate should have low absorption to minimize the amount of oil (binder) that will be required to make the asphalt mix.

Aggregate Base

Aggregate base (AB) is generally a 1-inch-minus graded mixture of crushed aggregate that is used as a base or foundation for most construction applications. AB is used under all road pavements and most structures and acts as a uniform, free draining, compacted base on which to place the concrete or asphalt. Where soils are very fine grained or clayey a large amount of AB may have to be used to stabilize construction sites sufficiently to support structures.

AB specifications are not nearly as stringent as those for concrete or asphalt; nevertheless, the material must have certain characteristics in gradation and durability. AB under pavements must also be relatively clean so it can freely drain. Excess clay fines are not desirable unless the AB needs a binder that will set up when exposed to the elements, for instance when it is used as a road surface by itself in a rural environment. Many smaller pits and most BLM pits in Nevada produce AB exclusively, especially in the Las Vegas area.

Other Uses

Other uses of construction aggregates that require relatively high quality material include drain rock, pipe bedding and backfill, riprap, ballast, decorative rock, mortar sand, and plaster sand. In overall production from the larger operations, these commodities are of limited tonnage compared to the three uses discussed above. However, some operations may specialize in one or more of these unique aggregate products. For instance, two deposits in the Las Vegas area have furnished the vast majority of the plaster sand (sometimes referred to as stucco sand) in the local market for many years, and plaster is extensively utilized in the area. Another example is the clean, durable, and specifically sized material needed for winter de-icing sand in northern Nevada.

Price Considerations

Because construction aggregate is a low-cost high-volume commodity, proximity to the market is very important. There are literally thousands of aggregate sources in the U.S. that supply local markets. Very little aggregate needs to be hauled long distances unless the geological environment for quality aggregate is lacking, or permits are unobtainable. In general, the further from the point of use an aggregate source is, the lower the F.O.B. price. This lower selling price at the more remote plants reflects the higher cost of transportation in delivering the product to market and remaining competitive. No matter how cheaply the material can be mined or how good the quality, beyond a certain distance from the market it cannot compete with material from closer sources due to transportation costs.

The cost of construction aggregate for all major uses in Nevada ranges from $3.00 to $8.00/ton, F.O.B. the mine site, depending on product. Concrete aggregate, including concrete sand, generally commands the highest price.

Concrete Aggregate in Las Vegas averages between $5.00 and $7.00/ton. Concrete Aggregate in the Reno area averages between $7.00 and $8.00/ton. AB prices in the Reno area are close to $5.00/ton, while in Las Vegas AB is less than $4.00/ton. Prices are lower in the Las Vegas area because of the current abundance of aggregate sources and, in the case of AB, because of the preponderance of localized producers at construction sites as described in more detail below.

Transportation costs in Nevada vary based on the accessibility of good transportation arteries and the size of the load. Freeway travel is faster than surface streets and therefore haul costs are cheaper per mile. Aggregate price at the point of use includes delivery time based on hourly rates for the haul trucks. Over the last two decades, load sizes in Nevada have increased to the point that trains of two to three trailers can legally haul as much as 42 tons on most major roads.

Geology of Nevada Aggregate Deposits

From a geologic perspective, the aggregate industry in Nevada is not dominated by any one type of deposit. In most of rural Nevada, sand and gravel is used, but in the major population centers, where demand is higher and land use restrictions more stringent, both sand and gravel and bedrock sources are used. The northern and southern parts of the state are not only geologically different, but also different from the perspective of the way that the aggregate industry approaches business.

Las Vegas-Clark County Area

The metropolitan Las Vegas area, which also includes the communities of North Las Vegas, Henderson, and Boulder City, is mostly in the Las Vegas basin, a major intermountain basin near the southern end of the state. The Las Vegas basin drains into the adjacent Colorado River and is not part of the Basin and Range province. Except for the nearby Colorado River and Virgin River valleys, it is the lowest terrain in the state, averaging approximately 2,000 feet in elevation. It is also a part of the Mojave Desert and sees temperatures of more than 110°F during the summer months.

Sand and Gravel

The majority of the sand and gravel sources in the Las Vegas area are alluvial fan deposits. Prior to the last decade, all of the aggregates used in the area came from sand and gravel sources in the extensive fans emanating from the surrounding mountains. In these fans, carbonate rocks are the dominant constituents to the west, north, and east, but volcanic detritus predominates to the south and southeast. Along the west side of the Las Vegas basin many of the fans have been cemented by secondary caliche, thereby strongly consolidating portions of the gravels and rendering them difficult to mine and process. In addition, material in some fans includes abundant silt, which requires extensive processing and sometimes washing to clean the aggregate so that it meets the more stringent specifications. The fines are generally eliminated by screening and wasting much of the minus 3/8-inch pit run material. Some of the aggregate operations in alluvial fans produce as much as 40% waste. Much of this fine material, however, can be used as ordinary fill or as part of AB if there is a local market (see discussion below).

An important aggregate marketing influence in Las Vegas in recent years is the practice of AB production on site at construction projects. Because much of the construction is now outside the interior of the basin on outlying alluvial fans, there is a considerable amount of material that contains relatively durable, coarse gravel mixed with sand and fines that will, with proper processing, make satisfactory AB at new construction sites. Producing AB is not difficult as specifications allow for higher fines content as compared to concrete aggregate, therefore washing may not be required. In the preparation and grading of the site, near surface gravels and even caliche can be excavated, crushed and screened using portable plants, and utilized as AB for on-site construction. Any unsuitable fines or oversize can also be used as ordinary fill material on the construction sites. This saves considerable expense in hauling AB from existing commercial aggregate pits. In some instances, considerable amounts of gravels are excavated, processed, and stockpiled for later use or for sales to nearby construction sites. In addition, large flood control basins have been excavated around the fringes of the Las Vegas basin, and the excavated material is processed into AB, stockpiled, and later sold offsite.

This production of AB from portable plants on construction sites has had a profound impact on some local aggregate producers, because AB used to be a major part of their production and sales. This preponderance of on-site portable plants making AB is the reason AB prices are low in the Las Vegas market. In addition, some of the principal sand and gravel producers that used to utilize undesirable fines in their deposits in AB now have to waste a considerably larger amount of material. This costs money and space, making operations less profitable and efficient, leading some producers to abandon sand and gravel operations for rock quarries that produce 100% crushed material and fewer fines.

The cleanest sand and gravel sources in the Las Vegas area are at Lone Mountain (fig. 2), where there are relatively young alluvial fan deposits. In general, the younger the sand and gravel, the cleaner and more durable it is. Older deposits tend to have more caliche, fines, and weathered clasts. The younger gravels are naturally washed and have not sat stagnant for thousands of years collecting fines during soil formation and wind deposition.

The Meadow Valley Wash, about 35 miles northeast of Las Vegas, is a major wash that drains many hundreds of square miles to the north. Relatively clean, fine sands occur locally along its course, and there is at least one active aggregate operation that produces sand from this wash just to the north of Moapa.

Quarried rock

Quarried rock sources in the Las Vegas area are increasing in importance as aggregate producers, primarily for two reasons. First, the gently sloping fan surfaces are being built on, and the property is becoming more valuable for development than for aggregate mining. Second, because of the proliferation of portable plants making AB at many construction sites, as described in detail above, existing sand and gravel sources in the older alluvial fans are unable to sell AB competitively. This leads to the generation of larger amounts of waste at long-term sand and gravel operations. Quarried rock sources produce less waste.

There are five major rock quarries in the Las Vegas area that produce construction materials. None were aggregate producers 20 years ago. Four of these sources are in Paleozoic carbonates and one is in Tertiary granite. One of the carbonate sources, Frehner's Sloan Quarry, was previously a source of high-quality dolomite feed for dolomitic lime production. Granite Construction's Apex aggregate source is operated in conjunction with Chemical Lime Inc.'s high-calcium lime plant at Apex. Granite accepts pit-run waste from Chemical Lime and processes it into aggregate. Las Vegas Paving's operation nearby is run in conjunction with the largest solid-waste landfill in the Las Vegas area. Here mining and processing of aggregate provides landfill space for the solid waste generated by Las Vegas, cover material for the landfill, and high-quality aggregate suitable for concrete and asphalt. The Tertiary granite is located at Railroad Pass, between Henderson and Boulder City, and is mined by Rinker Materials.

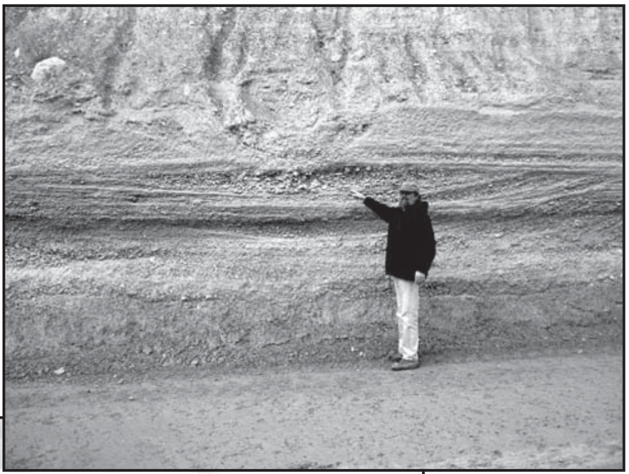
There is a single pumiceous rhyolite deposit in production in the Las Vegas area. It is approximately 30 miles to the south of the metropolitan area in Hidden Valley. The material is glassy pumiceous rhyolite that is part of a flow and tuff breccia deposit that is associated with a local silicic volcanic center. It is mined by Southern Nevada Liteweight and used in the manufacture of concrete masonry units. It also supplies most of the stucco sand used in the Las Vegas area.

Reno-Sparks-Carson City Area

The Reno-Sparks-Carson City area occupies basins in the rain shadow of the Sierra Nevada in northwestern Nevada. In addition to the cities of Reno, Sparks, and Carson City, it includes outlying communities. The Truckee River runs through Reno and Sparks; its source is the Lake Tahoe basin in the Sierra Nevada and it drains into Pyramid Lake about 30 miles to the northeast. The average elevation is over 4,000 feet.

Sand and Gravel

Prior to the 1980s, aggregate used in the Reno area came from abundant sand and gravel in glacial outwash deposits. The Truckee Meadows, in which Reno and Sparks are located, is a wide basin filled with a thick sequence of glacial outwash originating from melting glaciers between 10,000 and 100,000 years ago. During glacial periods, the Truckee River must have been considerably larger as evidenced by outwash extent and the large size of some of the boulders. The old Truckee River deposits include relatively thick, near surface, widespread, clean sands and gravels with occasional large boulders from catastrophic floods. The sands and gravels reflect the variety of rock types along the Truckee River drainage and in its extensive Sierra Nevada watershed, and are mostly composed of granitic and volcanic rocks with



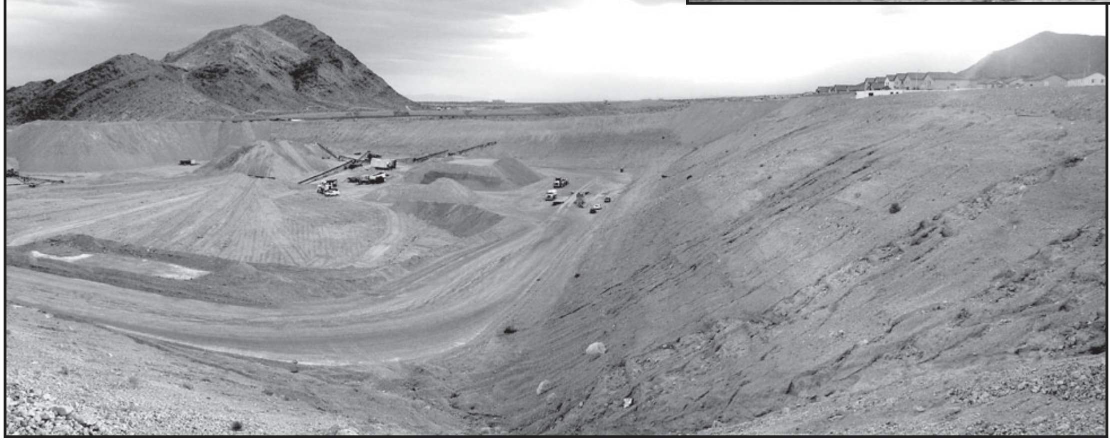


Figure 2. Lone Mountain sand and gravel.

some metavolcanic rocks. They constitute good quality aggregate material because they are relatively young and have been well washed during emplacement. The only soft, deleterious constituents are certain horizons containing soft diatomite or friable volcanic clasts from nearby sources upstream of the Truckee Meadows.

The mining of these sands and gravels in the Truckee Meadows and along the Truckee River was largely phased out due to continued development of the Truckee Meadows, other conflicting land uses, and changing attitudes concerning public impacts associated with aggregate production in populated areas.

Today the only active sand and gravel operation along the Truckee River is near Wadsworth on the Pyramid Lake Indian Reservation about 30 miles east of Sparks. This source, which has been exploited continuously for over 30 years, is now operated by RMC Nevada. These sands and gravels were deposited as the level of Lake Lahontan receded and the river cut into the soft lake sediments resulting in gravels both overlying and underlying fine silty sediments as the lake level fluctuated.

Alluvial fans in the Reno-Sparks-Carson City area have been utilized for construction materials but usually only for AB or occasional asphalt aggregate. The quality of the alluvial fans reflects the abundance of volcanic rocks in the area, which generally tend to be lower quality for aggregate usage. Quality depends on age, composition of parent rock, and degree of weathering. The older alluvial fans tend to contain some weathered particles, abundant fines including clays, and cemented horizons.

Relatively young alluvial fans emanating solely from rapidly eroding competent parent rock are more likely to contain materials that are suitable for the higher end uses such as concrete. For instance, the most recent landslide deposits at the base of Slide Mountain in Washoe Valley, between Reno and Carson City, contain material suitable for use in concrete. This is the result of granitic material, part of a catastrophic slide, mixing with water as it cascaded violently down a creek, washing the deleterious material away and leaving the more competent rock. In addition, north of Reno as part of Martin Marietta Materials' Spanish Springs quarry, sands eroding from the diorite bedrock being mined are suitable for concrete sand. These have been deposited at the mouth of a canyon as part of an alluvial fan.

An extensive paleo sand bar has been mined in a small basin in Lemmon Valley to the north of Reno for about 40 years (fig. 3). The material is used as concrete aggregate and as winter road sand in the Reno area. The adjacent rock is weathered granite (DG), which is unsuitable for concrete sand but, when subjected to the extensive, long-term washing action in a beach environment, was cleaned by having softer and finer material degraded and washed away. The resulting clean sand needs no washing, only screening, to make concrete aggregate.

Quarried Rock

Today aggregate production in the Reno area is dominated by quarried aggregate, primarily from plutonic igneous rocks including diorite and granodiorite, and volcanic rocks including basalt, andesite, and rhyolite. These sources produce durable rock suitable for both concrete and asphalt aggregate. However, the majority of igneous rocks in the Reno-Sparks-Carson City area are not suitable for higher quality aggregate because of composition and weathering.

Martin Marietta Materials mines a highly fractured diorite, which can be excavated without blasting, north of Reno in Spanish Springs Valley. This material is considered to be one of the highest quality concrete aggregates in the area (fig. 4). Granite Construction has two rock quarries, in granodiorite, also in Spanish Springs Valley, and in Tertiary andesite near Lockwood, a few miles east of Reno in the Truckee River canyon.

Much of the abundant granitic rock in the Reno area is deeply weathered. Some of this decomposed granite (locally called DG) is used as low quality construction material, generally for fill, landscaping sand, and unpaved road surfacing. It is not suitable for concrete aggregate. These deeply weathered granitic rocks, which are abundant throughout the Sierra Nevada, can be mined as sand

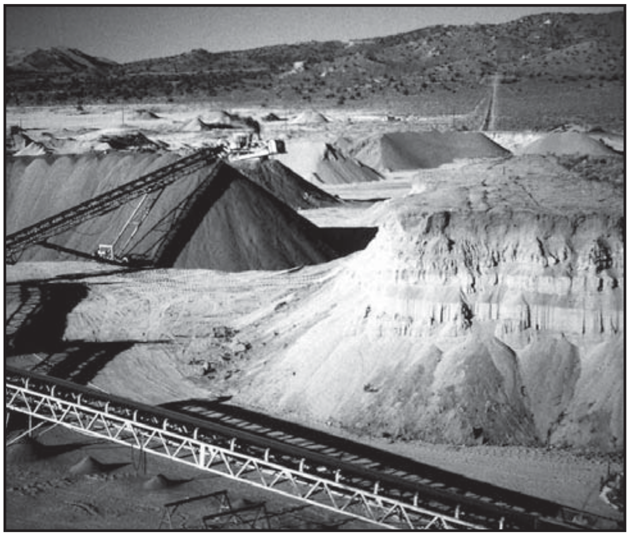


Figure 3. Lemmon Valley, paleo sand bar.

Figure 4. Martin Marietta Spanish Springs diorite quarry.

sources because they easily fall apart along grain boundaries. This Tertiary weathering may extend for thousands of feet vertically, as is evidenced by the extent of decomposed granitic rock in the Sierra Nevada to the west of the Reno area.

Two late Tertiary rhyolite domes are used as lightweight aggregate sources in the Reno area. The youngest, near Dayton, is a very lightweight, glassy, pumiceous rhyolite that is being mined by Basalite and used in concrete masonry units manufactured at a block plant in Carson City (fig. 5). Rilite Aggregate's deposit, in south Reno, is glassy rhyolite that is mined for use in semi-lightweight concrete and for mortar sand. Most of the high-rise concrete in the Reno area is made with Rilite Aggregate's material. These materials do not generally compete with the normal-weight concrete aggregates in the Reno area, but do meet most specifications for lightweight aggregate. RMC's deposit in Storey County a few miles east of Sparks is also in a dome but it is devitrified rhyolite that contains little or no glass. It is occasionally used in semi-lightweight applications.

A black to red cinder cone just north of Carson City is mined by Cinderlite for decorative stone, base rock, and occasionally block aggregate (architectural) in the Carson City-Reno area.

Figure 5. Basalite's Rhyolite Dome near Dayton.

Rural Nevada

In rural Nevada the vast majority of construction materials come from sand and gravel sources, primarily alluvial fans (fig. 6) but also more recent deposits along rivers, dry washes, and beach terraces. As previously discussed, the quality of aggregate from sand and gravel deposits depends on age and parent rock. The more recent sand and gravels associated with alluvial fans are often in incised drainages on the fan surfaces, where the materials are less indurated, cleaner, and less weathered than in the dissected fan.

Besides the Truckee River, the other river sand and gravel production in Nevada is associated with deposits along the Humboldt River, which originates in the extreme northeastern part of the state and flows west, emptying into the Carson Sink 60 miles east of Reno. Here the sands and gravels have been transported considerable distance along the river's course, being abraded and washed. The most recent deposits along the upper river basin tend to be clean, shallow deposits, composed primarily of sands, and contain detritus that ranges from Paleozoic carbonate to recent volcanic rocks.

One usually doesn't think of beach deposits in Nevada, but some beaches and gravel bars formed in Pleistocene lakes contain excellent sources of aggregate. The aggregate deposits were created by the washing action of waves on long-vanished beaches in lakes that were trapped in enclosed basins in the structurally active Great Basin. These enclosed basins coalesced into huge lakes at times of wetter climates when glaciers dominated the mountains. The highest water levels in the most recent wet episode were reached about 10,000 years ago. Where currents and topography were favorable, gravel bars and spits consisting of locally thick deposits of sand and gravel were formed. Depending on their location in the dynamic beach environment, the deposits range from those predominantly composed of sand to coarse gravel deposits that are devoid of sand. At one time the Pleistocene lakes, including Lake Lahontan,

Figure 6. Rural BLM community pit, Nye County.

covered a large part of northwestern Nevada, and there are several areas with commercial deposits. In addition to the Lemmon Valley deposit near Reno noted above, beach deposits have been mined in the Hawthorne, Lovelock, Fallon, Fernley, and Ely areas.

There are several volcanic cinder deposits in Nevada. Two are used as sources of construction material: the abovementioned Cinderlite deposit near Carson City, and a deposit near Lathrop Wells in Nye County. The Lathrop Wells operation is in a black to red cinder deposit, part of a well-preserved Pleistocene cinder cone. The cinder, mined by Cind-R-Lite, is used in the manufacture of concrete masonry units in the Las Vegas area.

Permitting Issues in Nevada

The mining industry is important in Nevada, and statewide regulatory agencies control some aspects of mining. However, construction aggregate mining is generally not overseen by state agencies. For example, although there is a state mining reclamation plan requirement that is managed by the Nevada Department of Environmental Protection (NDEP), it does not apply to construction aggregate operations. It is also interesting to note that the construction aggregate industry is taxed differently than the rest of the mining industry in the state. Most mines are taxed through a Net Proceeds of Mines tax; the aggregate industry pays a simple sales tax.

Permitting in Nevada depends on the location of the potential aggregate deposit. There are no overall state permitting requirements for aggregate operations; each county government sets its own requirements through the Special Use Permit process. Special Use Permit requirements vary depending on the population of the county and sophistication of the county government.

On federal lands the permitting process for aggregates is similar no matter where the location. Aggregates and other construction materials fall under the Material Sale regulations, where a successful bidder pays the government so much per yard of materials produced. For smaller operations there is a provision for non-competitive sales and for local or state government uses there are free use designated pits. There is also a type of operation designated as "community pit" mining where anyone can obtain small amounts of material for a price set by the federal agency (generally the BLM). Because Nevada is 87% federal land, there are a lot of aggregate pits and quarries on federal lands, the vast majority of which are administered by the BLM. The BLM district encompassing the Las Vegas area sells more construction aggregate than any other BLM district in the country. On federal lands, permitting requires compliance with the National Environmental Protection Act (NEPA).

As in most areas of the U.S., permitting of aggregate operations is becoming more complex, resulting in additional expense, time delays, and sometimes denial of permits.

Future Outlook for Construction Materials in Nevada

There is no shortage of adequate construction aggregate in Nevada, nor will there be for the foreseeable future. As in much of the rest of the country, aggregate shortages are the result of external influences rather than geologic inadequacies. Conflicting land uses, environmental constraints, and perceived negative public opinion, including the NIMBY ("not in my backyard") attitude, combine to limit the availability of suitable sources of construction aggregate. Inevitably, sand and gravel pits and crushed stone quarries are being pushed farther from urban and populated areas resulting in increased transportation costs. Encroaching development is illustrated at an aggregate operation in the Las Vegas area in figure 7.

Because of the preponderance of BLM-managed land in Nevada, the majority of the highways and therefore most of NDOT's pits are on public land. This is unique in comparison to most states in this country, where the vast majority of property is privately owned. In Nevada, federal lands suitable for use as aggregate raw materials along highways have historically been available for use by NDOT. However, many of these potential material sites were identified long before more onerous environmental considerations prevailed.

Permitting is becoming more complicated and time consuming, but a continuous supply of aggregates and other construction materials is vital to the continued growth of our fast-growing state.

Acknowledgments

Assistance with compiling the current aggregate producers in the Las Vegas area was provided by Ed Suem with the Las Vegas BLM office and Daniel Thorne of Materials Testing Corporation. John Torok assisted with information on producers in the Winnemucca and Elko areas of northern Nevada. We would also like to thank many of the companies who produce aggregate in Nevada for their assistance.

Figure 7. Las Vegas aggregate and encroaching development.

Borates in Western North America

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Abstract

In North America, economic deposits of borates are found only in the western quarter of the continent. All of the current borate mineral production is from California. The exploration, mining, and transportation of borates have figured prominently in the history and economic growth of California.

Economic deposits of borate minerals in North America are from two geologic environments: Quaternary to Pleistocene salt-encrusted, saline brine-rich, dry lakes; and Tertiary bedded deposits. The origins of these two types of borate deposits are quite different. The most valuable source of borates is in Tertiary bedded deposits, mined since the turn of the 20th century and today represented by the sodium borate (borax and kernite) deposit at Boron and calcium borate (colemanite and ulexite/probertite) deposits in Death Valley. Other important colemanite deposits include the Old Borate and Fort Cady mines in the central Mojave Desert.

Borate Minerals

Boron occurs in nature almost exclusively in oxide form, which is highly soluble in water. Borate minerals that form at the earth's surface are typically hydrates derived by evaporation. The important borate ore minerals are all hydrated borate compounds of sodium or calcium, the most common elements found in evaporite beds (table 1).

Geology of Borate Terrain

Because borate minerals are so soluble in the hydrosphere, their elemental components are typically washed to the sea during erosion. The main process that allows borates to form at the Earth's surface is evaporative concentration, and the prime environment for this process is in closed lake basins. The tectonically active western portion of North America hosts the most prospective terrain for borate formation on this continent, because its Tertiary history produced both trapping mechanisms (closed basins) and potential source fluids (hydrothermal activity). Subduction zones are believed to produce ideal conditions for this combination by providing subducted sediments with oceanic salinity, back-arc volcanism, active geothermal systems, faulted basins with internal drainage, and rain-shadow desert climates. Together these provide boron-rich fluids to a site where they can be concentrated and preserved.

Once concentrated, borate beds must be sealed from significant groundwater interaction, lest they be leached. Relatively undisturbed Tertiary lacustrine strata dominated by clays are therefore the principal hosts for bedded deposits. Most older lacustrine sequences have been subjected to tectonic and diagenetic activity that have removed the soluble borates.

Present-day borate concentrations derive from springs or surface waters that flow into young closed depressions,

Table 1. Current and historical borate deposits in western North America

Deposit(s)	Grade (%B_2O_3)	Maximum thickness	Production (ktons)	Reserves (ktons)	Recovered Minerals	Age (Ma)	References
Borax Lake, CA	≈12	0.1 m	2	small	borax	0–1	Garrett, 1998
Playas, CA	variable	<0.3 m	6	small	ulexite, borax	<3	
Playas, NV	variable	<0.3 m	12	small	ulexite, borax	<5	Papke, 1976
Death Valley, CA (early) Lila C., Ryan	11–31	50 m	5,500	18,000	colemanite	1–5	Evans and others, 1976
Old Borate, CA	15–20	4.6 m	1,000	mined out	colemanite	18–20	
Muddy Mtns., NV	20–26	10 m	220	3,500	colemanite	13–14	Castor, 1993
Death Valley, CA (recent) Billie, Boraxo	22	80 m	8,000	11,000	colemanite	5	Evans and others, 1976
Searles Lake, CA	1.0–1.2 (brine)	15 m	9,000	40,000	borax	.03–.15	Garrett, 1998
Fort Cady, CA	6.4	30 m	50	147,000	colemanite	19–23	Hartman,1996
Boron, CA	25	100 m	50,000	125,000	borax, kernite	19	Siefke, 1985

yielding playa deposits which can be brine-filled sands, muds, carbonates, or saline crusts. If there is enough boron present these brines or crusts can become an economic source of boron. Borate crystals growing at or below the lake bottom interface may also concentrate to form beds of economic borate deposits.

Host Rock Stratigraphy

In the Mojave Desert, bedded borate deposits occur in Tertiary strata that contain lacustrine sequences typically of sandstones, siltstones, claystones, interbedded tuffs, and minor carbonates. These include the Tropico group, the Barstow Formation and the Hector Formation, all of early to middle Miocene age. In most cases, these Tertiary sedimentary sequences rest directly upon granitic or metamorphic basement. The Tropico and Hector Formations, which may be nearly contemporaneous, are underlain by thick tuffaceous sections. Near Boron, basaltic volcanics lie within the section immediately below the ore horizon in the Tropico Formation. Fanglomerates, which lie both above and below the lakebeds at Boron, demonstrate the tectonic activity of basin development through the period of sedimentation. The Barstow Formation is somewhat younger, and perhaps bears only signs of waning volcanic activity in the region.

In the Death Valley region, basins include a similar range of continental sediments and the principal borate deposits. A trend of deposits in small lacustrine basins follows the Furnace Creek fault zone southeastward from Death Valley. These deposits occur in the Furnace Creek Formation of late Miocene to early Pliocene age.

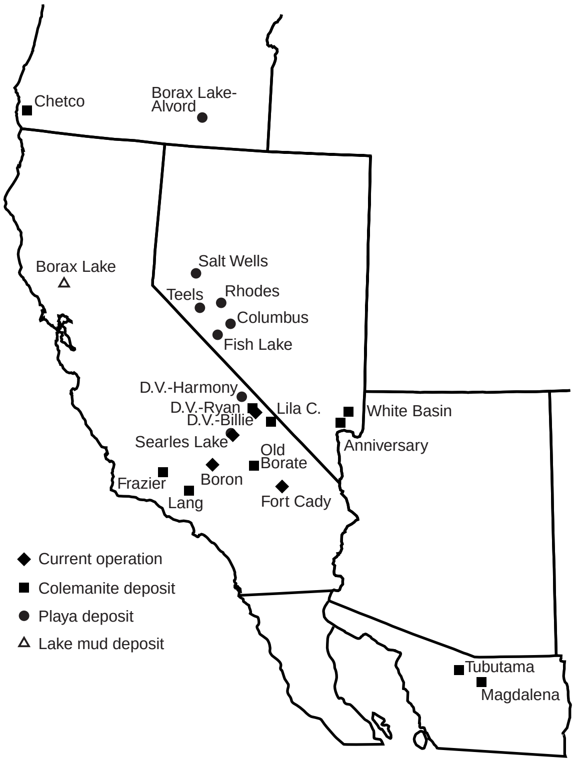

Figure 1. Borate deposits of western North America.

Brief History of Borate Production

Borax Lake Period

The first commercial borate deposit operated in the United States was at Borax Lake, about 80 miles northeast of San Francisco (fig. 1). Borax Lake was discovered by Dr. John Veatch about 1856 and by 1864 he had acquired land, organized the California Borax Co., and started production.

The borax crystals that grew in the lake-bottom clays were recovered by dropping a cofferdam from a raft onto the lake bottom. The lake mud and borax crystals were removed with clam-shell buckets, loaded on boats and taken to shore. They were then washed, drained, and dissolved in hot water beforebeing allowed to recrystallize in small lead-lined tanks. From 1864 to 1868 this deposit supplied almost all of the country’s borate needs; which at that time was about 500 tons per year (table 1).

Playa Period

As the demand and prices for borates began to rise, more entrepreneurs and prospectors were ready to cash in on the easily and relatively cheaply produced borax. Dry lakebeds, “playas” or “marshes” became the next source for supplying the growing demand for borate minerals. Western Nevada and eastern California became the site of feverish activity as claim staking and erecting of borax plants took place in the 1870s to 1880s.

Remote playas like Teel’s Marsh, Fish Lake Marsh, Columbus Marsh, Rhodes Marsh and Salt Wells (fig. 1) in western Nevada became the focal point of the American borax industry. These lakebed crusts did not produce for a long period before two similar California deposits, Harmony Borax Works in Death Valley and the operations at Searles Lake, took over as dominant producers in the rapidly growing borate industry (see fig. 2).

Most of the playa producers used a similar method for producing the final borax product. Usually the playas contained ulexite at, or just below, the surface. Some playas had a mixture of borax and ulexite, but the ulexite was the predominant mineral species being mined. The ulexite was typically dug and raked into windrows where it was allowed

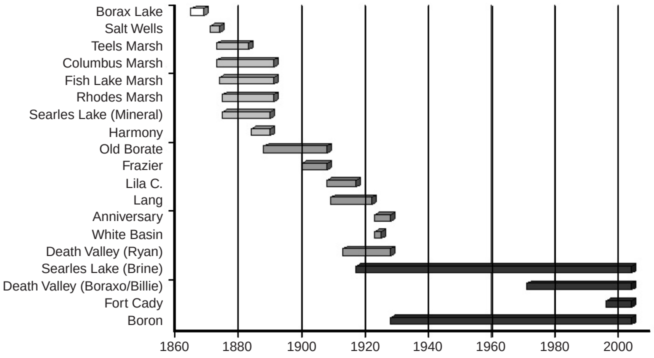

Figure 2. Timeline of North America borate mining.

to drain and dry out (fig. 3). The ore was then carted to the nearby plant where it was dissolved in hot water with some added sodium carbonate to form a borax solution. The solution was decanted into metal tanks with iron rods or plates suspended in them. As the solution cooled the borax crystallized on the rods, plates or the sides of the tanks. The borax crystals were removed and bagged for shipment. The mineral concentrate was transported to the nearest railhead by wagon or specially designed "Twenty Mule Team®" wagons.

Colemanite Period

Just before the turn of the century, demand for borates was rapidly increasing and prices were falling. A newer, richer source of borates was needed, and the next period of borate mining, utilization of the colemanite deposits, began. Although some colemanite deposits had already been discovered in Death Valley several years before, the ones closest to the cheaper transportation provided by the railroads were to be mined first.

The Old Borate deposit in the Calico Mountains near Barstow (fig. 4, table 1) was the first and largest to be mined in that area. Colemanite ore was transported to a nearby plant where the ore was calcined to produce a colemanite concentrate. This was then shipped to refineries on both the east and west coasts to produce borax. Borate-bearing shales were also mined by several small companies around this time in the Calico area. The shales, which contain <10% B_2O_3, were leached in vats with sulfuric acid to produce boric acid. But these operations lasted only a few years until the richer Death Valley colemanite deposits were brought into production.

Figure 3. Harvesting of ulexite for processing into borax circa 1885, Harmony Borax Works, Death Valley, California.

At about the same time (fig. 2) as the mining at Old Borate, colemanite was discovered in the Frazier Mountain area of northeastern Ventura County, California (fig. 1). The Frazier and Columbus mines operated there until 1907. The nearby Russell Mine produced ore from 1911 to 1913. All three mines are hosted in the Miocene Plush Ranch Formation. The borates occur in a relatively thin section of lacustrine rocks between two basalt flows.

When railroad access into the Death Valley region was established, the Lila C. Mine (fig. 2) was developed around 1907. This high-grade colemanite deposit put most of the remaining playa and borate-bearing shale mines out of business. As the Lila C. began to run out of ore a narrow gauge railroad was built to access the Ryan area mines (fig. 5). This included the Widow, Oakley, Grand View, Biddy, and Played Out Mines.

The success of the Death Valley deposits spurred prospecting for other deposits. Near the town of Shoshone, just southeast of Death Valley, a man prospecting for clay discovered colemanite at what would become the Gerstley Mine. Production began in 1924 and continued until 1936. Small tonnages for specialty uses were mined until just recently.

The Anniversary Mine in Lovell Wash, Nevada, north of what is now Lake Mead (fig. 1), was discovered in 1921. Hosted in the Miocene Horse Spring Formation, a colemanite bed occurs in a section of limestones, marls, calcareous shales, and tuff with some gypsum. Nearby, the White Basin deposit was discovered about the same time in a similar but thinner limestone, marl and gypsum section of the Horse Spring Formation. Both mines operated until the mid-1920s when the sodium borates at Boron were placed into production.

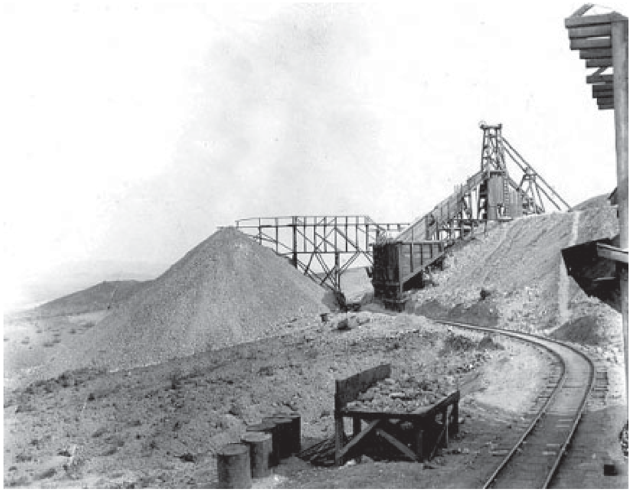

Figure 4. High Point Shaft 1902, Old Borate, Calico Mountains, California.

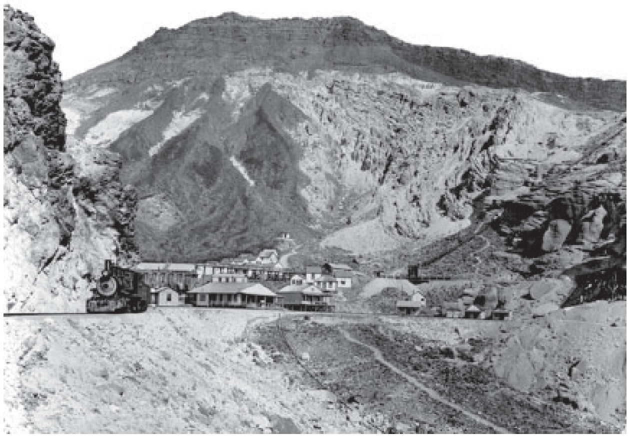

Figure 5. Mining town of Ryan, 1925, Greenwater Range, Death Valley, California.

Borax Period

The last and current period of borate history started by accident. In 1913 a homesteader drilled a water well and in the bottom of the hole found colemanite. Exploration drilling was initiated in the area and in 1925 resulted in the discovery of the first bedded sodium borates (fig. 6). Borax and kernite were mined underground from 1927 until 1957 (fig. 7), when the current open pit was started and mining began to phase out in the underground operation. U.S. Borax presently mines both borax and kernite by truck and shovel methods and processes them in an adjacent sodium borate refinery and boric acid plant (fig. 8).

Currently Operating Mines

Searles Lake

Searles Lake borate production of today is, in a sense, a holdover from the playa period. However, today the borates are recovered by IMC from brine in two salt bodies, the upper and lower salt, that lie deep beneath the playa surface (fig. 9). The borax that is produced here is a by-product of trona (sodium carbonate/sodium bicarbonate) extraction from brine pumped from a series of wells and treated in two adjacent refineries.

The upper salt averages 50 feet thick and has a brine content that averages 1.0% B_2O_3. The lower salt averages 40 feet thick with a brine content averaging 1.2% B_2O_3. A consistent brine content is maintained with natural recharge and dilute effluent from the refinery used to dissolve more salts. Brines from the upper and lower salt zones, which contain slightly different compositions, are pumped, and treated in the plants, separately.

Fort Cady

In the late 1950s and early 1960s a surge of borate exploration activity by several oil and gas and mineral companies as well as the U.S. Geological Survey, was prompted by U.S. government research into the use of borates to produce borane rocket fuel. Speculation about the increased demand for borate, to feed a burgeoning rocket and ballistic missile program, led to gravity surveys and drilling programs in several basins in the Mojave Desert.

Figure 6. 1919 Drilling rig at Kramer deposit, Boron, California.

Figure 8. Present day processing plant at Boron with boric acid plant in foreground.

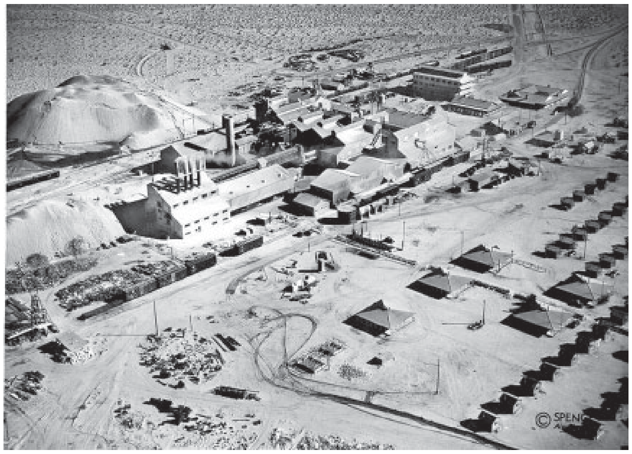

Figure 7. Pacific Coast Borax, Baker underground mine and plant 1938, Boron, California.

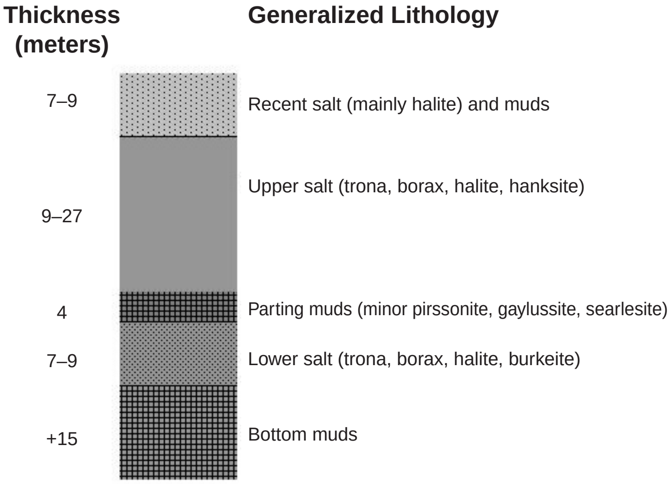

Figure 9. Searles Lake stratigraphy.

One of these areas explored was the Hector Basin, about 30 miles east of Barstow (fig. 2). AMAX conducted a gravity survey to identify possible sedimentary basins and a consulting firm, Congden and Carey, drilled three holes on three different gravity lows within the basin. Colemanite was found in lacustrine strata within one of these lows, at depths up to 1,700 feet (fig. 10). Exploration by Duval in the 1970s and 1980s delineated a large, (147 million tons) low-grade, (6.4% B_2O_3) colemanite orebody (table 1). Because the deposit is deep and low grade, solution mining was found to be the only economical method to recover the borate values. A pilot operation operates there by injecting hydrochloric acid into wells completed in the colemanite horizon. The solution was allowed to react and then pumped to the surface where lime is added to produce a synthetic colemanite. Production has been only a few hundred tons per month and as of early 2003 the operation was shut down and up for sale.

Billie Mine

An extension of the colemanite period of borate mining is represented by the Billie Mine which is operated by the American Borate Company adjacent to Death Valley National Park (fig. 1). The 18 borate deposits in the Death Valley region all occur in the lower Furnace Creek formation. The borate horizons lie within a sequence of mudstones, limestones conglomerates, tuffs, and basalts (fig. 11).

Up until the discovery of sodium borates at Boron, the Death Valley mines were the heart of the world borate industry. Most of them were moth-balled in 1927 with only minor production after that for specialty uses. In 1970 the predecessors of American Borate began mining the nearby Boraxo deposit by open pit methods. At the same time exploration was carried out on what would become the Billie Mine.

The Billie deposit is almost 4,000 feet long and 2,300 feet wide. It dips 20–30º southeast from outcrop to a depth of 1,300 feet. Reserves at the Billie orebody consist of 11 million tons of colemanite (table 1) and 5 million tons of ulexite/probertite averaging around 22% B_2O_3. Colemanite only is currently mined and trucked to the mill at nearby Stateline, Nevada for upgrading and then shipped mainly to the Far East for use in textile fiberglass production.

Boron

The Boron (or Kramer) deposit is located in the northwestern Mojave Desert (fig. 1) near the edge of a large Tertiary basin. Jurassic and Cretaceous granitics and metamorphics make up the basement. These are overlain by the Tropico Formation, an Early Miocene sequence of continental sediments; primarily arkosic sands and silts derived from the earlier granites, with volcanics and minor limestone. In the mine area the borates are underlain by a series of basalt flows and overlain by continental arkosic sands and coarse fanglomerate all in the Upper Tropico Formation (fig. 12).

The borate ore deposit consists of a lenticular body of borax, kernite and interbedded clays dipping about 10º south. It is about 1 mile long by 0.5 mile wide and up to 330 feet thick. Surrounding the central borax and kernite core is an envelope of ulexite, clay and minor colemanite. The deposit is postulated to have formed in a shallow, permanent lake fed by boron- and sodium-rich thermal springs that accompanied late-stages of volcanic activity associated with the underlying basalt. Shallow-water deposition is indicated by ripple marks in several tuff and tuffaceous clay beds that are interbedded with the borax.

Faulting, contemporaneous with deposition of the borates, controlled the original lake basin, especially on its southern margin. Continued fault movement tilted and dropped the lake sediments, which were then buried under as much as 2,700 feet of late Miocene and Pliocene arkosic

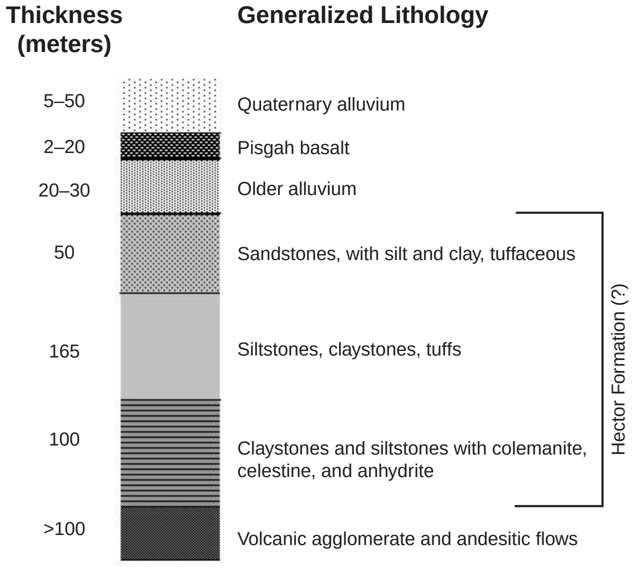

Figure 10. Fort Cady stratigraphy.

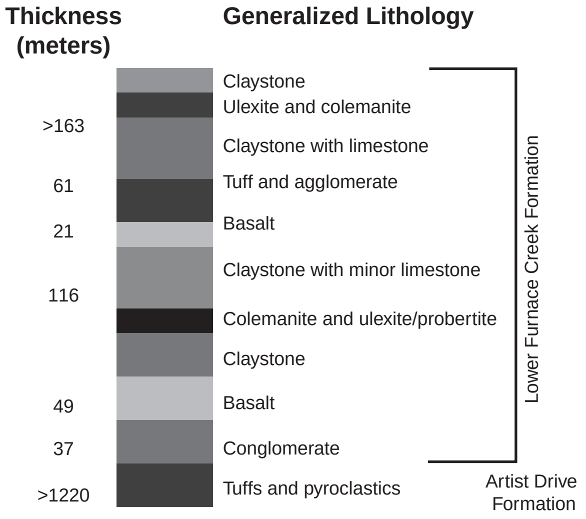

Figure 11. Death Valley stratigraphy.

sediments. The kernite in the deposit was formed at this time when the more deeply buried portions of the borax were metamorphosed. Plio-Pleistocene uplift raised the deposit, removed some of it by erosion and allowed the outer portions of the kernite facies to rehydrate to borax. Pleistocene and Recent sands and gravels as thick as 100 feet then covered the deposit.

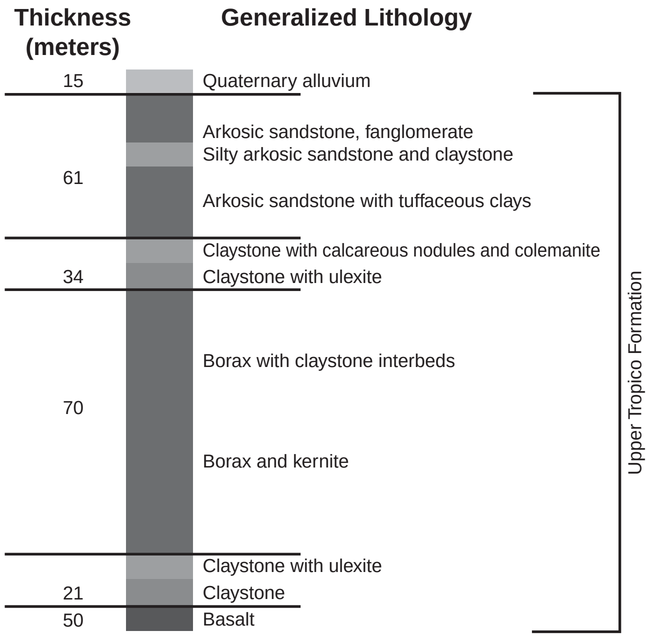

Figure 12. Boron stratigraphy.

Acknowledgments

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Industrial Minerals and Rocks in Nevada

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Abstract

The value of Nevada's industrial minerals has ranged between 10 and 15% of the state's total mineral production over the past decade. In order of estimated value, the state's industrial commodities are construction aggregate, lime, diatomite, cement, gypsum, barite, lithium, clay, magnesia, silica, dolomite, calcium carbonate, perlite, dimension stone, salt, zeolite, kalinite (potassium aluminum sulfate), and gemstones. Dumortierite, garnet, vermiculite, and wollastonite deposits have been evaluated in recent years, but are not currently mined. Nevada borate, fluorspar, and talc deposits were mined in the past.

Estimated yearly values for construction aggregate rose from $110 million to $160 million over the past decade. Sand and gravel accounts for about 80% of this value. Lime, mainly used in gold ore processing, comes from two primary plants, one in northeastern Nevada and one near Las Vegas. Both process Devonian carbonate. Diatomite, mainly marketed as filtration products, is mined from several Tertiary lacustrine deposits, mainly in northwestern Nevada.

Cement is mainly produced at a plant in northwestern Nevada. Gypsum is mined from Permian to Miocene deposits at two sites in northwestern Nevada and three sites near Las Vegas. Barite, once Nevada's most valuable industrial mineral commodity, came from 34 mines in the early 1980s. It is now mined from only five bedded Ordovician and Devonian deposits. Lithium is extracted from brine on a western Nevada playa, which is currently the only domestic source.

Five companies mine clay from more than ten Tertiary deposits in Nevada, including the only commercial sepiolite and saponite deposits in the United States. Two other companies have been developing clay deposits in Nevada. Light-burned magnesia is manufactured from magnesite mined in central Nevada. Silica comes from two Nevada deposits, with the largest production from friable Cretaceous sandstone in southern Nevada.

Introduction

In 2002, there were 41 active industrial mineral mines in Nevada (fig. 1, table 1). Estimated annual values for Nevada's industrial minerals increased from $285 million to more than $420 million over the past decade; however, industrial minerals have only accounted for 10 to 15% of the state's total mineral production during this period (fig. 2). Unlike in many other states, industrial mineral production value is relatively minor when compared with the value of metal mining in Nevada, which has been dominated by gold production since the 1980s. A preliminary estimate of industrial mineral value for 2002 is $425 million, compared with the value of all non-energy minerals at about $3.2 billion. In the late 1970s and early 1980s, the value of Nevada's industrial mineral production was nearly equal to that of metal production (fig. 2), due to relatively low metal production combined with a boom in barite mining.

Nevada currently produces 17 industrial mineral commodities. In order of estimated value, the most important are construction aggregate, lime, diatomite, cement, gypsum, barite, lithium, clay, magnesia, and silica, each valued at more than $10 million annually. Commodities with values of less than $10 million are dolomite, calcium carbonate, perlite, dimension stone, salt, zeolite, kalinite (potassium aluminum sulfate), and gemstones. Borate, perlite, and zeolite processed in Nevada but mined elsewhere are not included in the estimate of total industrial mineral value. Dumortierite, garnet, vermiculite, and wollastonite deposits in Nevada have been evaluated in recent years, but are not currently productive. Borate, fluorspar, and talc deposits have been productive in the past. A new map of Nevada's active and inactive industrial minerals deposits (Papke and Castor, 2003) is now available from the Nevada Bureau of Mines and Geology (NBMG). Data used for the above estimates, and data reported for individual commodities below, were obtained from the Nevada Division of Minerals, the U.S. Bureau of Land Management, or directly from companies that produced the industrial minerals.

Aggregate (Sand, Gravel, and Crushed Stone)

In terms of total value, construction aggregate is Nevada's most important mined industrial material. I estimate production of 35 million tons in 2002, with a value of $158 million.

Figure 3 shows the growth of construction aggregate production in Nevada since 1952. Data on aggregate production prior to 1978 are sparse, but show consistent growth; data since 1978 are more accurate, and the decrease between 1978 and 1985 may be a reflection of data quality, rather than an actual downturn in production.

Production from sand and gravel deposits accounts for about 80% of aggregate production statewide, with crushed stone and lightweight aggregate making up the balance. By comparison with Nevada's production, in 2002 the U.S. produced about 1.24 billion tons of construction sand and gravel and about 1.75 billion tons of crushed stone (U.S. Geological Survey Mineral Commodity Statistics and Information website). Some of the crushed stone in U.S. Geological Survey statistics is used in the manufacture of commodities such as cement and lime; such material is not included in our aggregate figures.

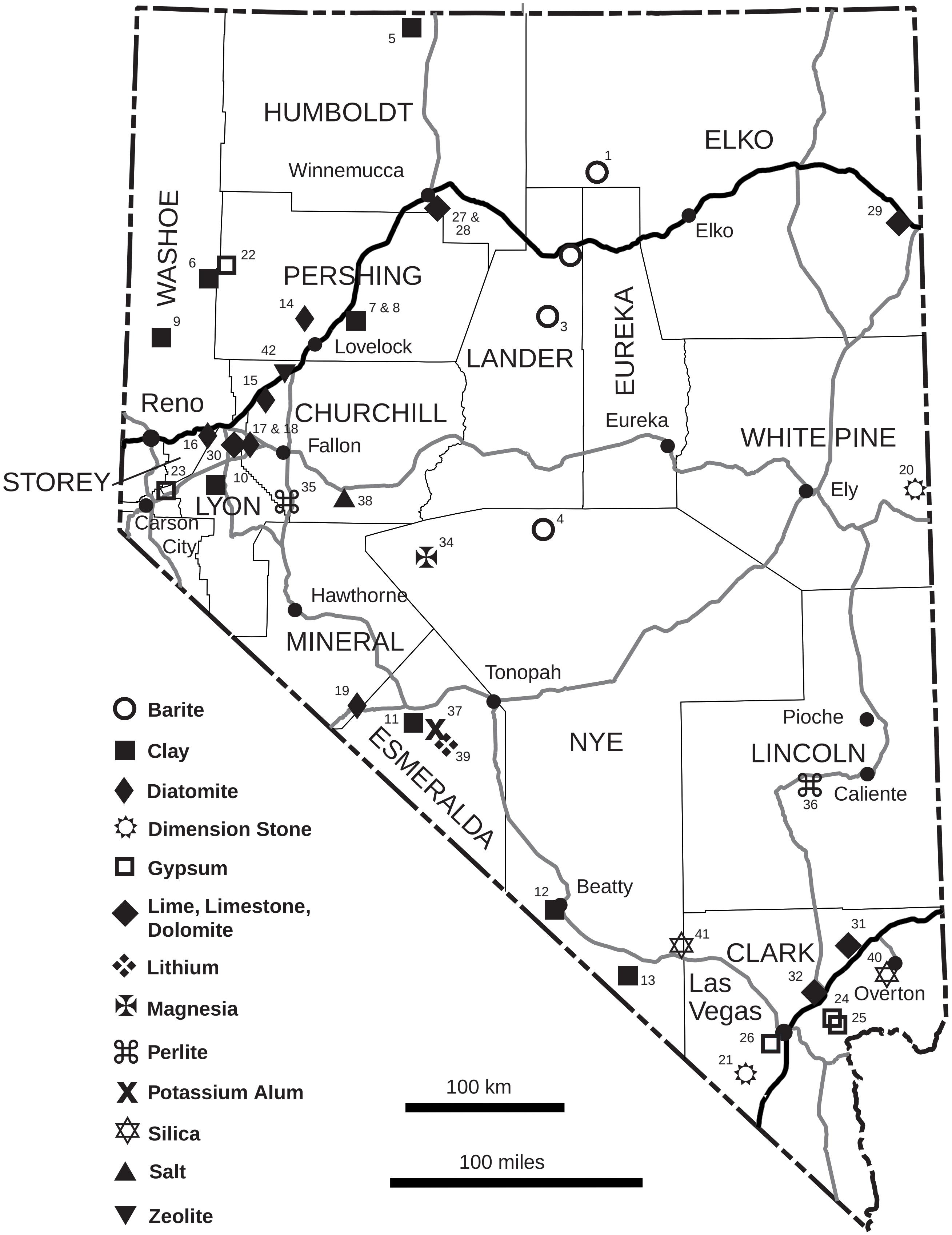

Figure 1. Active industrial mineral mines in Nevada excluding aggregate and gemstone operations. Map numbers correspond to numbers in table 1.

Table 1. Nevada industrial mineral mines active in 2002, excluding construction aggregate and gemstones.

MAP NO.	MINE OR QUARRY	COMPANY	LOCATION	COUNTY	2002* PROD	EMPLOYEES	COMMENTS
Barite							
1	Rossi Mine	N L Baroid, Inc.		Elko	125	53	Drilling grade barite
2	Argenta Mine	Baker Hughes INTEQ (Milpark, Inc.	Argenta	Lander	47	20	Drilling grade barite
3	Greystone Mine	M. I. Drilling Fluids Co.	Battle Mountain	Lander	204	75	Drilling grade barite
4	P & S Mine	Standard Industrial Minerals		Nye	1		White, paint-grade barite
Clay							
5	Disaster Peak	American Colloid		Humboldt	prop		Hectorite
6	Empire Mine	Moltan	Gerlach	Washoe	prop		Bentonite
7	Coal Canyon Mine	American Colloid	Lovelock	Pershing	prop		Montmorillonite
8	Buff Mine	Vanderbilt Minerals Co.	Lovelock	Pershing	prop	3	Bentonite
9	Terraced Hills Mine	Nevada Cement	Sutcliffe	Washoe	unkn		Halloysite for cement manufacture
10	Jupiter and Monty Mines	Art Wilson Co.	Wabuska	Churchill	unkn		Montmorillonite
11	Blanco Mine	Vanderbilt Minerals Co.	Coaldale	Esmeralda	unkn		
12	New Discovery Mine and Mill	Vanderbilt Minerals Co.	Beatty	Nye	2.2	7	Montmorillonite mined at several Nevada sites
13	IMV Nevada	Mud Camp Mining Co.	Ash Meadows	Nye	30.4	34	Saponite, sepiolite, and montmorillonite
Diatomite							
14	Colado Mine and Plant	Eagle-Picher Minerals, Inc.	Lovelock	Pershing	prop	132	Mostly filtration products
15	Moltan Mine and Plant	Moltan Co.	Fernley	Churchill	prop	49	Absorbents and cat litter
16	Clark Mine and Plant	Eagle-Picher Minerals, Inc.	Fernley	Storey	prop	63	Mostly filler and absorbent products
17	Celite Corp. Mine	World Minerals, Inc.	Hazen	Churchill	21	16	Mostly filler and absorbent products
18	Hazen Pit	Eagle-Picher Minerals, Inc.	Hazen	Lyon	prop	2	Insulation grade
19	Basalt Mine & Mill	Grefco, Inc.	Basalt	Mineral	prop	23	Mostly absorbent material
Dimension Stone							
20	Mount Moriah Quarries	Mount Moriah Stone	Baker	White Pine	unkn		Flagstone
21	Rainbow Quarries	Las Vegas Rock	Goodsprings	Clark	1.2	5	Flagstone and decorative stone
Gypsum		183					
22	Empire Mine and Mill	USG	Gerlach	Pershing	306	151	Wallboard, plaster, and cement
23	Adams Mine	Art Wilson Co.	Carson City		128	19	Agricultural and cement
24	PABCO Quarry & Plant	PABCO Gypsum	Las Vegas	Clark	774	120	Wallboard and plaster
25	Pioneer Gypsum Mine	D. L. Denman Construction Co.	Las Vegas	Clark	unkn	9	Agricultural and cement
26	Blue Diamond Mine	BPB	Las Vegas	Clark	543	130	Wallboard and plaster
Limestone and Dolomite							
27	MIN-AD Mine	MIN-AD, Inc.	Winnemucca		69	20	Agricultrual dolomite
28	Sexton Mine	Nutritional Additives Corp.	Winnemucca	Pershing	4	6	Dolomite
29	Pilot Peak Quarry	Graymont Western USA Inc.	Wendover	Elko	prop	48	Limestone for high-calcium lime
30	Nevada Cement Mine	Centex	Fernley	Lyon	prop	123	Limestone for cement
31	American Cement Mine	American Cement and Aggregate	Logandale	Clark	unkn	9	Limestone for cement
32	Apex Quarry	Chemical Lime	Las Vegas	Clark	prop		For high-calcium lime and dolime
Lithium							
33	Silver Peak Operation	Chemetall Foote Corp.	Clayton Valley	Esmeralda	prop	68	Lithium carbonate and hydroxide
Magnesia							
34	Gabbs Magnesite Mine	Premier Services Corp.	Gabbs	Nye	prop	80	Light-burned magnesia and brucite
Perlite							
35	Popcorn Mine	Eagle-Picher Minerals, Inc.	Fallon	Churchill	prop		Filtration products
36	Tenacity Mine and Mill	Wilkin Mining & Trucking Co.	Caliente	Lincoln	unkn	8	Agricultural products
Potassium alum							
37	Alum Mine	Rulco	Silver Peak	Esmeralda	2		For agricultural use
Salt							
38	Four Mile Flat	Huck Salt Co.	Fallon	Churchill	14	4	Road deicing material
Silica							
39	Simplot Silica Products	Simplot Industries	Overton	Clark	676	43	Mostly glass sand
40	Sugar Mine	Silica LLC	Mercury	Nye			
Zeolite							
41	Trinity Pit	Moltan Co.	Fernley	Churchill	prop	3	Absorbents and cat litter

***Production figures (2001 PROD) in thousands of short tons, prop=company proprietary information, unkn=unknown**

Most of Nevada's construction aggregate is produced and consumed in the Las Vegas area, the fastest growing metropolitan area in the nation (Brian and others, this volume). In 2002 production here was estimated at about 26 million tons. Continued growth in the Las Vegas area will likely maintain demand, and a planned new airport and associated urbanization south of Las Vegas constitute major future markets. Four companies in the Las Vegas area produced more than a million tons of aggregate in 2002: Las Vegas Paving Corp.; Rinker Materials; Nevada Ready Mix Corp.; and Frehner Construction. Other important producers were Wells Cargo Inc., CTC Crushing LLC, Hollywood Gravel Co., and Diamond Construction.

Sand and gravel mines in Las Vegas account for more than 80% of the construction aggregate production; however, the percentage of crushed stone in the market is increasing. The most important source of sand and gravel aggregate for Las Vegas is the Lone Mountain area northwest of Las Vegas, with production of about 5 million tons in 2002. Significant production also comes from sand and gravel pits in alluvial material in the southwest part of Las Vegas (e.g., fig. 4), and from crushed stone operations south, southeast, and northeast of Las Vegas. Community pits administered by the U.S. Bureau of Land Management and operated by several companies provide about 2.5 million tons of sand and gravel. Since the mid 1990s, portable crushers operating in alluvial fan material at construction sites have become increasingly important producers of base aggregate; recent estimates by industry personnel put such production at as much as 30% of the total aggregate production for Las Vegas. Lightweight aggregate has also become important in the Las Vegas market, and includes material from south of Las Vegas and as far away as Beatty in Nye County.

Production of construction aggregate in the Reno-Sparks-Carson City area is about 6 million tons. Crushed rock accounts for about 60% of the aggregate used in the area. Two companies produce more than a million tons of aggregate; Granite Construction Co. and Martin Marietta Materials Inc. RMC Industries recently entered the market, acquiring a lightweight aggregate quarry (fig. 5) and a sand and gravel pit. Frehner Construction, Rilite Aggregate, and A & K Earthmovers, Inc., are also important producers.

Relatively small amounts of aggregate are produced outside of the two major metropolitan areas. Operators in Nye County together produce an estimated 500,000 tons of aggregate annually. Churchill, Elko, Lander, Lyon, and White Pine County each produce more than 200,000 tons of aggregate; while Douglas, Eureka, Lincoln, Mineral, and Pershing Counties are thought to produce less than 150,000 tons of aggregate each.

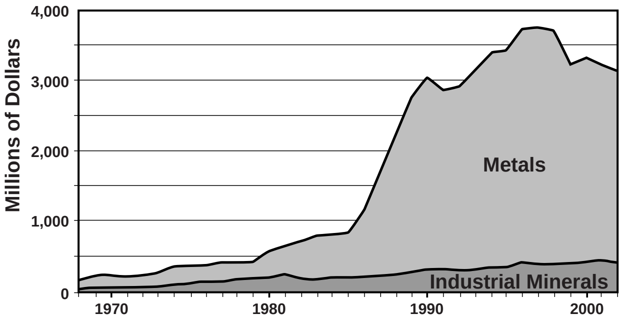

Figure 2. Value of metals and industrial minerals mined in Nevada between 1968 and 2002. Values are from U.S. Bureau of Mines data (1968 through 1987); from U.S. Bureau of Mines, Nevada Division of Minerals, and NBMG data (1988 through 1993); and from Nevada Division of Minerals and NBMG data (1994 through 2002).

Figure 4. Las Vegas Paving's Blue Diamond sand and gravel pit and plant in southwestern Las Vegas.

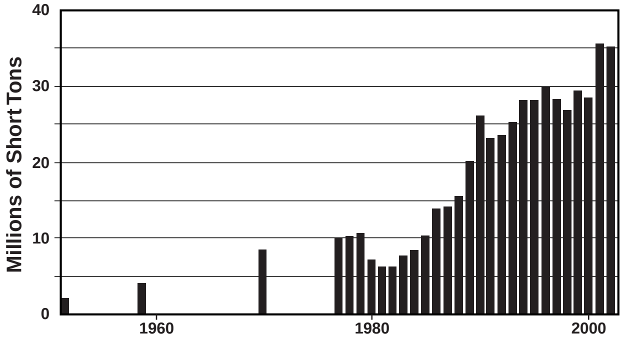

Figure 3. Construction aggregate production in Nevada, 1952 through 2002.

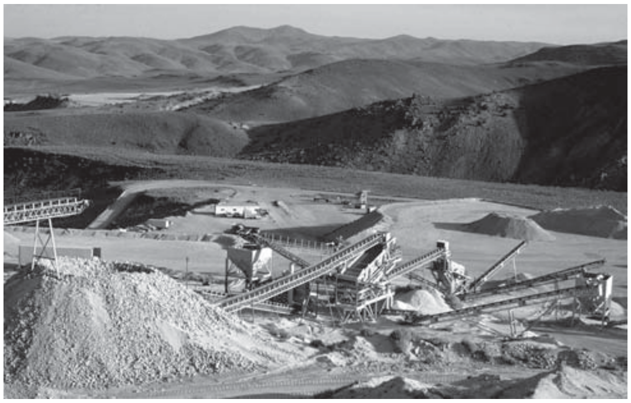

Figure 5. The All-Lite lightweight aggregate operation of RMC at Washington Hill, Storey County.

Barite

Nevada produces almost all of the barite mined in the United States. Nevada barite production in 2002 was estimated at 377,000 tons, only about 15% of the high in 1981, but about twice the 1987 production low (fig. 6). At present, four companies mine barite in Nevada; by contrast, in the early 1980s there were more than 25 Nevada producers. Foreign competition and relatively little domestic oil drilling are the main factors that have limited Nevada barite mining in recent years. According to the U.S. Geological Survey, the country imported about 1.4 million tons of barite in 2002, most of it from China. About 95% of the barite sold in the U.S. is used as a weighting agent in oil and gas well drilling fluids. Rises in oil and natural gas prices resulted in an increase in the number of operating domestic drilling rigs from 360 in 1999 to 1,270 in mid 2001, but the number decreased to 820 by the end of 2002. Such variations in drilling activity strongly impact the demand for barite (fig. 6); however, prices have remained relatively stable in recent years.

All Nevada barite produced in recent years has come from bedded deposits, which occur in a wide northeast-trending belt in central and northern Nevada. Most are in the Devonian Slaven Chert, but bedded barite has also been mined from Cambrian and Ordovician rocks. The deposits are mostly in complexly deformed rocks (fig. 7) in the upper plate of major thrust faults. An exhalative-sedimentary origin has been proposed for Nevada's bedded barite deposits (Papke, 1984). Extensive exploration during the barite boom years led to the discovery of many deposits that are now inactive. This period of intense exploration for an industrial mineral commodity was unique in modern Nevada mining history.

M. I. Drilling Fluids, which is jointly owned by Smith International and Schlumberger, has been the largest Nevada barite producer for many years, with production during 2002 of about 200,000 tons of screened and crushed high-grade ore from the Greystone Mine and ground and bagged barite from its Battle Mountain plant, both in Lander County.

Baroid Drilling Fluids, a subsidiary of Halliburton Co., mines barite from the Rossi Mine in Elko County and processes it at the Dunphy Mill in Eureka County. Baker Hughes INTEQ produces barite from its Argenta property near Battle Mountain in Lander County. Standard Industrial Minerals ships small amounts of white, paint-grade barite from the P and S Mine in Nye County to its processing plant near Bishop, California.

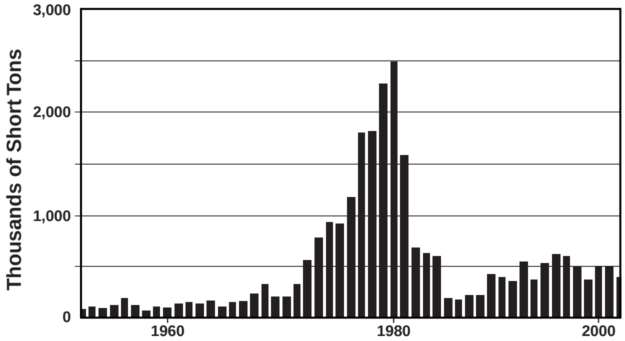

Figure 6. Barite production in Nevada, 1952 through 2002.

Borate

The American Borate Co. mines borate minerals at its Billie underground operation in Death Valley, California. The ore is processed in Nye County, Nevada at the Ash Meadows mill, which has a 22,000-ton annual capacity (B_2O_3 basis). Because the ore is from out of the state, this production is not included in the estimate of total value of Nevada minerals.

Nevada was the most important source of borate minerals in the world between 1873 and 1883, prior to the discovery of California borate deposits. This early production was from Holocene deposits such as at Teels and Rhodes Marsh in Mineral County (Papke, 1976). Later Nevada production came from Miocene colemanite deposits in the Muddy Mountains in Clark County during the 1920s and moderate tonnages of high-grade ore remain (Castor, 1993).

Cement

The Nevada Cement Co., a subsidiary of Centex Construction Products, Inc., produces portland cement at a plant at Fernley in Lyon County, where annual production exceeds 500,000 tons of cement. The cement is manufactured from limestone mined from a deposit a few miles south of Fernley, and other ingredients come from northern Nevada. The limestone deposit formed in a Tertiary lake, and shows many features that are similar to tufa deposited in northern Nevada's Pleistocene lakes (Hardy and others, this volume).

Limestone suitable for cement production is widespread in the Las Vegas area, and several attempts have been made to produce cement in the area without long-term success. In 1999, Royal Cement Co. restarted a small cement plant near Logandale in Clark County. Limestone was mined at a site near the plant, and other raw materials were purchased from

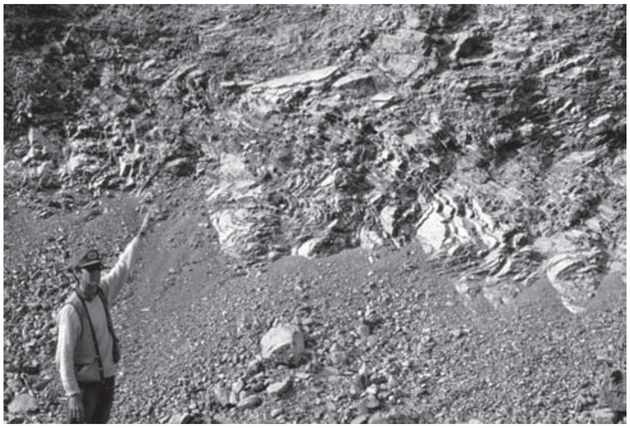

Figure 7. Folded chert beds at the Argenta barite mine, Lander County.

regional suppliers. According to the operator, production from this operation in 2000 was about 120,000 tons, but no data are available for 2001 or 2002, and recent examination of the plant indicated that it is idle or that production is sporadic.

Clay

Five companies mine clay from more than ten Tertiary deposits in Nevada, including the only commercial sepiolite and saponite deposits in the United States. Total Nevada clay shipments are in excess of 40,000 tons per year. In 2001, the state ranked fifth in domestic production of non-swelling bentonite in the U.S. (Virta, 2002).

In 2002, IMV Nevada, owned by Mud Camp Mining Company, LLC, produced about 30,000 tons of sepiolite, saponite, and bentonite from deposits in the Ash Meadows area of Nye County. The clay occurs in shallow, flat-lying deposits (fig. 8) in Pliocene lacustrine rocks (Hay and others, 1986). The company has a processing plant in Amargosa Valley, and exports a variety of clay products worldwide. It is the only producer of sepiolite and saponite in the United States.

Two companies campaign mine and ship relatively small amounts of Nevada clay from several sites for use in high-unit-value specialty products. At its mill near Beatty in Nye County, Vanderbilt Minerals Co. processes small amounts of clay stockpiled from several Nevada, Arizona, and California deposits. The clay, which is used in pharmaceutical and cosmetic products, is shipped to a plant in Kentucky. It includes white bentonite from the New Discovery Mine near Beatty and clay from other Nevada sites including the Blanco Mine in Esmeralda County and the Buff Mine in Pershing County. The American Colloid Co. mines white bentonite from Coal Canyon in Pershing County, and hectorite from the Disaster Peak Mine in Humboldt County. These materials are stockpiled at Lovelock and shipped to the company's plant in South Dakota, where they are blended into specialty clay products.

The Moltan Co. mines a minor amount of clay from a deposit near Gerlach in Washoe County and uses the clay with diatomite in clumping cat litter that is produced at a plant near Fernley. The Art Wilson Co. mines about 35,000 tons per year of halloysite from a deposit in Washoe County about 60 miles north of Reno for use by Nevada Cement, but it is not included as clay in NBMG mineral production figures because it is used in portland cement. In addition, the Art Wilson Co. occasionally ships minor amounts of montmorillonite from the Jupiter Mine in Lyon County, and the Specialty Clay Co., LLC, is developing a bentonite deposit near Fallon in Churchill County.

Figure 8. Amargosa Valley sepiolite pit of IMV Minerals (Mud Camp Mining), Nye County.

In 1999, Oil-Dri, the world's largest manufacturer of cat litter, announced discovery of a clay deposit with 300 million tons of proven reserves in Hungry Valley north of Reno (Heivilin, this volume). In 2000, the U.S. Bureau of Land Management ruled that the clay is a locatable mineral, and issued the final environmental impact statement (EIS) in 2001. The clay, considered to be excellent for making clumping cat litter, is mainly calcium montmorillonite. According to the EIS, the deposit consists of clay-rich lacustrine strata as much as 98 feet thick, is areally extensive, and is near the surface. The company planned to employ about 100 people at a Hungry Valley mine and plant, to mine about 270,000 tons of clay annually, and to process it into more than 200,000 tons of products for absorbent and agricultural markets. In 2002, Washoe County denied operating permits, and the company is now litigating this decision.

Nevada is fertile ground for clay mineral exploration because of the abundance of hydrothermally altered rock. Many of the state's montmorillonite deposits have been described by Papke (1970).

Diatomite

Nevada is second to California in diatomite production in the U.S., and accounts for more than 30% of domestic production. More than half of Nevada's diatomite is used in filtration with the remainder mostly used in absorbents, fillers, and cement. All of the Nevada diatomite deposits are of lacustrine origin, occurring in Miocene to Pliocene volcanic-sedimentary sequences mostly within 150 miles of Reno. The diatomite sequences, which are as much as 445 feet thick, contain beds of pure massive diatomite that probably formed in response to high silica content provided by hydrothermal activity or the breakdown of volcanic ash.

Eagle-Picher Minerals, Inc., a division of Eagle-Picher Industries, Inc., a wholly owned subsidiary of Granaria Holdings Ltd. of The Netherlands, is the second largest domestic diatomite producer. It produces most of Nevada's diatomite at three different operations with combined annual production of more than 200,000 tons. The most productive is the Colado operation in Pershing County, which consists of a plant near Lovelock that makes filtration products from diatomite mined from pits 15 to 20 miles northwest of Lovelock (fig. 9). The company also produces diatomite marketed mainly as fillers and absorbents at its Clark plant and mine in Storey County about 20 miles east of Reno, and diatomite used in insulation from a pit near Hazen in Lyon County.

Moltan Co. is the second largest diatomite producer in Nevada, producing absorbent products, cat litter, and soil conditioner at a mine and plant complex in Churchill County about 20 miles northeast of Fernley. Moltan, a privately-held company, ships diatomaceous earth absorbents under several labels. The company produces two types of cat litter in Nevada, a non-clumping diatomite product and a clumping product composed of diatomite and clay.

Other companies that produce diatomite in Nevada are the Celite Corp., a subsidiary of World Minerals Inc., with a mine at Hazen and a mill at Fernley in Lyon County, and Grefco Inc. with a mine and plant at Basalt near the Esmeralda/Mineral County line (fig. 1).

Dimension Stone

Nevada is not well known as a producer of dimension stone, and high-quality, cut and polished products are not currently produced from stone mined in the state. A recent attempt to market cut dimension stone made from several varieties of ash-flow tuff in the Beatty area was abandoned after several years due to competition in the Las Vegas market from stone imported from Mexico. However, split dimension stone products are produced at two localities in Nevada, and two new dimension stone operations are planned.

Las Vegas Rock produces flagstone, ashlar, boulders, and crushed landscape rock at its Rainbow Quarries operation (fig. 10) near Goodsprings, about 20 miles southwest of Las Vegas. The stone is quartz-cemented Jurassic Aztec Sandstone, a unit that crops out extensively in Clark County but is too friable at most localities for building stone. The company also markets some cut stone and is planning to produce polished slabs and custom stone shapes.

At least two companies quarry flaggy, light-gray Cambrian quartzite on the east flank of Mount Moriah in White Pine County. This material, which naturally splits into slabs up to 5 feet by 8 feet by 4 inches thick, is used for flagstone and other types of uncut building stone.

Potential new dimension stone operations are being evaluated for variously-colored marble deposits at the old Carrara marble quarries near Beatty in Nye County (Anderson, this volume), and for mottled pink to purple or blue dumortierite-andalusite-quartz rock at Lincoln Hill in Pershing County (Callicrate and Griffin, this volume). The Nevada Bureau of Mines and Geology, in conjunction with Geomapping Associates Ltd. of Vermont and Converse Consultants of Reno, has issued a report on dimension stone potential in Humboldt, Lander, Eureka, and White Pine Counties (Tingley and others, 2001).

Fluorspar

Metallurgical grade fluorspar was mined for more than 60 years from veins in Paleozoic carbonate rock in the Bare Mountain district near Beatty (Papke, 1979). The mining, which ceased in 1989, produced a total of 260,000 tons of fluorspar, more than 40% of the total in the state. Most of the Bare Mountain production came from the Daisy Mine, a small underground operation (fig. 11). There are at least two other areas in Nevada with potential for fluorspar mining.

Figure 10. Hand splitting flagstone at Las Vegas Rock's Rainbow Quarries, Clark County.

Figure 9. Diatomite beds in one of Eagle-Picher's mines, Pershing County.

Figure 11. The inactive Daisy underground fluorspar mine, Nye County.

Garnet

A deposit of alluvial garnet and associated garnet schist in Hampton Creek near the Utah state line in White Pine County has been evaluated as a source of abrasive by several companies over the years. In addition, Nevada contains many skarn deposits that are rich in garnet, particularly in the Yerington district of Lyon County.

Gemstones

Nevada has been an important source of turquoise since prehistoric times, mainly from deposits in a belt that trends north-northeasterly across the state from Mineral and Esmeralda Counties to Elko County (Morrissey, 1968). The Fox Mine near Cortez in Lander County reportedly produced more than 500,000 pounds of turquoise. In recent years, small amounts of turquoise have been produced near Cortez and near Tonopah in Nye County.

Nevada is also known as a source of precious opal that is recovered in small amounts from deposits in Virgin Valley, Humboldt County. Much of the opal is mined by amateurs from pay-to-dig operations and is unreported. Crystalline amethyst and citrine are recovered from Peterson Mountain north of Reno in Washoe County, mostly as unreported stones from pay-to-dig activity. Blue topaz of gem quality has been produced from the Zapot Mine in Mineral County. In addition, thulite has been produced from Douglas County under the trade name “Lapis Nevada” and semiprecious varieties of silica have come from many parts of the state. A recently published NBMG map (Castor and LaPointe, 2001) shows the locations of gemstone deposits in Nevada.

Gypsum

Gypsum production in Nevada has ranged between 1.3 to 2.2 million tons annually over the past ten years (fig. 12); in 2002, production in Nevada was about 1.8 million tons. The state accounts for more than 10% of domestic production, and ranks only behind Oklahoma and Iowa in gypsum production. Three large producers—PABCO Gypsum, BPB PLC, and USG—use most of this gypsum in local wallboard plants. Georgia-Pacific Corp., which operates a wallboard plant about 20 miles northeast of Las Vegas, stopped mining gypsum in Nevada in 1995 and now buys gypsum from a mine in Utah. Actively-mined Nevada gypsum deposits range from Permian marine deposits with more than 90% gypsum to Tertiary continental deposits that contain about 70% gypsum.

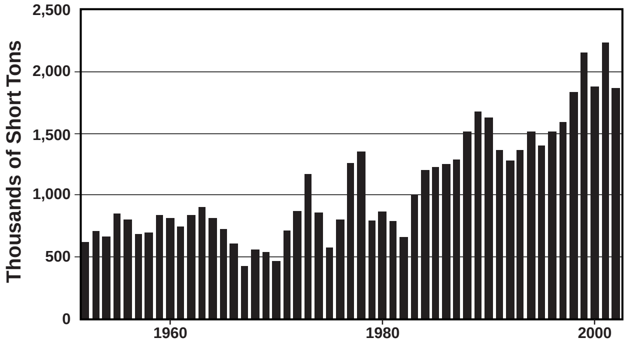

Figure 12. Gypsum production in Nevada, 1952 through 2002.

PABCO Gypsum in Clark County northeast of Las Vegas mined and processed more than a billion tons of gypsum ore in 2002. Although processing yields only about 70% by weight gypsum from the ore, the company still ranks as the largest producer in Nevada. The gypsum is in a nearly flat-lying late Miocene deposit (fig. 13) in excess of 120 feet thick that occurs atop a 5-square-mile mesa.

The Blue Diamond operation of BPB PLC (until recently owned by James Hardie Gypsum) southwest of Las Vegas in Clark County was the second largest producer (table 1). The gypsum deposit is the largest of several Permian deposits in the Las Vegas area. It consists of more-or-less flat-lying beds of pure gypsum as much as 30 feet thick (Papke, 1987) on a table mountain that overlooks the city. The Blue Diamond area has been the site of gypsum mining since 1925, but is now in the path of the metropolitan growth, and gypsum mining there may give way to up-scale housing development.

USG, the nation’s largest wallboard producer, was the third largest Nevada producer in 2002. The company mines gypsum in western Pershing County and processes it into wallboard and plaster at a plant at Empire in Washoe County. The gypsum is of Triassic or Jurassic age and forms several masses in a 2-square-mile area. The largest mass, the Selenite orebody, contains 85 to 95% gypsum and is generally well bedded with variable dips.

The Art Wilson Company of Carson City ships gypsum and anhydrite from a Mesozoic deposit at the Adams Mine in Lyon County. The D.L. Denman Construction Company mines gypsum at the Pioneer Gypsum Mine, which is near the PABCO operation east of Las Vegas (fig. 1). Gypsum from these relatively small operations is used in cement and agricultural applications.

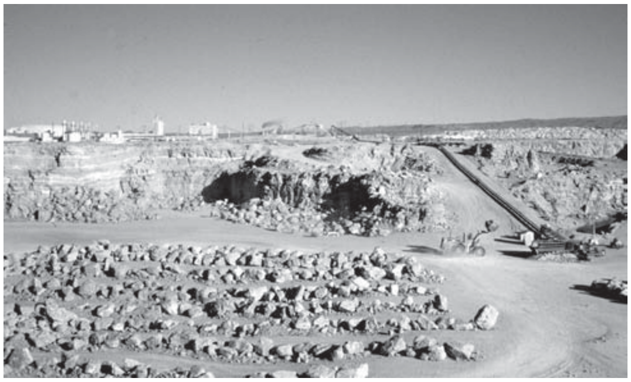

Figure 13. Gypsite beds at the PABCO gypsum mine, Clark County. PABCO’s wallboard plant is in the background.

Lime, Limestone, and Dolomite

In 1997, lime supplanted diatomite as Nevada's second most valuable industrial mineral. Limestone is mined for lime production at two sites in Nevada that are nearly at opposite ends of the state (fig. 1). The high-calcium limestone that is used at both sites is from the same Devonian limestone unit although it has been assigned different stratigraphic formation names. In addition to lime, relatively minor amounts of crushed limestone are shipped from both sites, and dolomite is mined at one of the sites.

The Pilot Peak high-calcium lime operation of Graymont Western US, Inc. (formerly Continental Lime, Inc.) near Wendover in Elko County shipped the most lime in 2002, mainly to gold-mining operations for use in cyanide-solution pH control. The Pilot Peak plant has three kilns with a combined capacity of more than 700,000 tons of quicklime per year and a hydrated lime plant capable of producing 350 tons per day. In 2000, the Pilot Peak plant was rated the ninth largest domestic lime producer. The raw material is limestone of the Devils Gate Formation.

Lime has been produced in the Las Vegas area for more than 80 years. Chemical Lime Co. produces lime at Apex about 20 miles northeast of Las Vegas from the Crystal Pass Member of the Sultan Limestone. The operation produces high-calcium quicklime used in metallurgical processing, paper manufacturing, and environmental markets. The company also produces dolomitic lime and hydrated high-calcium lime at Apex, mainly for construction uses. The Apex plant has four kilns (fig. 14), including one that is devoted to dolomitic lime production. The company processes the Apex dolomitic lime into hydrated dolomitic lime at a plant in nearby Henderson. The Chemical Lime dolomite quarry at Sloan ceased operation in 1997, and was purchased by Frehner Construction as a source of aggregate.

Other carbonate producers in Nevada are Min-Ad, Inc., which produces dolomite for agricultural uses, and Nutritional Additives Corp., which sells minor amounts of dolomite as a food additive. Both operations mine Mesozoic dolomite near Winnemucca.

Lithium

Chemetall Foote Co., a subsidiary of the German company Chemetall GmbH, produces lithium carbonate, lithium hydroxide monohydrate, and lithium hydroxide anhydrite at Silver Peak in Esmeralda County. This operation, which is the only primary lithium producer in the United States, produces these chemicals from brine that is pumped from beneath the Clayton Valley playa and evaporated in nearby ponds. The playa sediment contains 0.03–0.17% lithium, mainly in non-extractable form in clay; the brine carries about 0.02% lithium (Kunasz, 1970). Production figures are confidential; the latest public information available, from 1998 Securities Exchange data, showed annual production of about 12 million pounds of lithium carbonate and 5 million pounds of lithium hydroxide. U.S. prices have remained steady at about $2.00 per pound for lithium carbonate and $2.60 per pound for lithium hydroxide monohydrate since 1997, but since 1998 large shipments of lithium carbonate have sold at about half list price due to low pricing by South American brine operations. Since 1998, U.S. lithium imports have increased more than 250% and exports have fallen by more than 30%.

Magnesia

Premier Chemicals LLC of Cleveland, Ohio, owns the Gabbs magnesia operation in Nye County (fig. 15), where magnesium minerals have been mined since 1935. In the 1940s, magnesium minerals from Gabbs were used to make magnesium metal. From the 1950s to the 1980s, mining and processing was by Basic Industries, a major producer of refractory magnesia. In the 1990s, the availability of cheap Chinese refractory magnesia caused production at Gabbs to be switched to light-burned (caustic) magnesia that is mainly marketed for wastewater treatment and agricultural uses.

About 60% of U.S. magnesia production comes from seawater and natural brines, and the remainder from magnesite, brucite, and olivine. The mine at Gabbs is currently the only place in the United States where magnesite

Figure 14. Chemical Lime's Apex lime operation, Clark County.

Figure 15. Premier Chemical LLC's Gabbs magnesia operation, Nye County.

is mined. Magnesite with local brucite occurs at Gabbs over an area of about 2 square miles in complex replacement bodies in Triassic dolomite (Vitaliano and Callaghan, 1956). The magnesite is thought to have formed by hydrothermal activity related to emplacement of granite, and the brucite by alteration of the magnesite during later granodiorite intrusion (Schilling, 1968). Minor amounts of brucite are now mined from pods adjacent to igneous rocks in the magnesite pits. Nevada also contains deposits of sedimentary magnesite that have been evaluated for magnesia production, but never mined in significant amounts, at Overton in Clark County, and near Currant in Nye County.

Perlite

Nevada has large perlite resources and several deposits that were mined extensively in the past. The Hollinger Mine near Pioche in Lincoln County was the largest producer. However, current perlite production is restricted to relatively small-scale mining of two deposits for niche markets.

Wilkin Mining and Trucking Inc., mines perlite from the Tenacity Perlite Mine west of Caliente in Lincoln County. In the past, most of this perlite was shipped as crude ore; however, the company has a small popping plant in Caliente and now mostly sells expanded perlite. The perlite is somewhat unique because it can be expanded into a relatively coarse product, which is useful in horticultural applications. It is shipped to users as far away as Hawaii, where it is used as a growing medium for orchids. The Tenacity Mine ore is “onion skin” perlite that occurs as the basal vitrophyre of an ash-flow tuff.

Eagle-Picher Minerals Inc. produces expanded perlite at its Colado diatomite plant in Pershing County from perlite mined at the Popcorn Mine 18 miles south of Fallon in Churchill County. The perlite is marketed as a filter aid, and plant capacity is reportedly about 8,000 tons per year.

Silica

Simplot Silica Products in Clark County ships 600,000-700,000 tons per year of silica sand, which is mainly used in glass manufacture, as foundry sand, and in well-completion applications. The sand is mined from an open pit about 4,000 feet long and 1,000 feet wide (fig. 16) in the relatively friable Cretaceous Baseline Sandstone, washed in the pit, and transported via a slurry pipeline to a plant near Overton where it is dried, screened, and bagged.

In 2002 Silica LLC began mining quartzite from the Sugar mining claims about 3 miles southeast of Mercury in Nye County. A Plan of Operations submitted to the BLM in 2001 called for annual production of as much as 80,000 tons. The material, in the Ordovician Eureka Quartzite, was described as strongly brecciated and fractured and amenable to mining without blasting.

Caithness Operating Co. of Reno, in collaboration with the U.S. Department of Energy, has developed a method for production of high-purity silica from geothermal fluids for use in nano-scale materials and has set up a pilot plant in Nevada to evaluate the process. Estimated annual production of such material from a 50-megawatt geothermal power plant is about 6,000 tons.

Sodium Minerals

The Huck Salt Company produces about 15,000 tons of halite yearly from the Sand Springs Marsh in the Fourmile Flat playa about 25 miles southeast of Fallon in Churchill County. Although yearly production is small, total production has been more than 250,000 tons. The salt is recovered from a layer that is replenished by capillary movement and deposition at the surface. Salt has been harvested from this deposit using small-scale equipment (fig. 17) almost continuously since the 1860s when it was hauled to the mills that processed Comstock silver and gold ore. The modern operation mainly sells it locally as a road deicing agent.

Halite has been produced from other playa deposits in Nevada in the past, such as at Eagle Marsh and White Plains, both also in Churchill County. It was also mined prehistorically from exposed beds of halite in the Virgin River area of Clark County; the beds are now mostly covered

Figure 16. Open pit at Simplot Silica’s Overton operation, Clark County.

Figure 17. Salt harvester, Huck Salt operation, Fourmile Flat, Churchill County.

by Lake Mead. Drilling in the 1960s in the same area penetrated as much as 1,750 feet of halite-rich material without reaching the bottom (Mannion, 1963). Other sodium mineral deposits of note in Nevada include thick beds of gaylussite (sodium carbonate) at depth in Railroad Valley in Nye County (Papke, 1976), and a deposit of thenardite and mirabilite (sodium sulfate) in Miocene rocks near White Basin in the Muddy Mountains of Clark County.

Talc

Talc was mined from deposits in Esmeralda County from 1928 to 1980. Although other domestic deposits (such as those in Montana and Texas) and foreign deposits will probably meet talc demand for the foreseeable future, small-scale local markets could utilize production from Nevada. Nevada's talc deposits are described in detail in a Nevada Bureau of Mines and Geology publication (Papke, 1975).

Vermiculite

Vermiculite deposits are found at Mica Peak in the Gold Butte area in Clark County about 50 miles east of Las Vegas. The deposits, which are of interest because they contain high-quality vermiculite and are near potential markets in southern California, are in Precambrian ultramafic rocks (Leighton, 1967).

Wollastonite

In 1989, a wollastonite deposit was discovered in the Gilbert district, Esmeralda County, about 25 miles west of Tonopah. The deposit was considered for development in the mid 1990s by the American Wollastonite Mining Corp. of Vancouver, Canada. However, development of this wollastonite deposit in the near future is considered unlikely in a market dominated by long-term production from deposits in New York, China, and India.

Zeolites

Ash Meadows Zeolite LLC, a subsidiary of Badger Mining Corp., ships 1,000 to 2,000 tons annually of clinoptilolite used in water filtration, odor control, and nuclear clean-up from a plant in Ash Meadows in Nye County. The clinoptilolite is mined from a large deposit in California that extends into Nevada (Santini and Shapiro, 1982), and the company has evaluated plans to mine green clinoptilolite from the Nevada portion of the deposit for use in cat litter. Moltan Company mines small amounts of mordenite from its zeolite deposit in the Trinity Range in Churchill County about 40 miles northeast of Fernley; the company processes the zeolite at its Fernley absorbents and cat litter plant.

Nevada contains several large zeolite deposits that were discovered and evaluated during a flurry of zeolite exploration activity in the 1950s and 1960s. Many of these deposits were described in detail in a Nevada Bureau of Mines and Geology publication (Papke, 1972).

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Mountain Pass Rare Earth Deposit, California

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Abstract

The Molycorp Inc. Mountain Pass operation has produced rare earths since 1954 and was the world's largest source of rare earth commodities from the 1960s to the mid 1990s. Since 1998, Mountain Pass share of world production has declined substantially due to environmental constraints and Chinese competition. In the late 1980s, Mountain Pass shipped more than 20 rare earth commodities, including high-purity products with prices as high as $1600/kg. However, present shipments are mostly of bastnasite concentrate and lanthanum oxide from stockpile. Following acceptance of a new Mountain Pass environmental impact report, renewed mining and milling is planned. Plans to restart the extraction and separation plant are also being considered.

Mountain Pass rare earths come from a carbonatite deposit with reserves of more than 20 million metric tons of ore with an average grade of 8.9% rare earth oxide. The ore typically contains 10–15% bastnasite (the ore mineral), 65% calcite and/or dolomite, and 20–25 % barite, with minor amounts of other minerals. The carbonatite, a moderately dipping tabular intrusion in gneiss, has been dated at about 1.4 Ga. It is associated with ultrapotassic intrusions of similar age that occur in a narrow, north-trending zone at least 130 km long.

Although the Mountain Pass deposit shares features with other carbonatites, its geometry, mineralogy, chemistry, and igneous association distinguish it from most other carbonatites. Among the world's rare earth deposits, the Mountain Pass orebody is unique. The authors believe that similar primary rare earth carbonatite deposits, if they exist, will be found in association with ultrapotassic igneous rocks.

Rare Earths and Their Economics

The fifteen lanthanide elements and yttrium came to be called rare earth elements (REE) because they were originally isolated as oxides from rare minerals at the time of their discovery in the late 18th and early 19th centuries. However, most REE are not as uncommon in the natural environment as the name implies: cerium, the most abundant, comprises more of the earth's crust than copper or lead; most REE are more common than tin and molybdenum; and all but promethium are more common than silver or mercury. Promethium, best known as an artificial element, is very rare in nature because it has no long-lived isotopes.

The lanthanide elements have traditionally been divided into two groups: the light rare earths (LREE), lanthanum through europium; and the heavy rare earths (HREE), gadolinium through lutetium. Although yttrium is the lightest REE, it is usually grouped with the HREE to which it is chemically and physically similar.

The REE invariably occur together in nature because they are all trivalent (although cerium also occurs as Ce^{+4} and europium also occurs as Eu^{+2}) and they have similar ionic radii. Increase in atomic number within the lanthanide group is accompanied by addition of electrons to an inner level rather than to the outer shell of electrons. Consequently, there is no change in valence with change in atomic number, and the lanthanides all fall into the same cell in most versions of the periodic table. Chemical and physical differences that do exist are caused by small differences in ionic radius, and generally lead to the segregation of REE into deposits enriched in either LREE or HREE plus yttrium.

Classical uses for REE, such as in mischmetal and lighter flints, no longer drive REE markets, and much of the profit in REE processing lies in providing high-purity individual compounds for high-tech uses (table 1). Strong demand for such commodities during the 1980s led to price increases, particularly for neodymium, samarium, and yttrium oxide (table 2).

Global production of REE has grown by more than 700% since the mid 1960s (fig. 1). During the 1950s and early 1960s, most production was from by-product monazite from Australian beach placers. From 1966 to 1985, the U.S.was the dominant producing country, mainly from Mountain Pass bastnasite, although placer monazite continued to provide substantial amounts of REE. Mining

Table 1. Examples of uses for some rare earth commodities.

Mixed REE	mischmetal, steel alloys
Lanthanum	autocatalysts, petrocatalysts, rechargeable batteries
Cerium	glass polish, autocatalysts, glass decolorizer, fluorescent lighting
Praseodymium	ceramic pigment, high-temperature batteries, petrocatalysts
Neodymium	permanent magnets, dental laser, glass pigment, petrocatalysts
Samarium	permanent magnets, laser glass
Europium	red phosphor for CRTs and LCDs, fluorescent lighting
Gadolinium	phosphors, high-temperature batteries, garnet laser
Terbium	phosphors
Dysprosium	phosphors
Holmium	lasers
Erbium	fiber-optic cable, glass pigment, lasers, nuclear reactors
Thulium	medical imaging, phosphors
Ytterbium	metallurgical and chemical experiments
Lutetium	single crystal scintillator
Yttrium	phosphors, fluorescent lighting, high-temperature batteries

Table 2. Comparisons of prices for selected high-purity rare earth commodities between 1979 and 2003. Sources: 1979 - Shannon (1983); 1989 - Hedrick and Templeton (1991); 2003 - American Metal Market and High Tech Materials web sites. Values not adjusted for inflation.

Commodity	Minimum purity (%)	Price (US$/kg), to nearest $ 1979	1989	2003
Cerium oxide	99.0	18	19	12
Cerium metal	99.9	108	no data	40
Lanthanum oxide	99.99	17	19	5
Neodymium oxide	99.9	65	88	19
Neodymium metal	99.0	250	no data	19
Samarium oxide	96.0	110	143	13
Samarium metal	99.9	280	no data	65
Europium oxide	99.99	1650	1639	425
Terbium oxide	99.9	825	825	198
Thulium oxide	99.9	2650	3600	1000
Yttrium oxide	99.99	74	116	25

commenced at Mountain Pass in 1954, and from the 1960s to the mid 1990s it was the world's leading producer of REE. In 1966, Molycorp completed construction of an extraction and separation plant to produce high-purity REE compounds at Mountain Pass, and in the early 1980s a second separation plant was added to produce samarium and gadolinium oxide.

In 1985, Chinese production of REE, mainly as by product from the Bayon Obo iron deposit in Inner Mongolia, began to impact the market significantly. By 1994, the combined weight of production from China and Mountain Pass had nearly squeezed placer monazite sources out of the market (fig. 1). In the late 1980s and early 1990s, Molycorp marketed more than twenty REE commodities, most produced on site, including high-purity chemical products with prices as high as $1,639/kg (table 1). In 1998, after experiencing environmental regulation problems, most of the Mountain Pass operation was shut down, and the United States ceased to be a major player in global REE markets. Molycorp currently ships about 3,000 metric tons of REO per year, mainly bastnasite concentrate marketed as an abrasive and lanthanum oxide used as a catalyst. Both are shipped from stockpiles.

Molycorp recently completed a new Mountain Pass environmental impact report (essentially a 30-year operational plan) for pit and overburden storage expansions, a new tailings facility, and new evaporation ponds. Renewed mining and milling is planned for 2007. Plans are being formulated to restart the extraction and separation plant; it is in working order and could resume production if the environmental concerns of federal and state agencies can be addressed. However, the operation faces stiff competition from a strong, high-tech Asian REE industry.

The impact of the Asian REE industry, which consists of mines and plants in China and processing operations in Japan, on REE commodity prices has been extreme (table 2). Cerium oxide, the least-affected commodity, has decreased in value by more than 40% since 1989. Prices for other commodities have tumbled even more, from 75% to more than 90%. Although REE production has doubled since the mid 1980s, the price decreases have caused the overall value of global REE production to fall below the value at that time.

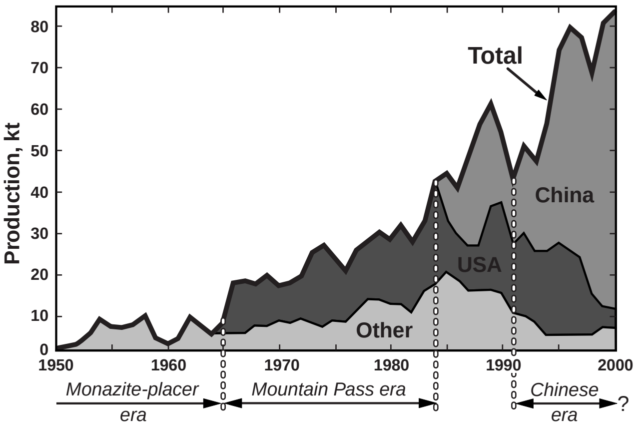

Figure 1. Global production of rare-earth oxides, 1950–2000. From USGS Fact Sheet 087-02, by Haxel and others, 2002. "Other" mainly Australia, Russia, Malaysia, Brazil, and India.

Discovery and General Geology of the Mountain Pass Carbonatite

REE minerals were first discovered in a carbonatite dike at Mountain Pass in southeastern California (fig. 2) in 1949 by Herbert Woodward, Clarence Watkins, and P.A. Simon while prospecting for uranium with a Geiger counter. The prospectors staked the Birthday group of claims in an area about 900 m northwest of the present open-pit mine. Molycorp (then Molybdenum Corporation of America) entered the picture in 1950 by purchasing the Birthday claims from the discoverers. The Sulphide Queen carbonatite, which includes the Mountain Pass orebody, was discovered in 1950 by J.C. Olson and D.F. Hewett of the U.S. Geological Survey (Olson and others, 1954). In part,

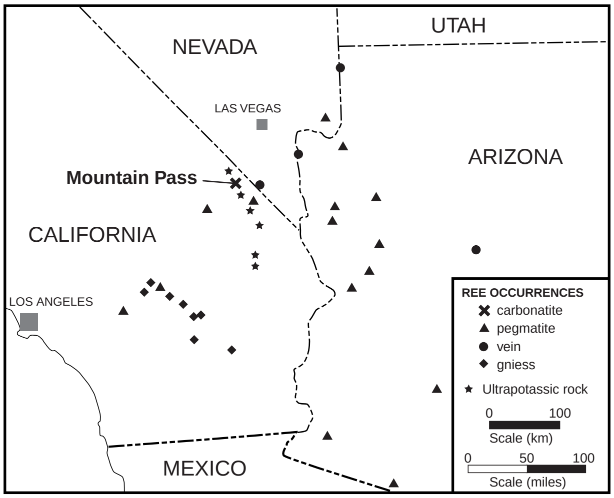

Figure 2. Location map showing Mountain Pass, other rare earth mineral occurrences, and ultra-potassic rock occurrences in the region. From Castor (1991).

the Sulphide Queen carbonatite was located on claims owned by Fred Piehl, who discovered gold at the nearby Sulphide Queen Mine in the 1930s. Molycorp's predecessor purchased these and other claims in the area in the early 1950s.

In 1987, the Mountain Pass orebody had estimated reserves of about 29 million metric tons of ore with an average grade of 8.9% rare earth oxide (REO) based on a 5% cutoff grade (Castor, 1991). It is likely that about 25 million metric tons remain. The Mountain Pass orebody is the only deposit in the world mined exclusively for REE, and the only ore mineral is bastnasite, although nine other REE minerals occur at Mountain Pass (table 3). The ore typically contains about 10 to 15% bastnasite, 65% calcite and/or dolomite, and 20 to 25% barite. Other gangue minerals, such as strontianite and talc, are present in significant amounts locally. Galena is locally abundant, but other sulfide minerals are rare. REEs in Mountain Pass bastnasite concentrate are dominated by LREE.

The Sulphide Queen carbonatite, which is about 1.4 Ga (DeWitt and others, 1987), is a moderately dipping tabular intrusion (fig. 3). It is associated with 1.4-Ga alkaline plutons of similar size and orientation, as well as abundant carbonatite and alkaline dikes. Carbonatite dikes at Mountain Pass clearly postdate granite dikes, but the temporal relationship between carbonatite and late melasyenite dikes is not clear. Concentric, circular to ovoid plan patterns that are characteristic of alkaline/carbonatite complexes worldwide are not present at Mountain Pass. Instead, the main carbonatite and alkaline rock bodies are crudely tabular, floored intrusions with northwest trends that dip moderately to shallowly southwest. Abundant shonkinite to granite dikes up to 75 m wide occur in the Mountain Pass area. The dikes dip steeply and mostly occur in two sets, one with northwesterly strikes, and another with strikes that cluster closely about an east-west direction.

Host Rocks

Host rocks for the carbonatite and alkaline intrusions at Mountain Pass are part of a regional Proterozoic rock package that ranges in age between 1.7 Ga and 1.8 Ga (Condie, 1981; Miller and others, 1982). They are interlayered and folded granulitic-facies gneiss and schist with variable amounts of quartz, microcline, biotite, garnet, hornblende, hypersthene, and sillimanite.

On the basis of drill data, the Sulphide Queen carbonatite is surrounded by an envelope of carbonatite dikes and associated fenitic alteration that is more than 200 m thick in places in the host metamorphic rocks. These fenitized rocks generally contain brick-red to pink potash feldspar, dark magnesium-rich mica, and carbonate. Magnesioriebeckite commonly replaces amphibole and pyroxene, and it occurs widely in small amounts along fractures. Chlorite and hematite are also widespread alteration minerals. Fluorite is present in places, generally in veinlets. The alkaline intrusive rocks are locally affected by fenitization, which may generally be distinguished by the presence of red alkali feldspar, blue to green magnesioriebeckite, and hematite.

A zone of radioactive fenitized gneiss as much as 30 m wide in the Mountain Pass area has been interpreted as a pre-Laramide shear zone (Olson and others, 1954). This zone extends for about 2 km south-southeast from the Sulphide Queen carbonatite. To the southeast, it has been displaced about 2 km eastward along a west-northwest-striking fault, and it extends for at least another 3 km. It is the locus of several REE prospects, including an occurrence of allanite-rich fenitized gneiss with as much as 9% REO, and occurrences of carbonatite dikes.

Table 3. Rare earth minerals found at Mountain Pass. Ln = lanthanide elements, REO = rare earth oxides, * REO content calculated from formula.

Mineral	Formula	REO wt. %
Allanite (orthite)	$(Ca,Ln)_2Fe\ Al_2Si_3O_{12}(OH)$	30
Ancylite	$SrLn(CO_3)_2(OH)H_2O$	46
Apatite	$Ca_5(PO_4)_3(F,OH,Cl)$	2
Bastnasite	$LnCO_3F$	75
Cerite	$Ln_9Fe_3(SiO_4)_6[(SiO_3)(OH)](OH)_3$	65
Florencite	$LnAl_3(PO_4)_2(OH)_6$	32*
Hydroxylbastnasite	$LnCO_3OH$	76*
Monazite	$LnPO_4$	71
Parisite	$CaLn_2(CO_3)_3F_2$	64
Sahamalite	$(Mg,Fe)Ln_2(CO_3)_4$	72*
Synchisite	$CaLn(CO_3)_2F$	51*

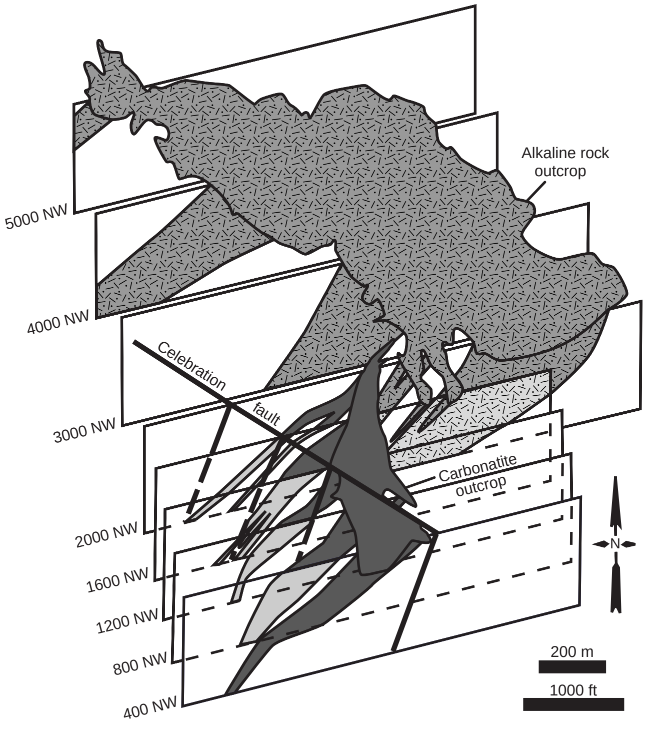

Figure 3. Stacked cross sections through the Mountain Pass carbonatite (gray) and the major associated alkaline rock mass (patterned).

Ultrapotassic Alkaline Rocks

The potassic character of the alkaline intrusions at Mountain Pass has been known for some time (Olson and others, 1954), and their ultrapotassic nature has been noted (Castor and Gleason, 1989; Castor, 1990), but no comprehensive comparison of these rocks with classical ultrapotassic provinces has been made. Mountain Pass is in a narrow, 130-km-long belt in southeastern California that is defined by ultrapotassic rock occurrences (fig. 1) (Gleason, 1988; Castor and Gleason, 1989; Castor, 1991). Ultrapotassic intrusions in the north part of this belt, including those in the Mountain Pass area, are unmetamorphosed rocks in granulite facies host rocks. By contrast, host rocks and ultrapotassic intrusions in the south part of the belt were overprinted by Mesozoic greenschist-grade metamorphism. The ultrapotassic belt is near the southwestern end of a northeast-trending belt of Proterozoic anorogenic granitic rocks that crosses North America (Anderson, 1983; Castor, 1993). Some of these rocks are as old as 1.6 Ga and some as young as 1.1 Ga; dated examples in Arizona and California are 1.4 to 1.5 Ga (Anderson, 1983).

Mafic (< 55 wt. % SiO_2) alkaline rocks in the Mountain Pass area contain more than 3 wt.% K_2O, 3 wt.% MgO, and have $K_2O/Na_2O > 2$, satisfying the definition for ultrapotassic rocks of Foley and others (1987). They also satisfy many of the chemical and mineralogical requirements listed by Bergman (1987) and Scott-Smith (1996) for the lamproite class of ultrapotassic rocks. However, Mountain Pass alkaline rocks differ somewhat in mineralogy from classical lamproitic occurrences, are significantly different in the range of silica content, and are generally higher in alumina and lower in titania. In addition, the Mountain Pass ultrapotassic rocks are unique in their association with carbonatite.

In the Mountain Pass area, the alkaline rocks occur in fine- to coarse-grained plutons as much as 1.8 km across, and as fine-grained dikes. Olson and others (1954) divided the alkaline rocks into four types on the basis of mineralogy: shonkinite, syenite, quartz syenite, and granite. Using the IUGS classification scheme of Le Maitre and others (2002), shonkinite is dark syenite with more than 60% mafic minerals in the mode. On the basis of our work, much of the rock originally mapped as shonkinite in the area is dark-colored rock with less than 60% mafic minerals; alkali feldspar melasyenite in the IUGS classification. We refer to these rocks as melasyenite. Rocks herein called syenites are light colored, contain less than 30% mafic minerals, and are mostly alkali feldspar syenite using the IUGS classification.

Shonkinite and melasyenite comprise about 80% of the exposed alkaline rocks in the Mountain Pass area, with syenite, quartz syenite, and granite together comprising about 20%. In general, Mountain Pass alkaline intrusions have crosscutting relationships indicating a progression from older most mafic rocks to younger silicic rocks. Shonkinite and melasyenite plutons are cut by syenite, quartz syenite, and granite dikes. Late, fine-grained, melasyenite dikes are exceptions to this general mafic to felsic intrusive sequence; they cut syenite bodies and granite dikes.

Mineral Assemblages in the Alkaline Rocks

Shonkinite and melasyenite in the Mountain Pass area are dark-green to mottled green and pink or purple rocks that contain major amounts of phlogopite and pyroxene with variable amounts of potash feldspar, amphibole, and olivine (table 4). Apatite and magnetite are accessory, while ilmenite, rutile, zircon, fluorite, barite, monazite, badelleyite, and thorite generally occur in trace amounts. The late melasyenite dikes consist of fine-grained, gray rock with mica and pyroxene in a matrix of potash feldspar.

Phlogopite in Mountain Pass shonkinite and melasyenite occurs mostly as 1- to 8-mm books with reddish-brown to yellow pleochroism. Based on microprobe analyses (table 5), it has atomic Mg/Fe of 3.7 to 5.2 and is titanian (2.0% or more TiO_2). Pyroxene in shonkinite has optical characteristics of diopside, and microprobe analyses indicate it is rich in Ca and Mg. Olivine in shonkinite from the Mountain Pass area is mostly altered to fine talc and(or) serpentine, but unaltered olivine has been reported (Olson and others, 1954). It was never present in some shonkinite and melasyenite, and the most mafic rock analyzed (sample CSH, table 4) did not contain olivine. Unaltered olivine in melasyenite (fig. 4) is forsteritic (table 5).

Although magnesian sodic amphibole occurs in Mountain Pass shonkinite, pale yellow to pink pleochroism observed in most of the primary amphibole indicates that it is K-richterite, which is supported by microprobe analyses (table 5). Magnesioriebeckite occurs in shonkinite from the large mass north of the Sulphide Queen carbonatite; this may be secondary amphibole related to fenitization during carbonatite intrusion. SEM/EDX analyses indicate that apatite in Mountain Pass shonkinite has relatively low REE contents; however, Roeder and others (1987) reported more than 2% REO in apatite from Mountain Pass shonkinite. Magnetite that contains up to 8% Cr_2O_3 generally comprises 1–2% of the shonkinite. Fluorite, generally a trace mineral, comprises as much as 1% of some shonkinite.

Microcline is interstitial and commonly forms poikilitic masses to more than 2 cm in diameter. It contains little or no Na_2O and minor to significant amounts of BaO (table 5). The most mafic shonkinite contains less than 5% interstitial microcline, which ranges from barian microcline to low-Ba microcline with barite enclaves. Melasyenite from the Sulphide Queen area and the Tors area 1 km to the southeast contains cloudy pseudoleucite grains, some with distinctly trapezohedral shapes (fig. 5) surrounded by clear, late barian microcline. Microprobe analyses show that the pseudoleucite, which is mainly low-Ba potash feldspar, contains patches of potassic and sodic aluminum silicate that are thought to include analcime and other zeolite minerals, along with patches of iron-rich biotite.

Most rocks mapped as syenite in the Mountain Pass area contain less than 25% mafic minerals. They are light-colored, fine- to coarse-grained rocks that grade into quartz syenite. A typical syenite from the Tors area contains more than 65% perthitic microcline or orthoclase. Albite as separate grains is a rare constituent. Accessory minerals are

Table 4. Chemical and modal compositions of selected alkaline igneous rocks from Mountain Pass.

Rock Type	Shonkinite		Melasyenite			Syenite	Quartz Syenite		Granite	
Sample	**CSH**	**HP1**	**TORSH**	**CMSY**	**FSH**	**TORSY**	**HP13**	**TQSY**	**G6**	**HP7**
SiO_2	42.77	43.50	44.31	47.47	52.42	53.59	60.45	61.84	67.87	75.79
Al_2O_3	5.66	7.56	9.30	9.32	11.56	12.72	13.76	14.41	11.09	11.57
Fe_2O_3	7.27	9.48	6.99	7.96	4.92	6.83	6.84	3.11	6.04	3.24
MgO	15.51	14.24	12.78	9.75	5.79	3.49	1.64	1.01	0.76	0.19
CaO	11.32	8.86	6.87	5.42	4.33	2.44	2.22	0.86	1.09	0.31
Na_2O	1.05	0.47	1.17	1.22	2.92	1.99	2.36	3.21	4.08	3.80
K_2O	5.19	6.10	8.36	9.91	7.54	12.47	9.24	12.11	5.66	4.75
MnO	0.11	0.12	0.10	0.13	0.07	0.08	0.08	0.04	0.12	0.01
TiO_2	1.80	2.49	0.89	0.91	1.11	0.74	0.90	0.32	0.51	0.14
P_2O_5	2.74	2.35	1.49	0.94	2.24	0.65	0.43	0.25	0.11	<0.01
BaO	1.51	0.94	0.78	0.71	1.19	0.66	0.79	0.49	0.09	0.06
SrO	0.31	0.15	0.38	0.16	0.20	0.11	0.08	0.07	0.04	0.01
CO_2	0.62	0.11	1.50	1.87	0.18	0.55	0.04	0.07	0.11	0.36
SO_3	0.25	0.18	0.38	0.50	0.52	0.77	0.15	0.28	0.15	0.02
F	1.98	1.20	0.86	0.86	0.70	na	na	na	0.62	na
LOI	2.68	2.69	3.90	3.43	4.42	2.85	1.16	1.73	1.79	0.44
Total	100.77	100.44	100.07	100.55	100.11	99.94	100.13	99.80	100.13	100.69
mK/(K+Na)	0.76	0.90	0.82	0.84	0.63	0.80	0.72	0.71	0.48	0.45
Mg no.	0.89	0.86	0.88	0.83	0.82	0.67	0.49	0.56	0.33	0.19
Cr	460	700	870	260	200	81	<20	32	68	<20
Co	50	54	49	42	17	22	11	<5	<5	<5
Ni	306	217	447	295	160	61	9	7	30	7
Zn	199	108	120	195	108	142	50	62	108	<10
Rb	210	350	584	607	280	651	501	514	569	330
Y	71	40	43	51	39	43	52	29	81	14
Zr	551	227	692	479	529	1379	348	382	2405	1001
Nb	19	6	25	17	56	23	29	26	192	35
La	424	180	285	230	320	221	130	130	256	12
Ce	985	450	660	510	683	546	350	300	533	48
Sm	77.6	37.5	45.7	42.9	35.8	39.7	33.5	20.3	26.3	8.3
Eu	20	8	10	10	9	10	5	5	7	2
Tb	4.9	2.4	2.7	3.0	2.0	2.6	2.9	1.4	2.9	1.5
Yb	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Lu	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Hf	15	6	12	12	19	27	11	10	63	36
Ta	1.0	0.5	1.0	1.2	1.5	1.0	2.8	2.2	10.0	4.9
Th	136	30	77	49	66	158	92	139	430	260
U	11	3	10	8	14	17	12	11	70	25
Diopside	33.1	30.0	14.9	18.0	14.1			0.3		
Na-Pyroxene						5.0		5.4	10.0	
Phlogopite	44.5	32.0	20.9	25.4	22.0					
Olivine			7.5							
Biotite						7.0		2.4	0.5	
K-Feldspar	6.5	24.0	46.6	49.0	46.9	67.0	64.0	81.4	56.0	59.5
Plagioclase									3.0	
K-Richterite	5.4		1.2	2.0						
Na-Amphibole					10.6	15.0	15.0	3.8	6.0	
Quartz							11.0	6.2	20.0	30.6
Apatite	7.4	4.0	1.3	2.0	3.6		<1.0			1.0
Opaque	0.9	2.0	0.5	0.2	0.8		1.0	0.5	3.0	
Barite	0.5	tr	tr	tr	2.0	tr	tr			
Carbonate	tr		tr			2.0				
Sphene							3.0			
Fluorite	1.0		0.4						0.5	
Other(tr)	B,T,U,Z	B	An,G,M	A,G,M,P, Pa,T,Z	T,U	M,P,R,S, T,Z	T,U,Z	M,T	M,R,T,Z	
Alt. Minerals	0.8	8.0	6.7	3.4						9.0

Oxide, F, and LOI data in wt. %. Analyses by fusion ICP-ES from ACME Laboratories, Vancouver, British Columbia, except F by colorimetry from NBMG Laboratory, Reno, Nevada. Total Fe as Fe_2O_3, LOI at 850∫ C - CO_2, na = not analyzed, m = molar, Mg no. = mMg/(mMg+mFe). Trace element data in ppm by INAA from Bondar Clegg, Denver, Colorado, except Ni, Zn, Y, and Zr by fusion ICP-ES from ACME. Other minerals: B = badelleyite, A = allanite, An = ancylite, G = galena, M = monazite, P = pyrite, Pa = parisite, R = rutile, S = synchisite, T = thorite, U = unknown Th+Zr+REE+Ca silicate, Z = zircon. Alt.(alteration) minerals include clay minerals, talc, chlorite, and sericite.

Mg-Na amphibole, phlogopite or magnesian biotite, and aegerine (table 5). Trace minerals include apatite, rutile, magnetite, ilmenite, pyrite, zircon, thorite, allanite, and monazite. Syenite from the Tors area has interstitial calcite with skeletal rutile pseudomorphs after sphene and late REE-Ca carbonate (probably synchisite) along biotite cleavage and with thorite in monazite.

Table 5. Microprobe analyses of minerals from ultrapotassic rocks at Mountain Pass.

Sample	TORSH	TORSH	TORSH	TORSY	TORSH	TORSY
Mineral	Olivine	Diopside	Diopside	Aegerine	K-richterite	Mg-riebeckite
SiO_2	40.40	52.95	53.35	52.61	55.33	54.73
Al_2O_3	0.00	0.71	0.83	0.40	0.73	0.66
FeO	13.13	4.08	3.74	26.45	3.70	14.30
MgO	46.86	17.18	17.53	1.97	21.48	14.91
CaO	0.13	23.03	23.00	3.04	6.05	3.79
Na_2O	0.03	0.60	0.35	12.66	4.54	6.03
K_2O	0.00	0.00	0.00	0.08	4.38	1.26
MnO	0.43	0.14	0.07	0.04	0.10	0.35
TiO_2	0.01	0.66	0.44	0.27	0.04	0.18
BaO	0.01	0.01	0.00	0.06	0.03	0.05
Cr_2O_3	0.04	0.24	0.41	0.10	0.06	0.04
Total	0.52	1.65	1.27	13.21	9.15	7.91
Mg/Fe	6.36	7.51	8.35			

Sample	TORSH	TORSY	TORSY	TORSH	TORSH	TORSY
Mineral	Phlogopite	Biotite	Biotite	Kspar	Kspar	Kspar
SiO_2	38.71	37.82	39.32	61.94	63.89	63.67
Al_2O_3	11.26	11.76	9.20	17.83	18.68	17.62
FeO	7.24	15.49	16.44	1.97	0.05	1.03
MgO	21.31	14.88	16.10	0.03	0.02	0.01
CaO	0.00	0.04	0.01	0.00	0.00	0.00
Na_2O	0.19	0.08	0.00	0.20	0.63	0.32
K_2O	8.94	9.26	9.93	15.35	16.47	16.13
MnO	0.07	0.21	0.20	0.01	0.00	0.01
TiO_2	4.42	2.86	3.78	0.16	0.01	0.02
BaO	3.22	0.53	0.14	2.93	0.27	0.56
Cr_2O_3	0.16	0.48	0.01	0.00	0.00	0.00
Total	17.00	13.42	14.06	18.65	17.38	17.04
Mg/Fe	5.25	1.71	1.75			

Data, in wt %, from Washington State University; total Fe as FeO; atomic Mg/Fe given for some minerals.

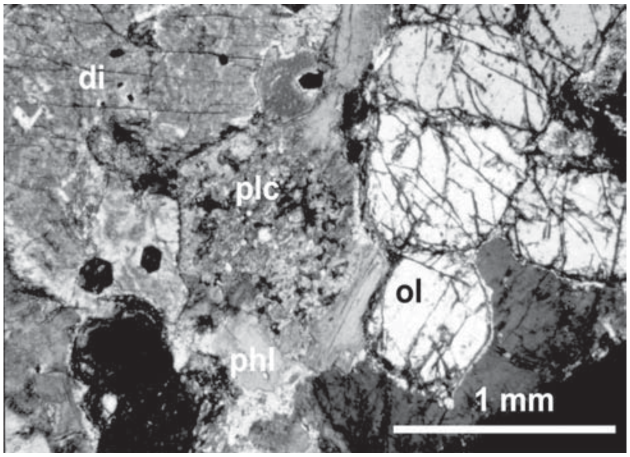

Figure 4. Diopside (di), "pseudoleucite" (plc), olivine (ol), phlogopite (phl), and potash feldspar in melasyenite, cross-polarized light.

Fine-grained, leucocratic, syenite and quartz syenite mostly form dikes in the Mountain Pass area. Some are porphyritic. In many cases, mafic minerals in these rocks are altered. Quartz syenite porphyry dike rock consists of abundant perthitic microcline, sparse mica, and rare amphibole phenocrysts in a matrix of fine potash feldspar, quartz, and sodic amphibole. On the basis of SEM/EDX, zoned mica phenocrysts have phlogopitic cores and magnesian biotite rims. The potash feldspar contains no detectable BaO, but barite enclaves were identified by SEM/EDX. Sphene, a minor accessory in some samples of quartz syenite, does itself not have detectable REE, but it contains inclusions of monazite and possible bastnasite and synchisite. Zoned zircon crystals up to 0.5 mm long are present in trace amounts.

Most granite intrusions at Mountain Pass are aplite or porphyry dikes, but the Mineral Hill pluton, about 5 km southeast of the Sulfide Queen carbonatite, is mostly medium-grained granite. Relatively unaltered Mineral Hill samples consist mostly of perthitic microcline, quartz, and albite. They contain accessory aegerine, sodic amphibole, and ilmenite; and traces of biotite, fluorite, rutile, and thorite. Trace zircon occurs in crystals similar to those in the syenite and quartz syenite.

Chemistry of the Alkaline Rocks

Although the Mountain Pass suite includes rocks that are saturated to oversaturated with SiO_2, it is clearly alkaline. The ratio $(K_2O+Na_2O)/CaO$ is at unity for the suite at a silica content of about 48 wt%, putting it in Peacock's alkaline rock field. The Mountain Pass alkaline igneous suite has chemical features of ultrapotassic suites such as those in the Leucite Hills, Wyoming (Kuehner and others, 1981), the West Kimberley region, Australia (Wade and Prider, 1939; Jaques and others, 1984; Nixon and others, 1984), southeastern Spain (Venturelli and others, 1984; Nixon and others, 1984), and Holsteinsborg, Greenland (Scott, 1979). As their name implies, ultrapotassic igneous rocks have very high potash contents. They are further distinguished from other alkaline rocks by relatively low soda contents, and because the ratio $K_2O/(Na_2O + K_2O)$ for ultrapotassic rocks does not increase with increasing silica (fig. 6). In this way, Mountain Pass alkaline rocks are distinct from the sodic alkaline rocks typically associated with carbonatite, such as at Magnet Cove, Arkansas (Erickson and Blade, 1963). With the exception of the rocks from southeastern Spain, most ultrapotassic suites do not include rocks with more than 60% SiO_2. However, the Mountain Pass suite includes granite with more than 75% SiO_2 (table 4).

As in other utrapotassic suites, alumina is low in the mafic alkaline rocks in the Mountain Pass area, but is present in higher amounts in the syenites and granites (table 4). On the basis of Mg number, magnesia in Mountain Pass alkaline rocks is similar to other ultrapotassic suites, with the exception of the southeastern Spain suite (fig. 6). Mountain Pass rocks have lime and iron oxide contents similar to those in other ultrapotassic suites, but titania is relatively low.

BaO, a trace component in most igneous rocks, exceeds 0.5% in many ultrapotassic rocks. It is listed as a major oxide because it generally exceeds MnO, and it exceeds Na_2O and P_2O_2 in some cases. The Mountain Pass alkaline rocks have BaO as high as 1.5%; as with other ultrapotassic series, mafic members of the suite have the highest amounts (fig. 7), which is unusual among igneous rock series. REE contents in the Mountain Pass alkaline rocks show a similar trend (fig. 8). Concentrations of both compatible trace elements (e.g. Cr, Ni) and incompatible trace elements (e.g. LREE, Th, Zr), which are typically elevated in ultrapotassic igneous rocks (Foley and others, 1987), are also high in Mountain Pass alkaline rocks (fig. 9, table 4).

Legend for Figures 5–9

■ Leucite Hills	◇ Magnet Cove
▲ West Kimberly	△ Cascade Range
× SE Spain	● Mountain Pass
◆ Holsteinsborg	

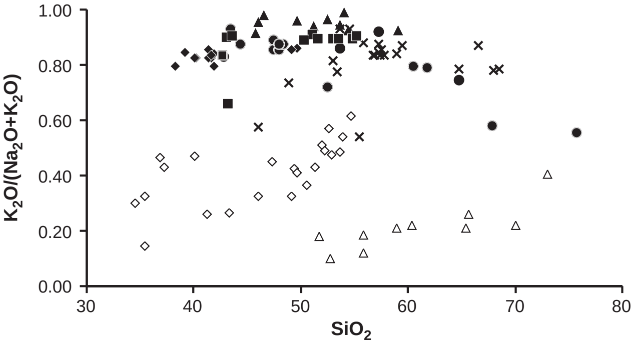

Figure 5. Potash/total alkalis vs. silica in Mountain Pass alkaline rocks compared to classical ultrapotassic suites, Magnet Cove alkaline rocks, and Cascade Range igneous rocks. Data for suites other than Mountain Pass are from Erickson and Blade (1963), Jaques and others (1984), Kuehner and others (1981), McBirney (1984), Nixon and others (1984), Scott (1979), and Venturelli and others (1984).

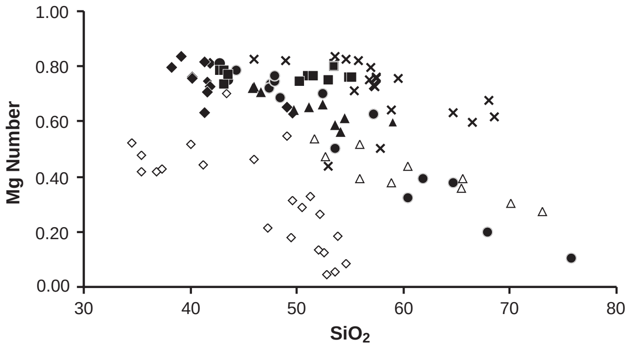

Figure 6. Mg number (atomic Mg/Mg+Fe) vs. silica in Mountain Pass alkaline rocks, classical ultrapotassic suites, Magnet Cove alkaline rocks, and Cascade Range igneous rocks. Data sources as in figure 5.

The carbonatite orebody at Mountain Pass is unusual among large carbonatite bodies because of its extreme REE enrichment. Similarly, ultrapotassic rocks have high REE contents relative to other alkaline rock types. Chondrite-normalized REE distributions for Mountain Pass alkaline rocks are characterized by steep, nearly linear, LREE-dominated curves with nonexistent or insignificant Eu anomalies (Castor, 1991). Such REE distribution patterns are typical for ultrapotassic rocks (Foley and others, 1987).

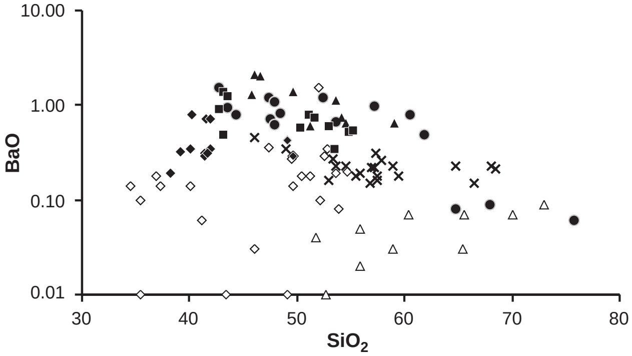

Figure 7. Barium oxide vs. silica in Mountain Pass alkaline rocks, classical ultrapotassic suites, Magnet Cove alkaline rocks, and Cascade Range igneous rocks. Data sources as in figure 5.

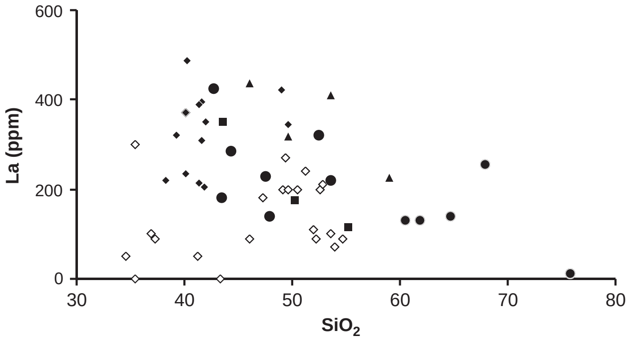

Figure 8. Lanthanum vs. silica in Mountain Pass alkaline rocks, classical ultrapotassic suites, and Magnet Cove alkaline rocks. Data sources as in figure 5.

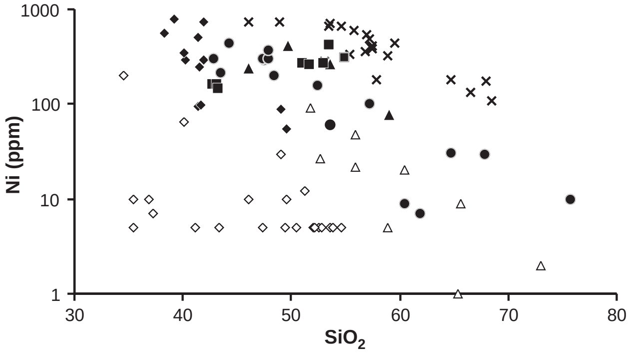

Figure 9. Nickel vs. silica in Mountain Pass alkaline rocks, classical ultrapotassic suites, Magnet Cove alkaline rocks, and Cascade Range rocks. Data sources as in figure 5.

Carbonatites

Carbonatite at Mountain Pass includes the large Sulphide Queen carbonatite and dikes that range from a few millimeters to 3 m thick. Although there is considerable mineralogic and chemical variability, carbonatite in the Sulphide Queen deposit consists mainly of bastnasite-barite-calcite carbonatite (sovite) and bastnasite-barite-dolomite carbonatite (beforsite), or of rock that is intermediate between these two types (bastnasite-barite dolosovite). These rock types generally constitute ore (5% or more REO) and locally contain as much as 25% REO over 2-m drill core intervals. On the basis of surface mapping of the carbonatite, early workers noted that sovite was the dominant type (Olson and others, 1954). However, core drill sampling, mine mapping, and petrologic work by Molycorp geologists showed later that dolomitic carbonatites (beforsite and dolosovite) are more abundant than sovite. Unpublished petrographic work by R.L. Sherer and A.N. Mariano during the late 1970s and early 1980s was particularly instrumental in unravelling carbonatite mineralogical complexity at Mountain Pass.

In addition to the ore types, several other types of carbonatite occur in, and adjacent to, the orebody. These include parisite-barite sovite along with monazite-bearing sovite, dolosovite, and beforsite. The orebody is further complicated by the presence, particularly in the hanging wall, and at its northern and southern ends, of breccia containing variable amounts of carbonatite matrix and altered country rock clasts.

Dikes of carbonatite are common in the vicinity of the Sulphide Queen orebody. They are present, but far less abundant, in a wider area from 1 km northwest of the orebody to 10 km southeast of the orebody. Notable among these dikes is the Birthday vein, which contains coarse calcite, barite, and bastnasite, and may be a carbonatite pegmatite. A silicified carbonatite dike in the same area contains strontianite, galena, and the rare mineral cerite. Although some dikes in the Mountain Pass area contain bastnasite or parisite and as much as 10% REO, most contain minor monazite and about 3% REO.

Carbonatite Mineral Assemblages

Bastnasite-barite sovite—Sovitic carbonation forms the basal part of the orebody, and most of the ore where the carbonatite narrows in the north part of the pit. In the thick, southern part of the orebody, it makes up less than half of the ore thickness. The sovitic ore contains relatively coarse, early-formed bastnasite, along with recrystallized barite phenocrysts, in a matrix of fine-grained calcite and barite. Where unaltered, it is pink to mottled white and reddish brown rock that typically contains about 65% calcite, 25% strontian barite, and 10% bastnasite. However, relative amounts of these three phases vary considerably (table 6), and alteration following magmatic crystallization produced more complex mineral assemblages.

Bastnasite in sovitic ore is typically coarse grained (fig. 10); on the basis of data from 126 samples collected during pit mapping, average bastnasite crystal diameter is about 300 microns. Bastnasite in the sovite generally forms hexagonal prisms strongly elongated along the c crystallographic axis. Parisite, which occurs locally in the sovite, commonly forms fan-like intergrowths with bastnasite (fig. 11). For the most part, monazite occurs sparingly in the sovite, generally as small primary euhedra and patches of radial secondary needles.

Much of the sovitic ore has been altered. Silicification is common; fine-grained, anhedral quartz comprises as much as 60% of the rock locally (table 6), generally as pervasive flooding or stockwork veining. The silicification was mainly at the expense of calcite, although partial replacement of barite and bastnasite also took place. Sovite with weak to severe talc replacement (table 6) occurs in the north part of the pit, mostly as schistose gray-green rock with brick-red barite augens and deformed bastnasite prims. Allanite occurs locally in talc-altered sovite. Other alteration minerals are chlorite, phlogopite, and magnesioriebeckite, which generally occur in xenoliths, but locally in the carbonatite. Strontianite replacement of calcite and strontian barite is

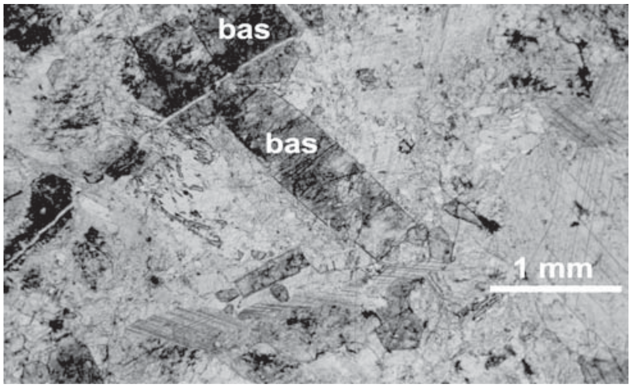

Figure 10. Coarse bastnasite prisms (bas) in sovite, plane polarized light.

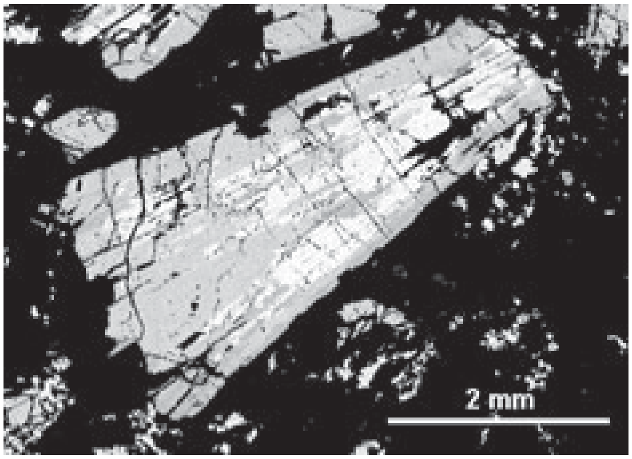

Figure 11. Parisite (gray) with bastnasite (light gray), back-scattered electron image.

Table 6. Major oxide and trace element chemistry of carbonatite samples from Mountain Pass with modes.

	Bastnasite-barite sovite			Silicified bastnasite-barite sovite		Talc-rich bastnasite-barite sovite		Bastnasite-barite beforsite		Bastnasite-barite dolosovite			Monazite carbonatite Beforsite	Monazite carbonatite Dolosovite	Breccia
Sample no.	85-4*	HP 20B*	Q-648	Q-654A	R-772	Q-646	R-735	R-724*	O-822	O-833	R-711	R-744	R-757	R-733	84-6-30
SiO_2	0.40	7.09	12.20	24.60	47.50	13.70	13.50	1.63	2.20	14.10	1.30	1.50	0.50	1.40	30.50
Al_2O_3	0.01	1.29	0.06	0.05	0.16	0.08	0.03	0.01	0.17	0.08	0.02	0.04	0.02	0.03	6.40
Fe_2O_3*	0.24	4.71	0.25	1.30	2.70	2.70	3.20	1.77	1.80	2.40	1.60	4.30	6.60	2.20	8.60
MgO	0.04	0.86	0.22	2.40	0.82	2.80	2.50	6.41	4.70	2.40	1.20	5.30	14.60	8.10	6.60
CaO	21.30	38.04	33.70	9.10	2.40	21.00	17.00	11.73	10.40	22.20	12.70	21.40	26.80	20.10	17.70
Na_2O	0.05	0.06	na	na	na	na	na	0.07	na	na	na	na	na	na	na
K_2O	0.05	0.85	na	na	na	na	na	0.09	na	na	na	na	na	na	na
MnO	0.24	0.18	0.30	0.08	0.41	0.41	0.50	0.45	0.46	0.51	0.38	0.83	1.40	0.52	0.22
TiO_2	0.01	0.10	na	na	na	na	na	0.01	na	na	na	na	na	na	na
P_2O_5	0.04	0.10	0.30	0.26	0.12	1.40	0.48	0.29	0.18	0.30	0.57	0.58	0.34	1.70	1.30
BaO	14.63	5.85	10.00	13.80	17.70	8.80	16.30	25.12	33.10	10.00	22.80	15.10	1.70	19.70	2.40
SrO	14.15	0.14	2.20	13.20	1.40	0.36	5.50	2.49	2.10	7.00	12.00	5.40	2.10	4.70	0.47
CO_2	19.84	21.43	29.70	18.30	5.20	20.90	17.60	18.26	16.90	25.80	20.60	27.20	43.80	25.90	16.90
SO_3	18.26	2.55	3.70	5.50	8.20	4.50	9.30	15.43	17.00	4.10	11.50	8.30	0.80	11.60	1.40
F	0.70	na	na	na	na	na	na	1.40	na	na	na	na	na	na	na
PbO	na	na	0.11	0.25	0.29	0.04	1.64	na	0.01	0.71	0.39	0.02	0.05	0.64	0.02
RE_2O_3	9.89	3.73	3.77	4.94	8.44	13.05	5.45	13.18	6.72	6.51	8.86	6.85	1.24	2.48	1.40
Total	99.85	86.97	96.51	93.78	95.34	89.74	93.00	98.34	95.74	96.11	93.92	96.82	99.95	99.07	93.91
Cr	14	41						27							
Ni	5	12						12							
La	38071							51224							
Ce	37931	28643						50112							
Y	146	650						89							
Zr	5	17						25							
Nb	5	<10						31							
Calcite	55	80	65	20		25	55	7	3	40	1	41	1	27	
Dolomite	0.0	5						51	69	15	8	23	97	34	
Strontianite			1.5	32			5.5			25	46	tr	0.5	3	
Barite	21	0.5	15	25	25	11	11.5	16	18	10	32.5	22		30	
Celestine	11		10												
Bastnasite	12.5	5	5	15	10	10	10	25	5	4.5	7.5	5.5			
Monazite			0.5			3.5	0.5	1	0.5			1.5	1	2.5	
Quartz	0.5		1.5	8	55					1					
Talc						50	15								
Iron oxide		1.5	1.5		10	0.5	2.5		4.5		5	7	0.5	3.5	
Other		8x								4.5c					

* Major oxides and trace elements by ICP-ES analyses at Acme Laboratory, Vancouver, B.C.; F by colorimetric analysis, Nevada Bureau of Mines and Geology Laboratory; RE_2O_3 by calculation from La and Ce. Other samples: major oxides by ICP-ES (except SiO_2 and PbO) at Skyline Laboratories, Tucson, AZ; SiO_2 by gravimetric method, PbO by AA at same lab; RE_2O_3 by XRF analysis from Molycorp Lab, Mountain Pass, Total Fe as Fe_2O_3. Modes by visual estimate; other minerals: x = chloritized xenoliths, fluorite, parisite; c = chlorite, galena

common, and celestine occurs as bladed replacements and overgrowths of strontian barite and as late veins. Iron hydroxide is locally abundant, particularly in silicified ore.

Bastnasite-barite beforsite—Beforsitic ore was only found in the southwestern corner of the pit in the early 1980s, but on lower levels it was found to stretch further to the north along the hanging wall of the orebody. This ore type typically overlies sovitic ore and is separated from it by dolosovite.

The beforsitic ore contains ferroan dolomite as the major carbonate phase. The average mode is about 55% dolomite, 25% barite, 15% bastnasite, and 5 % calcite (table 6). It is light-gray to pale-brown or pale-pinkish-brown rock that contains abundant gray, white, or pale-red to pink barite phenocrysts, commonly as single crystals rather than recrystallized aggregates. Barite-rich zones noted in drill core and during pit mapping may represent cumulates along internal intrusive contacts in the beforsite. The dolomite, which occurs as pale-yellowish-brown to brown rhombs, crystallized after formation of the barite phenocrysts. The dolomite rhombs are set in fine-grained, pale-yellow, interstitial material that consists of bastnasite, calcite, and barite. Along the south wall of the pit, the beforsite contains crude, nearly vertical banding that consists of braided discontinuous veins of late bastnasite+calcite. The texture may have formed by upward streaming of residual REE- and Ca-rich fluids.

Bastnasite in beforsite ore is relatively fine grained (fig. 12), with an average crystal diameter of 87 microns (based on data from 118 specimens) and occurs as stubby hexagonal prisms weakly elongated along the c axis. Monazite content of the beforsite ore is variable, but locally is as much as 5% and occurs as irregular late veinlets (fig. 13) with microcrystalline granular to radiating acicular texture (“bone” monazite). Rare parisite occurs as intergrowths with bastnasite. Sahamalite and synchisite are REE minerals thought to have originated as secondary phases in the beforsite.

Most of the beforsite is unaltered. Locally it contains minor amounts of quartz, in places as discrete poikilitic crystals as much as 1.5 mm in diameter, some of which are dipyramidal euhedra, indicating high-temperature origin. A few irregular masses of greasy gray quartz to 30 cm across were noted in the beforsite during pit mapping. Dark brown limonitic alteration occurs in places in the beforsite, particularly along faults and in brecciated zones, and commonly as pseudomorphs after dolomite rhombs.

Bastnasite-barite dolosovite—Dolomitic sovite (dolosovite) ore occurs in a 30- to 60-m-wide zone between the sovitic and beforsitic ore types. It contains both dolomite and calcite in variable amounts, and the carbonate minerals show evidence of secondary redistribution such as calcite veining and dolomitization. Dolosovite is generally limonitic, commonly as dark brown pseudomorphs after dolomite rhombs. Barite phenocrysts are typically white to pink and recrystallized. Some dolosovite contains coarse bastnasite as in the sovite, and some has fine-grained, late beforsite-style bastnasite. On grain-size distribution maps, a line drawn between coarse bastnasite average sizes (over 150 microns), and fine average sizes (under 150 microns) roughly bisects the dolosovite zone. The bastnasite in dolosovite is generally yellowish brown or brown, rather than the paler colors seen in the other ore types.

Dolosovite ore has high strontianite contents, particularly in rock with coarse bastnasite. It is also locally rich in fine-grained, anhedral silica. It rarely contains talc. “Black ore,” which is dark-brown, earthy, and commonly porous material with abundant white calcite veins, is mainly restricted to the dolosovite. It locally contains extremely high bastnasite contents due to calcite and dolomite removal. Although REE minerals other than bastnasite are common in dolosovite, they mostly occur in minor amounts. “Bone” monazite is more abundant than primary monazite. Synchisite occurs as a partial replacement of bastnasite, and secondary sahamalite and ancylite have also been identified. These minerals generally occur with secondary calcite.

We consider the dolosovite to be a hybrid rock, not a separate intrusive type. It probably formed by carbonate redistribution during and after intrusion of the beforsite. On the basis of bastnasite grain size (the most reliable way to differentiate beforsite and sovite ore in the absence of original carbonate mineralogy) some dolosovite was originally sovite and some beforsite.

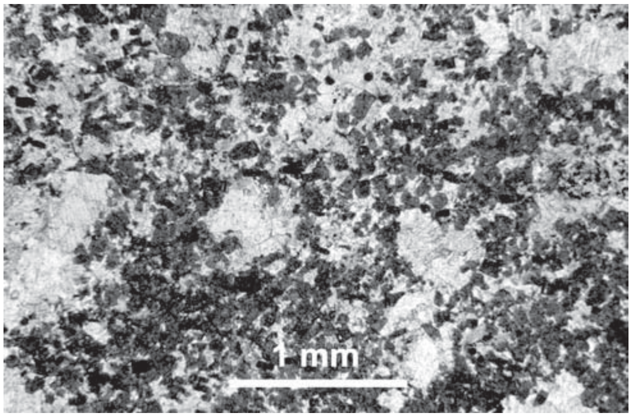

Figure 12. Fine bastnasite (dark colored grains) in beforsite, plane polarized light.

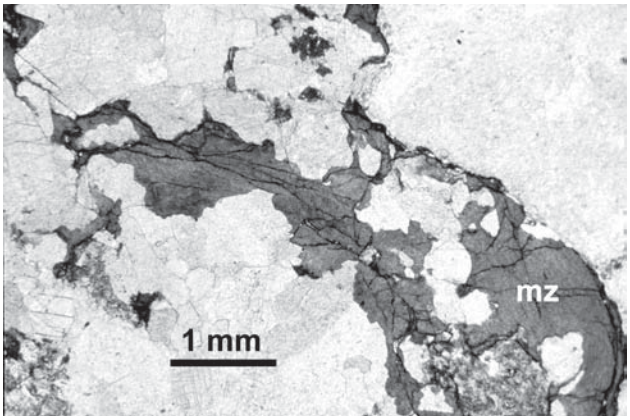

Figure 13. “Bone” monazite (mz) in beforsite, plane-polarized light.

White bastnasite-barite sovite—Relatively small amounts of white sovite ore occur in the southwest part of the pit where it forms a sheet-like mass as much as 25 m thick above beforsitic ore. It contains no dolomite but it differs from the basal sovite in that it contains fine-grained late bastnasite, single-crystal barite phenocrysts, and "bone" monazite like the beforsite. This minor ore type, which has very high bastnasite contents, may be the product of late-stage calcitization of the beforsite by rising residual fluids responsible for late bastnasite and calcite deposition in the underlying beforsite.

Parisite-barite sovite—Parisite is present in some of the ore as a minor mineral. However, parisite sovite with little or no bastnasite was reported by R.L. Sherer (unpub. data, 1979) as a thin, sheet-like intrusion below the orebody in the south wall of the pit. This intrusion, which was subsequently intersected by drilling in the mid 1980s, contains about 20% of flow-oriented, pale-green parisite, distinguished petrographically as hexagonal plates with the shortest dimension along the c axis. Parisite also occurs abundantly as coarse greenish plates in carbonatite on the Windy claim about 20 km southeast of the Sulphide Queen orebody. Because parisite contains less REE than bastnasite (table 3), it lowers concentrate grade and is not considered an ore mineral.

Monazite-bearing carbonatites—Carbonatite that contains monazite in amounts that approach or exceed bastnasite occurs in and adjacent to the Sulphide Queen orebody. In addition, monazitic sovite comprises many carbonatite dikes in the vicinity of the orebody. Monazite is not taken into solution during REE extraction at Mountain Pass, and the effect of adding rock with significant amounts of monazite to mill feed is therefore deleterious.

Monazite sovites and beforsites both occur at Mountain Pass, but nearly all of the monazitic carbonatite in the ore body is dolosovite constituting a mass about 20 m across in the hanging wall and significant amounts at the north and south ends of the orebody. In hand specimen, the monazite carbonatite is generally equigranular because barite phenocrysts are sparse or lacking. The monazite occurs predominantly as primary crystals, although "bone" monazite is present in some samples. Where present, bastnasite occurs as sparse corroded grains, possibly xenocrysts, that are generally in coarse sizes similar to bastnasite in the sovite.

Most of the monazite carbonatite is associated with breccia, and it commonly contains small phlogopite-rich clasts. At the north and south ends of the pit, it occurs around breccia; and in the hanging wall of the orebody, it locally contains abundant xenoliths of country rock. Its distribution in and adjacent to the orebody, association with breccia, and the general lack of barite and bastnasite phenocrysts suggest that the monazite carbonatite formed from magma pressed out of adjacent breccia.

Breccia—Breccia with fenitized country rock clasts and carbonatite matrix comprises significant amounts of the Sulphide Queen carbonatite. It occurs abundantly at the north and south ends of the pit. In the hanging wall of the orebody, it ranges from a stockwork of randomly oriented to sheeted dikes in altered gneiss, through clast-supported breccia, to matrix-supported breccia that grades into monazitic carbonatite. In places it seems to have formed in situ, by intrusive stoping and injection of carbonatite magma into shattered country rock. However, breccia that occurs locally in sheet-like masses in the orebody may have been emplaced as intrusive breccia. Clasts of country rock in carbonatite are invariably fenitized, giving some the appearance of pink to red syenite with rims of dark phlogopite and(or) chlorite (fig. 14). In the footwall of the orebody, much of the breccia is composed of rounded clasts of gneiss, shonkinite, and syenite in crushed rock matrix with talc, chlorite, and magnesioriebeckite and little or no carbonatite. This breccia was, in part, formed prior to carbonatite intrusion. Breccia in the north part of the pit is strongly altered to talc, which renders clast identification difficult.

Chemistry of the Carbonatites

Carbonatite at Mountain Pass has been characterized as ferrocarbonate on the basis of its high Ba and REE content (Le Bas, 1987). Ferrocarbonatite, which is typified by high Fe and Mn contents (Woolley and Kemp, 1989), occurs as late-stage intrusions in some carbonatite complexes following emplacement of more typical carbonatites that are enriched in P, Nb, Ti, and Si. However, no such early carbonatites are present at Mountain Pass, and although some of the carbonate is relatively iron rich, ferrocarbonatite is rare or not found at Mountain Pass. Instead, most of the carbonatite is chemically calciocarbonatite (sovite), magnesiocarbonatite (beforsite), or intermediate between these two types (dolosovite) (fig. 15). Mountain Pass carbonatite with ferrocarbonatite or near-ferrocarbonatite chemistry has been altered or contaminated by country rock.

Carbonatite chemistry varies widely at Mountain Pass, as might be suspected given the mineralogic variability

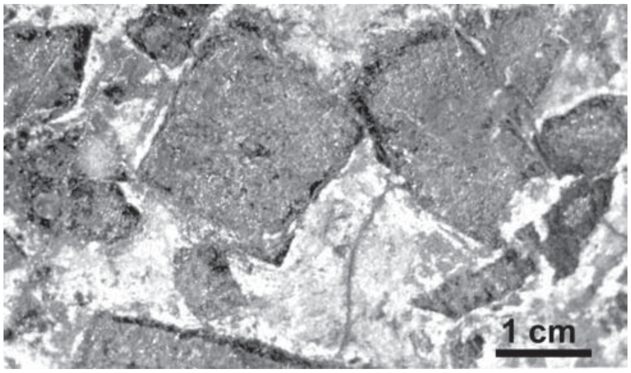

Figure 14. Breccia: clasts of dark fenitized country rock, with dark phlogopitic rims, set in light-colored carbonatite.

(table 6). Although individual samples may be highly variable, sovite ore is typically high in CaO, BaO, and SrO, and it has low Fe oxide and MgO. On the basis of data from hundreds of 30-m blast-hole analyses, average REO content is 7%. Sample HP-20B, taken from a bastnasite sovite dike about 2 km southwest of the orebody, has relatively low REO and BaO content, along with high silica and Fe oxide due to the presence of xenoliths.

Beforsite ore typically has relatively high MgO and Fe oxide (table 6), along with relatively low SrO and CaO. Such ore generally has high REO content; blast-hole samples from beforsite in the southwest corner of the pit consistantly contain more than 10% REO, and in some instances more than 15% REO.

Genesis of Mountain Pass Ultrapotassic Rocks and Carbonatite

As noted above, ultrapotassic rocks are distinguished from other, more common, alkaline rocks using mineral and chemical parameters. On the basis of their chemistry, mafic alkaline rocks at Mountain Pass fall into the Group I (Foley and others, 1987) or lamproitic (Bergman, 1987) subclass of ultrapotassic igneous rocks. The origin of southeastern California ultrapotassic rocks is inferred to be similar to that proposed for such rocks.

Theories about ultrapotassic rock origin have evolved from early proposals of magma contamination or fractionation in the crust to more recent ideas involving partial mantle melts and(or) mantle metasomatism (Sahama, 1974; Foley and others, 1987; Bergman, 1987).

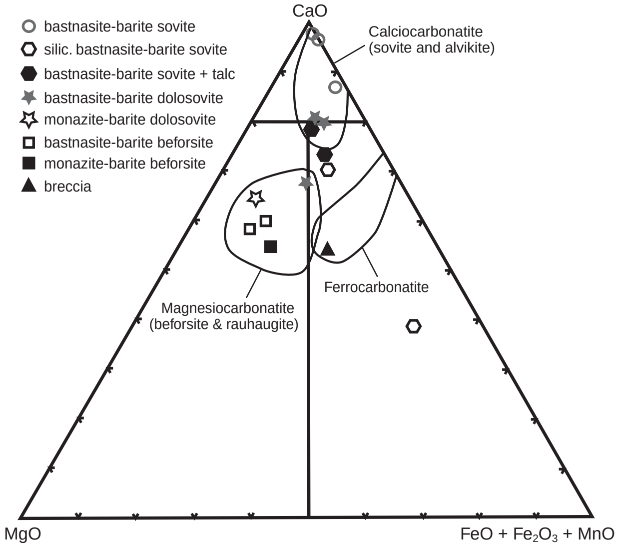

Figure 15. Chemistry of Mountain Pass carbonatites compared with fields that represent the three carbonatite classes. Carbonatite class fields represent the densest accumulations of calciocarbonatite, magnesiocarbonatite, and ferrocarbonatite plots from Woolley and Kempe (1989); however, many carbonatite analyses fall outside these fields.

Assimilation of crustal material is not now considered a major factor in the genesis of ultrapotassic rocks (Foley and others,1987). The chemistry of ultrapotassic rocks is unique when compared with other, more-abundant rock types thought to originate in the mantle, and it has been cited as evidence of zone-melting in the mantle (Harris, 1957) or less than 1% partial melting of primitive deep mantle (Kay and Gast, 1973). Other proposals entail partial melting of metasomatized mantle (Nixon and others, 1984; Jaques and others, 1984), or mantle contamination by subducted crustal rocks (Venturelli and others, 1984). Ultramafic xenoliths found in ultrapotassic occurrences have been cited as direct evidence of mantle derivation (Foley and others, 1987), but such xenoliths have not been found in the southeastern California ultrapotassic rocks. Bergman (1987) cited other evidence for mantle derivation of ultrapotassic rocks, including calculated crystallization pressures and temperatures, and the presence of diamonds in some lamproite.

Features unique to Mountain Pass ultrapotassic rocks, when compared with other ultrapotassic series, are the presence of more felsic rocks and the association of carbonatite. Relatively high silica in felsic members of the ultrapotassic suite may be due to crystallization of leucite and extended fractionation in a plutonic environment. Slow crystallization in a plutonic environment offers possibilities for crystal-liquid fractionation such as crystal settling or filter pressing, which would lead to more evolved rocks by removal of mafic phases as mafic cumulates (possibly represented by samples CSH and HP1, table 4). Gleason (1988) considered shonkinite in the Barrel Spring area to be crystal cumulate from an intermediate magma, whereas Crow (1984) proposed that the shonkinite at Mountain Pass represents parental mantle-derived magma that gave rise to offspring syenitic magmas.

Plutonic textures exhibited by relatively large masses of ultrapotassic rock in the Mountain Pass area suggest relatively deep emplacement. Experimental work on Leucite Hills, Wyoming, rocks shows that leucite is unstable above 1 kbar PH_2O (Barton and Hamilton, 1978), and the occurrence of pseudoleucite in melasyenite with plutonic texture from the Mountain Pass area indicates emplacement at depths near the maximum for leucite stability (2 to 3 km).

The elevated silica and association of carbonatite at Mountain Pass may be due to the more thoroughly evolved nature of the alkaline series relative to other ultrapotassic suites. Separation of alkaline silicate and carbonatite magmas due to liquid immiscibility at late stages of crystallization of alkaline magmas (Kogarko and others, 1979) could account for this association. However, compelling evidence for liquid immiscibility such as that found in kimberlites (Wyllie, 1978) has not been found in Mountain Pass rocks. Mafic alkaline rocks (shonkinite and melasyenite) at Mountain Pass crystallized from magma with high Ca, Ba, F, and LREE contents, and therefore this magma is a likely candidate for the separation of a Mountain Pass-type carbonatite fluid.

The Mountain Pass ultrapotassic suite shows a general progression in intrusive sequence from shonkinite to granite that could have resulted from intrusion of mafic magma into the crust followed by more-or-less in-situ differentiation to more felsic magmas. However, late melasyenite dikes that locally crosscut felsic rocks indicate renewed intrusion of mafic magma. Based on detailed geologic mapping and evidence of intrusive sequence, Watson and others (1974) proposed that Mountain Pass intrusions came from more than one differentiating source. Petrogenetic modelling based on REE contents led Crow (1984) to propose a separate origin for granite than for shonkinite and syenite at Mountain Pass. However, high contents of elements such as Cr, Ni, and Zn in Mountain Pass granites (table 4) relative to most other granites, indicate that they are closely related to the mafic alkaline rocks at Mountain Pass.

Although carbonatite at Mountain Pass shares some chemical characteristics with other carbonatites, it is uniquely enriched in certain elements (Ba and REE) and relatively low in others (particularly P, Nb, and Fe). It is noteworthy that the Mountain Pass carbonatite is highly enriched in elements that are also inordinately abundant in the associated ultrapotassic rocks. Bastnasite, the most abundant REE mineral in the carbonatite, is of primary igneous origin, a feature that is generally not shared with other carbonatites (Mariano, 1989). Furthermore, the geometry of Mountain Pass carbonatite intrusions is similar to the associated ultrapotassic plutons; both occurring as moderately dipping, sill-like intrusions or as steeply dipping dikes. It is likely that Mountain Pass carbonatite is genetically related to the associated ultrapotassic rocks. If the origin of the carbonatite is related to processes that also gave rise to the ultrapotassic magmatism, a parent magma similar to that which typically produces carbonatites in nephelinitic complexes, as proposed by Jones and Wyllie (1983), is not necessary.

The relationship between the southeastern California ultrapotassic rocks and coeval anorogenic granitic rocks in the southwestern U.S. is unclear. The ultrapotassic suite has some chemical affinities with the anorogenic granites, particularly those at Gold Butte, Nevada, and the Hualapai Mountains, Arizona, which have high K, Ba, F, and REE (Volborth, 1962; Kwok, 1987; Anderson, 1989). However, Middle Proterozoic anorogenic granites are relatively aluminum rich (some are peraluminous), only marginally alkaline, and have REE distributions with large negative Eu anomalies (Anderson, 1983), suggesting genesis that is very different from that of the ultrapotassic rocks. Most of the data indicate that the anorogenic granites are of crustal origin (Anderson, 1989), although they are associated with probable mantle-derived products such as anorthosite (Emslie, 1978). The abundance of felsic rock types in the Mountain Pass suite in comparison to other ultrapotassic suites suggests mixing of mantle-derived ultrapotassic magma with crustally derived granitic magma. It is possible that both the anorogenic granite and ultrapotassic series were produced by a single extended Middle Proterozoic thermal episode originating in the mantle. Mantle upwelling under a thick supercontinent has been postulated to account for the Middle Proterozoic anorogenic magmatism (Hoffman, 1989; Anderson, 1989); and mantle metasomatism, which is considered necessary for ultrapotassic magmatism, is thought to occur under relatively thick continental crust (Foley and others, 1987).

Restriction of the southeastern California ultrapotassic rocks to a narrow northerly zone was probably due to local deep-seated crustal rupturing within the northeast-trending anorogenic magmatic belt. In this regard, the time of emplacement of the ultrapotassic rocks may be significant; it is approximately equivalent to the age postulated for the opening of Middle Proterozoic basins (e.g., the Belt basin in the northwestern United States, Obradovich and others, 1984). The zone of ultrapotassic rocks in southeastern California is inboard, but near and roughly parallel to, the western boundary of the North American Precambrian continent (Kistler, 1990), which is thought to have separated from the Siberian platform (Piper, 1983) during a much later event (0.6 Ga). Middle Proterozoic ultrapotassic magmatism in southeastern California may have been associated with rifting that was not consummated in continental breakup until later.

Regardless of their origin, the carbonatite and ultrapotassic rocks at Mountain Pass constitute a unique occurrence. If other REE orebodies like the Sulphide Queen carbonatite occur globally, they are probably associated with ultrapotassic igneous rocks.

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Discovery of Jadeite in Guatemala

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In 2001 local prospectors discovered a new occurrence of green and greenish blue jadeite south of the Motagua River Valley (fig. 1) about 80 km northeast of Guatemala City. All of the jade deposits known in Guatemala are found within the Motagua fault zone, an east-trending, seismically active, structural boundary between the North American and Caribbean tectonic plates (fig. 2). Along and adjacent to this zone, numerous sheared serpentinite bodies are present in an area 10 to 40 km wide and 100 km long (fig. 3). Jadeite occurs within the serpentinites as veins, lenses, and pods a few meters wide and up to tens, or even hundreds, of meters long. These primary jadeite bodies are the sources of the large alluvial jadeite boulders (fig. 4) found throughout the region. The jadeite is thought to have crystallized directly from a hydrous fluid at pressures of 5–12 kbar and temperatures of 200°–450°C (Harlow, 1994; Johnson and Harlow, 1999). Jadeite forms as vein-like pods within larger bodies of blueschist and eclogite. Protoliths for the blueschist and eclogite are graywacke and basalt/gabbro respectively. Both of these rocks were once part of the oceanic crust.

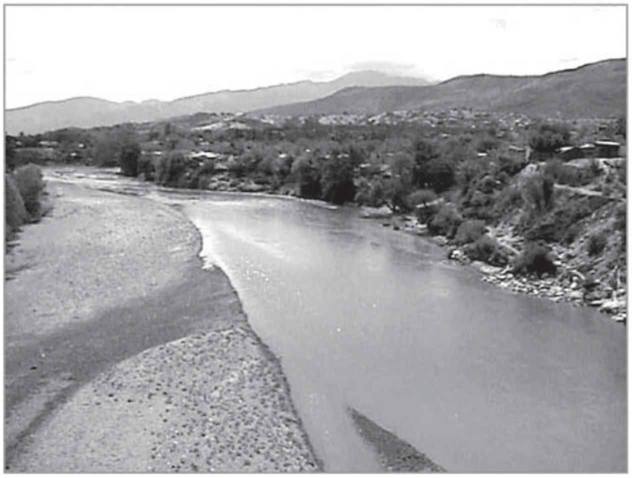

Figure 1. Motagua River Valley looking east.

The recent finds of green jadeite in Guatemala are similar to the type of stone associated with royalty in the Olmec culture more than 2,000 years ago. This beautiful deep-green material is described as "Olmec Imperial" jadeite. A different material found for the first time in the field and not described in the archaeological record is termed "New Blue" jadeite.

Production of both the Olmec Imperial and the New Blue jadeite by the local jade prospectors has historically been only from creek beds and alluvial terrace deposits downstream of the giant boulders. The local jade hunters sell most of their rough to the several jewelry manufacturers

Figure 2. Location and tectonic map of Guatemala and the Caribbean basin. (Map courtesy of George E. Harlow, American Museum of Natural History, New York.)

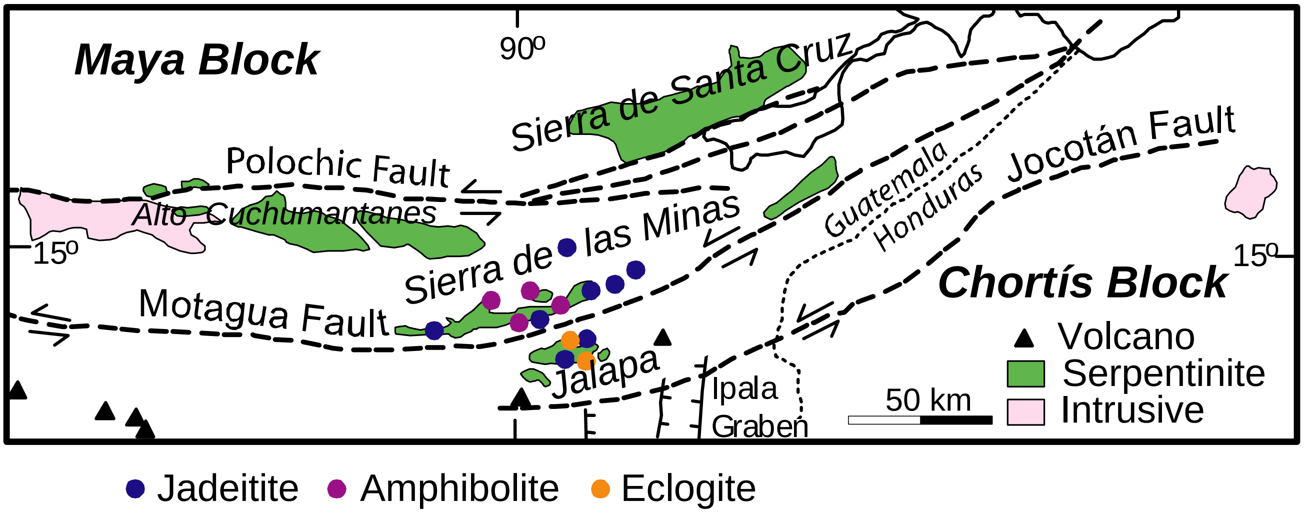

Figure 3. Tectonic map of the Motagua valley. (Map courtesy of George E. Harlow.)

in Antigua, Guatemala. These manufacturers sell almost all of their jewelry to the local tourist trade.

Ventana Mining Company has been awarded several mining concessions in Guatemala. Ventana intends to quarry the jadeite, and to manufacture and sell both fine jadeite jewelry and jadeite tile and dimension stone. Jadeite dimension stone is a completely new product.

The physical properties of jadeite with respect to its application as a polished dimension stone are truly extraordinary. Jadeite has a compressive strength of 54,000 psi, twice the average strength of granite. Sierra Testing Labs reported that the jadeite samples Ventana submitted had the highest compressive strength of any rock material that lab had ever tested, and that the samples dented and deformed the stainless steel platens which held the samples in the hydraulic press. The jadeite sample Ventana tested had flexural strength of 7,450 psi, more than twice the flexural strength of the average granite. It had an abrasion resistance number of 0.02% in the test of abrasion resistance to foot traffic. This means that only 0.02% of the jadeite was abraded away during the test. In comparison, 12% of the average marble is lost by abrasion in the same test, indicating that jadeite is roughly 600 times more abrasion resistant than marble. Jadeite tile and polished slabs are clearly more scratch, chip, and heat resistant than any other dimension stone on the market today.

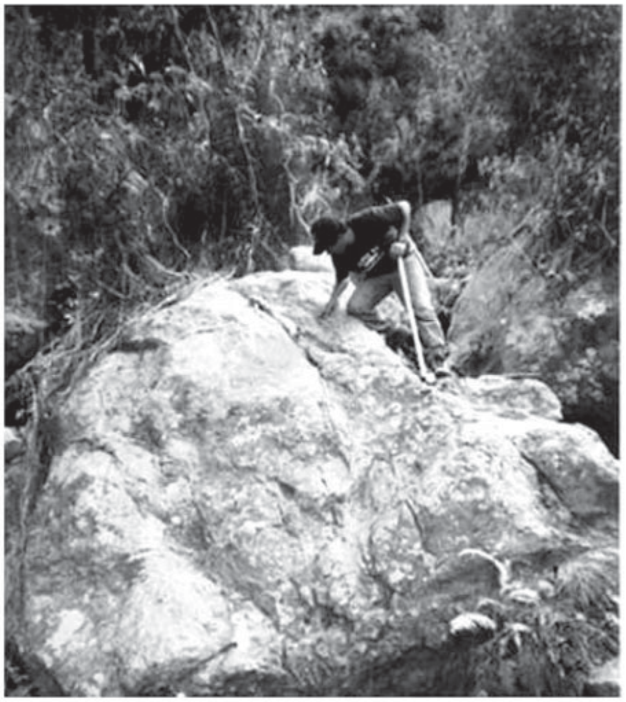

Figure 4. Carlos Gonzales on newly discovered 340-ton Guatamalan jadeite boulder.

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2000 Years of History—What Future for Ball Clay Extraction in the UK?

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"In these days we are less sure of ourselves—we fear the rising tide of change and seek to preserve for ever, or at least for the foreseeable future, a particular stage in a natural evolution." Man and the Land, Dudley Stamp, 1953.

"Our aim should not be a landscape frozen in time-important wetland sites came from mineral workings." A Better Quality of Life: A Strategy for Sustainable Development for the UK, Department for the Environment, Transport and the Regions, 1999.

"All the heath purples, browns and greens had merged in a uniform dress without airiness or graduation." The Return of the Native, Thomas Hardy, 1878

Introduction

The title of this paper raises a somewhat rhetorical question. As the paper will describe, the commercial future for UK ball clays[1] is assured as the resources are present and economically workable, the technical quality of the material is demonstrable, and the resource is relatively unique in the world. Demand for UK ball clay, particularly for its use in sanitaryware, a significant area of growth if sanitation is to be improved throughout the world, remains strong and on general trends looks to grow. As a world-class resource, there should be no question as to the future.

However, what is not assured, and can only be speculated at present, is the extent to which demand for clay from all the productive basins in the UK can be satisfied given the apparent severe and irresolvable constraints imposed by other resource management considerations, notably the stringent considerations relating to wildlife and habitat conservation and the protection of landscape quality. These two factors are intimately related because the perceived landscape quality flows mainly from the vegetation cover.

Economic resources of UK ball clay are located entirely in three small Palaeogene basins in southwest England, the Bovey and Petrockstowe Basins in Devon, and the Wareham Basin in Dorset. Ball clay has been extracted in at least the Wareham Basin for use in ceramics for over 2000 years. Current production is at an all time high of over 1 million metric tons per year, of which 83% is exported, principally to Western Europe where the plasticity, high white firing, and rheological properties of the UK clays are sought. While the UK would not normally be considered as a major mineral producer, it contains a world-class resource in ball clay, which is of international value and significance.

While the clay from each basin may have particular attributes, blending of clays creates what is in effect a single interrelated resource. However, as the resource development issues in the three producing basins are different and complex, this paper will concentrate on the Wareham Basin where constraints and conflict appear to be most severe and polarised.

The Wareham Basin

The Wareham Basin is a low-lying undulating area underlain by a sequence of sands and clays with overlying alluvial gravels surrounded by the chalk uplands of the Dorset Downs. Four of the clays host discontinuous deposits of ball clay and are worked for that mineral. The sands and the gravels are worked for aggregate and industrial sand. The most valuable and productive ball clays are generally thicker, more extensive, and of better quality in the southern part of the area. The host clays and the contained ball clays feather out to the north and west. The host clays thicken to the east but the clay quality deteriorates.

The sands, gravels, and clays mainly give rise to neutral to acidic soils with acidic mires and bogs with peat in enclosed shallow drainage basins. However, major river valleys that rise in the chalk uplands beyond the basin, and loess type deposits on gravels can produce calcareous and highly productive soils.

The vegetation cover on the neutral to acidic soils in this area consists of a mixture of oak woodlands, extensive areas of conifers, marginal agricultural land, but also large areas of 'heathland.' The conifers were originally planted (mainly on the heathland because it was the poorest of the low productivity agricultural land) for national 'strategic' reasons after World War I to ensure a supply of pit props for underground coal mines.

That now produces the perverse situation that a former national objective (now effectively defunct) constrains directly an international objective in nature conservation. A significant knock on effect is that the remaining area of heathland is less and is considered to be under threat. It is therefore considered to be desirable to protect that remaining heathland from development, which objective then seriously inhibits the international resource consideration in the supply of ball clay.

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[1] The term 'ball clay' is derived from the old method of working. The clay was cut into cubes about 9 inches (250 mm) square, with a spade-like tool called a 'tuball.' Because of the plastic nature of the clay, these cubes became rounded and assumed a ball shape during handling. Clay was traded by the 'ball' until universal acceptance of tons with the introduction of weights and measures; hence the name became widely used and is now universally accepted as a description for plastic kaolinitic clays.

'Heathland,' or 'the heath,' is a term describing both a habitat and a landscape predominantly composed of heathers, a low-growing ericaceous shrub, with associated flora. The heathland habitat includes a range of types varying from valley mires to dry hilltop heath and includes associated wetlands. Heathland supports a range of fauna that benefits from the particular characteristics of the vegetation. The Wareham Basin adjoins the sea and benefits from a relatively mild maritime climate and low levels of atmospheric pollution. This has helped to maintain perhaps the most equitable climate in the UK providing for a range of species in the Basin, that is otherwise rare in the UK. That has lead to many sites within the basin being designated as Ramsar sites, being areas of global nature conservation significance, or being designated as Special Areas of Conservation or Special Protection Ares in accordance with European Directives due to their European nature conservation importance. Many sites are covered by all three designations.

'Heathland' also describes a land-use practice. The heath, at its largest extent, was never a natural feature, but was an area of 'extensive' agriculture practice (developed over 3,500 years), which reflected, utilised, and managed (within practical and economic limits) this area of low agricultural productivity as an adjunct to more productive land. Much of the heath was managed as common land (wherein specific rights of 'commoners' existed to, for example, cut peat or turf as fuel, cut gorse or 'furze' for animal feed, let stock loose to graze, etc). Many of these practices gradually declined during the late nineteenth century as the heath depopulated to more urban areas. The extent of the heath was and is therefore an anthropomorphic aberration related to social and economic conditions at a moment in time.

However, the landscape of the basin contrasts dramatically with the intensively managed surrounding Chalk hills and the typical farming landscape of lowland England. It conveys a sense of 'wildscape' otherwise missing from lowland England and the colours and vistas portray a less ordered and a more sombre aspect. For these reasons the landscape itself is valued nationally and part of the basin has been designated as an Area of Outstanding Natural Beauty (AONB) as it is perceived as a landscape of national importance.

The heath landscape has become an important cultural element, both actually and metaphorically, via the novels of Thomas Hardy. Hardy set a number of his novels in or adjacent to the heath and transferred the dour and 'unmanaged' landscape into the characters populating his novels. Perhaps more than any other locality in the UK, this cultural significance is strongly identifiable. This relationship has, however, become self-enforcing as more readers seek to understand this character and seek to find a landscape that only existed as described by Hardy in his novels. This has unfortunately created a false view of the extent, form, and permanence of the heath.

Unfortunately, a significant proportion of the ball clay resource in the basin is overlain by both the nature conservation and landscape designations. This has led to the adoption of a policy position severely inhibiting the extraction of ball clay. We therefore seem to have a situation where two international resource considerations are in direct and apparently severe conflict. The perceived prospect is that protection of one would harm the other.

Indeed, some have concluded that the restraints are so severe in themselves and in relation to 'sustainability' considerations, because of the presumed and perceived irretrievable harm that mineral extraction would cause to habitat, species, and landscape, that conservation of habitat, species, and landscape should have primacy over provision of ball clay. In response to this perceived potential for harm there is an underlying theme of land use planning policies within the basin with an objective that would preclude access to the most productive areas and those deposits of greatest value.

Such a policy objective may cause significant limitations on production from the Wareham Basin in the future. However, is such a policy conclusion justified? Has the extent of the conflict been heightened, inadvertently, by over-enthusiastic, perhaps unbalanced adoption of conservation needs and legislation? Has uncertainty about the impacts of habitat or landscape change created an attitude in regulators and environmental agencies that cannot accept or risk change? Is policy overtly restrictive so as to prevent any risk of harm, or to prevent a regulatory agency apparently condoning action that might risk harm? Is it easier, although perhaps unjustified, for regulatory and environmental agencies to adopt a seemingly sustainable 'correct' policy to prevent development, when it might be possible, although difficult and contentious, to achieve what might more truly be a sustainable solution? Finally is this policy stance a reflection of substantive environmental and economic objectives?

These issues are considered below. The description of the current state of play presented by the authors flows partly from their contributions to a recent research project funded by the UK government on the Wareham Basin and their extensive involvement in the subject and other mineral issues throughout the UK over the last 30 years. The paper cannot describe in depth the matters under consideration or the details of the regulatory process. However, it is hoped that it presents an adequate overview of the situation. The paper and its conclusions are the views of the authors.

Mineral Planning in the UK

"Mineral planning is to me a question of balance. —As far as possible we must avoid damaging or destroying our most sensitive and treasured places and landscapes. We must ensure that we only extract material that is essential and for which there is no alternative."

Nick Raynsford MP, Minister of Planning, Housing and Construction, Department of the Environment, *Transport and the Regions. Opening Address to the 2nd European Conference on Mineral Planning, Harrogate, UK 1999.*

Since 1948 the UK has operated what must be one of the most comprehensive and rigorous land use planning systems in the world. The system is primarily enacted through the town and country planning legislation (and subsidiary legislation and guidance), within which a number of discretionary opportunities exist, but with significant input from associated legislation.

The fundamental objective of the legislation is to regulate the use of land 'in the public interest.' The 'public interest' is a vague term and concept, but in the context of a planning process that is 'discretionary,' this term is of necessity vague to allow discretion in policy and decisions. One aspect is clear, however, and that is that the public interest of land regulation is not, and never can or should be, the interest of one sector of society but has to be a balance of the needs and demands of all relevant interests.

Regulation of the use of land means that all 'development' requires 'permission' from the relevant planning authority, unless it has been defined as 'permitted development' by statute. 'Development' includes change of use of land, structural development, and engineering operations.

Mineral extraction is an 'engineering operation' and, while forestry and farming as a land use were excluded from planning control, mineral extraction was made subject to planning control. However, mineral extraction has long been recognised as having special characteristics. The primary difference is that most other development has a short construction stage followed by a long period of no change in use. Mineral development is effectively only a temporary 'construction' stage, generally over a specific short period, before the land is restored to another use.

There is a second significant difference in that minerals can only be extracted from locations where they are found in economically workable concentrations. They can only be worked where they occur. Society, and therefore the planning process, cannot move or relocate mineral deposits to those areas where extraction would be more acceptable. This is clearly different from the considerations that relate to urban and infrastructure development where many options for location exist. It is also different from many other resource management decisions where alternatives can be provided. For example, forestry can be relocated; agricultural land can be moved, created and improved; groundwater recharge can create new water resources; and wildlife habitat can be moved and increased in quality. Indeed, all these resources can be moved, expanded, or contracted over a relatively short timeframe to reflect changing economic, environmental, or social objectives. Mineral deposits can expand or contract only due to economic conditions (setting aside their sterilisation) and cannot be moved.

Due to the above considerations mineral development may not fit easily into the planning process. However, despite various reviews over the years mineral extraction is still subject to the main planning legislation.

There is no doubt that planning legislation was and is needed. The UK is one of the most densely populated nations and therefore a procedure that provides for the most rational use of resources, commensurate with social and economic objectives was, and remains, essential. The process has been described as being 'a sort of benevolent despotism' and, if it is used as a means to an end and not as an end in itself, it will be acceptable and serve a useful purpose.

The planning process has had to adapt to the changing pressures on resources and the changing objectives of society, otherwise it would have become irrelevant or, worse still, it would harm that which it supposedly seeks to protect. That said, the planning process should not adopt the latest fashion or the desires of special interest groups unless those also serve the public interest.

The planning process in the UK is described as being 'plan-led.' This means that all decisions on development proposals are generally determined in accordance with statutory 'development plans.' However, as the planning process is also discretionary, a decision is not bound by the 'plan' as other 'material considerations' may be taken into account. Material considerations are not defined in statute but the courts have held that various factors, such as the existence of up-to-date or relevant policies, can be material considerations.

The planning process in the UK is a local process. It is the responsibility of local planning authorities acting in accordance with broad national guidelines and the adopted development plan to determine applications. There is provision for applicants to appeal to the Secretary of State and any interested party can seek redress in relation to a decision through the courts.

Sustainability

Sustainability objectives are key concepts that underpin the whole approach of the UK's planning system at both local and national level. The objectives stress the importance of integrated policies in meeting four broad goals that need to be addressed equally:

- Social progress that recognises the needs of everyone,
- Effective protection of the environment,
- Prudent use of natural resources, and
- Maintenance of high and stable levels of economic growth and employment.

Thus economic growth needs to take place in a way that ensures effective protection of the environment and prudent use of resources. But importantly sustainability is not solely the provision of environmental goods but a balance of both environmental and economic goods. Meeting these goals is not easy. It is exceedingly difficult for the planning system to balance proactively the complex provision of environmental and economic objectives when its vision and procedures now heavily lean towards protection and limitation of development.

There is a further substantial element of sustainability, which is of major importance but quite frequently ignored by planning at all levels in the UK. That element requires that the UK consider the application of sustainability objectives and the impact of decisions in a global context. Decisions must take account of implications on the economy and environment of other nations for example so that the UK does not export environmental costs or deprive other nations of material goods necessary for social, health, or economic purposes. Sustainability, therefore, requires us to ensure an adequate provision of minerals to support downstream manufacturing industries in the UK and, where relevant, to industry in other nations dependent upon resources available in the UK. It also requires that more valuable environmental assets in the rest of the world are not harmed just to protect environmental assets of less significance in the UK.

The Development Plan

The development plan for an area defines the desired and acceptable future land use changes for an area and indicates these in policies and on a map. The development plan is prepared by the same local authority responsible for determining applications for development in that area. This may ensure the linkage between a decision on development and the objectives of policy, but the process has a significant element of 'judge and jury,' which is reinforced by the process involved in the preparation of development plans. This is a quasi-judicial process with public involvement overseen, evaluated, and reported on by an independent inspector.

However, while the inspector may recommend amendments to the plan, it is the local authority itself that finally determines what amendments shall be made. The local authority may choose to discard changes suggested by the inspector even where such changes more properly reflect national guidance or requirements in the area. Local authorities, being elected bodies and susceptible to pressure from special interest groups or concerned with maintaining the controlling political party in power, may finalise the content of the plan by rejecting, for example, a proposed mineral working allocation that is in general accordance with central government advice and is recommended by the inspector but is contentious locally.

One of the authors has been involved in such situations a number of times. An applicant may therefore need to submit his application for permission knowing full well that it will be refused (because of noncompliance with the plan) but with the objective of winning consent by an appeal to the Secretary of State, who will then hold a public inquiry into the proposal. In evaluating the application, the decision of the Secretary of State will be influenced first by the policies and allocations in the plan but will then take account of 'material considerations.' If the case is sound, permission will be given.

'All's well that ends well' may be a dispassionate conclusion. However, the cost and delay caused by this process can be substantial to both the public and the private purse with no net benefit to any party. Such a process also harms the faith that the public may have in land use planning.

The statutory requirement is that local planning authorities prepare and adopt the development plan (an 'adopted' plan is one that has completed all statutory processes and is fully operative) to give guidance for a future period of 10 years, review it every 5 years to make such necessary amendments (to provide replacement land, to reflect changes in objectives) and then determine development applications in accordance with the 'plan.'

The first conceptual problem with this approach is the lack of association with the relevant timescales involved in mineral extraction and sustainability. Sustainability objectives strongly indicate a framework of at least 25 years. Any consideration of mineral development issues has a similar timescale, particularly bearing in mind long-term security of supply to manufacturers and restoration issues. Yet while the planning process and participants are required to think in a sustainable manner, the administrative procedures actually prevent compliance with real sustainable timeframes.

Secondly, it has proved almost impossible to comply with the simple short-term concept. Some district local plans (including one that covers one of the ball clay basins) still await adoption after almost 30 years. Mineral local plans are in a similar state. There is no adopted mineral local plan for Devon as yet, and the Dorset mineral plan, while adopted in 1999, only covered the period 1991 to 2001, and is now out of date and has never been reviewed. At the public inquiry into the mineral local plan for Somerset in 2001 (which county adjoins both Devon and Dorset and is a major source of aggregate in the UK), the advocate for the authority opened his case with a long explanation as to why it had taken over 35 years to reach that stage. No substantive reason was produced and we still do not have an adopted plan in place.

Ball Clay in the UK

Ball clays are plastic mainly kaolinitic clays. They are a key component in the manufacture (with kaolin [China clay], fluxes, and quartz) of whiteware ceramics (sanitaryware, tableware, and tiles) due to their cream to white fired colour, rheological properties, plasticity, and strength.

Economic resources of UK ball clay are located entirely in three Palaeogene basins in southwest England. These are the Bovey and Petrockstow Basins of Oligocene age in Devon on the Lustleigh-Sticklepath Fault zone and the Wareham Basin of Eocene age in Dorset. These deposits have many geological parallels with the Kentucky-Tennessee clays and Troup clays of Texas. Ball clays are secondary clays transported from their point of origin and then deposited in fresh or brackish water.

UK ball clays have been worked for over 2000 years. However, the introduction of tobacco from Virginia stimulated a demand for clay pipes in the 17th century for which ball clays were utilised. This inevitably led to a wider awareness amongst 18th century potters of the of unique properties of ball clays leading to the rapid expansion of use during the industrial revolution, particularly with the development of whiteware, earthenwares, and tiles.

Ball Clay Production

With three highly individual resource areas in relative close geographic proximity, UK ball clay resources are an almost unique occurrence worldwide. Each resource has its own highly distinctive characteristics (table 1) resulting in excess of 100 distinct commercial grades suitable for the entire spectrum of ceramic production. Annual production from the three areas is near 1.1 million metric tons.

Technical Properties

Most primary kaolins (China clays) are coarse in particle size, of low plasticity and surface area, due to the ordered crystal structure. However, ball clays, which are secondary clays derived from intense chemical weathering, have a finer particle size and are high in disordered kaolinite. Secondary clays rarely occur in a pure form; therefore most ball clays are primarily a mixture of varying proportions of kaolinite, illite, and quartz, with or without carbonaceous matter and deleterious minerals of iron and titania.

Ball clays are valued in ceramics due to the presence of fine- to very fine-grained kaolin imparting high green strength and plasticity. The important ceramic properties imparted are consistent firing contraction, a white firing nature, and optimum body packing and surface properties.

Operations

Ball clay production in the UK is exclusively controlled by two multinational companies, Sibelco and Imerys under the former company identities, WBB Devon Clays and ECC International with a market share of about 60/40 respectively, although each company has particular strengths according to market. As the three ball clay areas are geographically relatively close (within 120 km), it is possible to use the diversity of clays in each basin to allow for the development of very sophisticated blends, optimising the most versatile ceramic properties and further enhancing the economic importance of UK ball clays to the UK, Europe, and the world. Extraction is exclusively by opencast methods though underground mining has only recently ceased (1999).

Bovey Basin

The Bovey clays are renowned for their use in tableware and sanitaryware, and the Bovey Basin is probably the single largest and most diverse economic ball clay deposit in the world. It is a multi-seam deposit currently worked from 14 open pits. The clays are fine to coarse in particle size with a high content of low- to medium-disorder kaolinite, giving clays of high-fired whiteness with stable rheology and casting performance.

Petrockstowe Basin

Generally described as stoneware clays, the key feature of these clays are fine particle size and high silica content coupled with disordered kaolin, illite, and traces of smectitic clay minerals giving high strength and plasticity mainly valued in sanitaryware and tableware blends.

Wareham Basin

Dorset ball clay is much older than its Devon counterparts and is derived from a diverse suite of country rocks. The deposits are mostly single seam or small multiples of two to four seams. The clays are very fine and comprise highly disordered kaolinite with illite and quartz and are valued for high green strength and plasticity. The clay is used in wall and floor tile, sanitaryware, earthenware, tableware, electrical porcelain, and refractories.

Economic Significance

UK ball clays are used in 50% and 75% respectively of worldwide and European vitreous sanitaryware production. The UK home ceramic industry benefits greatly from having access to a wide range of locally produced clays. UK ball clays are the preferred plastic component for many other ceramic applications principally wall and floor tiles and tableware throughout the world.

Table 1. UK Ball Clay Deposits.

Deposit	Basin Area Waste	Source Rock	Typical Seam	Overburden Interseam	Annual Production	Global Resource Estimate
S. Devon (Bovey Basin)	35 km^2	Granite Shales Sandstones	0.3–5 m	Gravel, Sand Lignite	600,000 t	>50 Mt
N. Devon (Petrockstowe Basin)	8 km^2	Shales Sandstones	0.5–3 m	Sand and Sandy Clays	200,000 t	<10 Mt
Dorset (Wareham Basin)	150 km^2	Clays Limestones Sandstones	1–5 m	Sand Sandy Clays	220,000 t	<10 Mt

t = metric tons Mt = million metric tons

The value of raw material production amounted to £56 million ($84 million) in 2000 with a total downstream benefit to the UK and European economics in the region of £4-5 billion ($7.5 billion, 7.5E billion). Direct and indirect employment in the UK ball clay industry is around 950 jobs but in the ceramic manufacturing industry this figure is 46,000 jobs (in Europe, 70-80,000 jobs). Exports are mainly to Europe but clays are exported worldwide to over 80 countries, where UK clays are used either exclusively or in blends with local clays to impart consistency, stability, and technical versatility, particularly in sanitaryware.

Future Markets

UK ball clays serve a very wide portfolio of ceramic uses. Changes in UK, European, and worldwide ceramic manufacturing have seen a steady growth in sanitaryware usage of clays but a decline in earthenware tableware, refractories, and electrical porcelain. Growth of demand for the wall and floor tile clays has been stimulated by developments in fast-firing tile technology.

The global ceramics industry has been consolidating. In sanitaryware, industry leaders like American Standard (ldeal Standard in Europe), Laufen, Roca, Sanitec, Toto, and a handful of others lead global production of sanitaryware in demanding consistent and technically more versatile clays. UK ball clays are technically well suited to meeting this challenge.

In recent years the proportion of UK ball clay used in the European sanitaryware industry has grown to exceed 75%. This clearly underpins the technical and economic significance of UK ball clays. On a worldwide basis it is UK sanitaryware clays that are used most widely, be it in many cases to provide a stable base to utilise local raw materials.

This technical dependency is founded on the unique nature of the UK ball clays possessing key innate properties of mineralogy, particle size and rheology that cannot be easily replicated elsewhere. The ability of the industry to innovate and use its technical knowledge to provide general and customised products to match particular applications adds to the strengths of the industry and provides manufactures with consistent, competitive products delivering technical performance, efficiency, and low losses necessary to compete in the global marketplace.

The Conflict Issues

As previously noted, the Wareham Basin has an exceptionally high concentration and coverage of statutory national and international nature conservation and landscape designations. The nature conservation designations include Ramsar sites designated as of global importance in accordance with the Ramsar Convention 1971, sites designated as of European importance in accordance with European Directives as Special Areas of Conservation (SACs) or Special Protection Areas (SPAs) and national sites designated as National Nature Reserves or Sites of Special Scientific Interest. The national landscape designations include parts of the Dorset Area of Outstanding Natural Beauty and the Purbeck Heritage Coast. The extent of these areas is shown in table 2.

A significant element of these designations is concentrated in the southern part of the basin where the most productive and valuable ball clay deposits are found, although nature conservation designations are found across the basin. The principal nature conservation interest in these areas is ‘heathland’ and the associated flora and fauna.

Development affecting the international nature conservation designations would only be permitted if the development would not adversely harm the interest of the site, or where there are ‘imperative reasons of overriding public-interest, including those of a social or economic nature’ why it should be permitted and provided there is no more acceptable alternative site. As in the UK context the term ‘public interest’ is not defined, and current case law only reflects ‘social’ requirements of a nation, or the European Union (EU), and not the ‘economic’ considerations of a nation or the EU.

In national nature conservation designations, a proposed development must demonstrate that the social, economic or other environmental benefits of the proposal outweigh any impact on the purposes for which the area was designated.

The primary objective of the national landscape designation (Area of Outstanding Natural Beauty) is the conservation of the landscape. To be permitted a development proposal must demonstrate that it not only conserves the landscape but that it also enhances the landscape.

Heathland

‘Heathland,’ in its broadest sense, describes the whole complex of plant communities which are associated with the poorer sandy soils including areas dominated by *Calluna* and *Erica* species, but also valley mires, pine heath, thickets of *Ulex*, and *Agrostis setacea* and *Molinia* grasslands. The heaths depend on a temperate climate with cool moist summers and warm moist winters.

Topography, which in turn affects hydrology, produces considerable local variation in heath vegetation. There is a clearly marked series of interrelated types. Dry heath develops on freely draining soils above the water table and is typified by podsolic soil development. Humid heath occurs where the water table fluctuates near the surface and drainage is impeded. In wet heath, drainage is impeded and the water

Table 2. Area of selected planning factors within the Wareham Basin.

Designation	Area (hectares)	Percentage
Area of Outstanding Natural Beauty	10,799	33%
Heritage Coast	5,337	16%
Special Area of Conservation	5,289	16%
Special Protection Area	6,291	19%
Ramsar Site	6,345	19%
National Nature Reserve	1,182	4%
Site of Special Scientific Interest	7,158	22%
Extent of Wareham Basin	32,684	

table is very close or even at the surface. Valley mires occur where the water level is at or above the surface, resulting in peat formation.

In the UK, about 58,000 hectares of heathland (in its broadest sense) exists. A national biodiversity action target is to maintain this area and, through restoration and recreation, increase it by 6,000 hectares. A significant justification for protection of heathland is the apparent loss of the habitat over the last 300 years or so. It has been estimated that heathland in Dorset has declined from an estimated 40,000 hectares in the mid-18th century to about 7,000 hectares, mostly due to urban development, forestry, and farming.

This estimate of decline is widely accepted. However, the suggested 40,000 hectares was derived from very basic maps. The area defined includes extensive areas of nutrient-rich soils and probably included a major element of rough grassland, rather than true heath. That figure probably therefore considerably overestimates both the extent of heathland habitat and therefore the past population and distribution of rare species.

Nevertheless, it is clear that the heathland habitat has declined in extent over the last 150 years, particularly from forestry and urban development. In addition, as traditional heathland land use practice has ceased almost everywhere on the heath, some of the remaining heathland has disappeared under the climax vegetation of scrub and trees.

To maintain and conserve the extent of heathland requires active management. In the absence of an economic incentive to continue the former extensive agricultural practice, a considerable amount of public money has been spent on heathland management works by conservation agencies, although without any increase to date in either the quantity or quality of the heathland stock.

It should be noted that the pools, mires, and wet heaths will "degenerate" into drier habitat by natural processes of colonisation. Management of these habitats to preserve their current state will be difficult or impracticable, due to ground conditions and may be unacceptable due to the degree of disturbance involved (it could seriously harm the existing habitat). Therefore, unless some method of creating new areas of ponds and impeded drainage to mimic the past actions of peat digging and drainage works (and bombs dropped by the Luftwaffe in World War II) is adopted, the stock of such habitat will decline.

Perversely perhaps, old mineral workings have by design or adventitiously provided heathland including dry heath and the more scarce humid and wet heaths with small pools and valuable new colonising zones. Virtually all these past workings are now designated as national and international habitat sites. This demonstrates that restoration of clay mineral workings can in time provide real gains in biodiversity.

It is accepted from the outset that there are habitats (such as ponds, peat bogs, and mires) that, because of their historical inadvertent origins, are difficult to engineer in detail or in accordance with a defined plan. However, given a broad enough approach, the conditions suitable for such habitats can be provided. The problem here is that both the conservation agencies and the planning authorities require certainty in schemes and see uncertainty as a risk that cannot be countenanced (or a cynic might say they use the risk of uncertainty to protect a strong position, to prevent innovation, and to maximise the value they receive from their involvement in the management and protection of the habitats and species).

Species

The significance of 'heathland,' in the broadest sense, for conservation of species is stated to relate to the presence of species that are rare. There is no doubt that certain flora and microfauna in the area (such as the Dorset heath [*Erica ciliaris*] and the southern damselfly [*Coenagrion mercuriale*]) appear to be rare and at risk in a UK, a European or a global context. However, appearances may be deceptive. This locality is one where extensive research into the flora and fauna has been undertaken over many decades and therefore, in comparison with other localities both in the UK and Europe, it appears to show a species 'richness' and/or 'uniqueness.'

That may be a distortion due to the level of research in the locality. Whether that 'richness' exists elsewhere is not clear. What also is not clear is the extent to which the level of research has created an 'ownership' attitude to the locality reinforcing, and perhaps distorting, the perception of value by conservation agencies and thereby the strength of the resistance to change.

The macrofauna are key icons for conservation in the locality. Conservation interests commonly draw out the rarity of such fauna, the fragility of their presence, and the volatility of their populations. Reference is also made to the need to maintain large protected areas under management and protected from development to provide the necessary range for these species. The main macrofauna species of interest are reptiles and birds, and the area is the stronghold of a number of species rare elsewhere in the UK. For reptiles the location has perhaps the most benign climate in the UK and clearly is their UK stronghold. Similarly the local climate enables certain bird species to maintain a presence in the UK. However, what we are describing here is not the rarity of species in a global or European context but the rarity of species in a locality because that locality represents the fringe of their range.

Any species on the fringe of its range will be rare, will display relatively significant variation in numbers in the short-term (due to minor variables in climate, disturbance, food, etc) and will appear to be under considerable threat, but that does not equate to rarity itself or a substantive threat to the viability of the species itself. Such a situation should not justify conservation policies that create onerous restrictions on other development.

To properly consider the merits of rigorous species conservation designations in a fringe locality one should assess the global strength of that species in relation to the viability of the populations in the core areas and normally if conservation action is necessary, it should be concentrated in such areas.

Using three examples of the main species of conservation interest in the locality it would appear that the conservation case in the UK has been overemphasised and may primarily reflect concerns of special interest groups and environmental agencies to help to maximise numbers of species, and numbers of each species, for ‘interest’ reasons rather than for substantive conservation reasons.

The Dartford Warbler is the key bird species for conservation in the locality. It is the symbol of the apparent fragility of species in the locality and its success or failure is often linked to the success or failure of conservation policies and the need for action. Currently some 700 pairs, amounting to some 40% of the UK population, breed in the area. In the UK context, the area is of vital importance as it has provided the stock from which the UK population can grow following major death rates due to severe winters. The 1962/63 winter was particularly harsh, leaving only a residual population of some 11 pairs in the UK, 10 of which were based in the basin. However, the world population is over 4.5 million pairs with a strong core of birds in northwestern Spain and western France (the UK population amounts to some 0.00016% of the global population). The species is perhaps always going to be marginal and at risk in the locality from severe weather and, while its presence here may be interesting to ornithologists, that is no substantive conservation justification.

The Mediterranean Gull has a population of only about 30 pairs in the UK, of which the largest concentration is in the basin. However, while rare in the UK, the global population is strong in its core area of the Black Sea with around 300,000 pairs. The global population is rapidly increasing and expanding its range out of the eastern Mediterranean into the Baltic, the North Sea, and the Irish Sea, where it is competing with and hybridising with the Black-headed Gull. It seems difficult to understand why this species should be conserved in the UK when the real objective should be to treat it as an invasive pest. The problem is that the species was ‘rare’ in the European part of its core area and is therefore identified in European conservation legislation as a species in need of protection. One could argue that the European conservation legislation is clearly too blunt an instrument in the context of this and other species, skewing conservation policy in an irrational way and therefore in need of rapid and substantial overhaul.

The Sand Lizard is the primary reptile conservation target in the area, which contains about 90% of the UK population. Debate about the conservation importance of this species draws on the significance of the local population in relation to apparent rarity. However, again the UK lies at the fringe of its range, which stretches from the western seaboard of Europe to Siberia and from Sweden to the Alps, with its core in central Europe. The species is always going to have a fragile existence in the UK due to climatic influences. Subspecies are recognised, including subspecies within the UK. This appears to reflect colouring and marking related to dominant vegetation type rather than any morphological differences. The presence of the Sand Lizard is an ‘interesting’ feature but it is difficult to see that protection in the locality is of major international conservation importance. Increasing or maintaining the presence of this species in the UK should be supported provided such actions do not prevent other objectives. Interestingly the colonising stage of mineral site restoration works provides ideal habitat for the species and Sand Lizard conservationists commonly undertake a degree of flora destruction in their reserves to maximise conditions for the species (bare mineral surfaces, slopes, etc).

In a habitat context one clearly should not reduce the strength of the conservation case by merely looking at individual species: a holistic assessment of the habitat is desirable. Equally, that holistic assessment should properly consider the wider conservation picture.

The Conservation Case

The strength of the conservation case does therefore appear to be flawed for a number of reasons. First, the historical evidence shows no significant harm (and generally shows an enhancement) of these assets following mineral working. Second, the argument of ‘harm’ is substantially based on a dogmatic view (contrary to evidence and designation of old mineral workings) that any mineral development in a protected area must be harmful.

Third, due to human action, the amount of the habitat now in existence is both larger in total extent and larger in size of the individual components than would naturally occur Therefore, protection of manufactured habitat exceeds real conservation justification and is probably driven by the innate objective of ‘specialists’ to seek to maximise the things they perceive to be of value.

Fourth, almost all conservation agencies, both governmental and independent, are unwilling to accept the concept that habitat or landscape quality can be recreated, although the evidence exists on the ground. The justification for this stance, in light of the evidence, has not been explained. However, one can appreciate that a conservation agency will always be wary of accepting that such an apparently complex habitat and ecosystem can be recreated, because such acceptance might then undermine the strength of the case protecting any part of that habitat from development. If the concept of recreation is accepted it may then become difficult for the agency to defend a limit to development such that rejection of the concept supports the status quo and the strength of the conservation designations. The rejection is therefore probably institutionally and administratively embedded. The justification for rejection of recreation is, however, even less understandable given that UK biodiversity objectives, actively promoted and supported by those agencies, provide for a substantial increase in heathland habitat (over what from experience of previous heathland restoration is an unrealistic period). That must imply that heathland can be recreated.

Finally, the conservation case may be flawed because some of the conservation objectives appear to be scientifically unsound, because of flaws in the European legislation itself (or in a blinkered blanket interpretation and application of that legislation) or in the sense that they are not based on the core objectives of species conservation but reflect the not unnatural desires of enthusiasts, such as bird watchers ('twitchers' in the UK parlance) to maximise their interest. Of course, there is nothing wrong in special interest groups expressing their desires, or in society meeting those desires, provided it does not harm other objectives of society and other individuals in society, including the majority who are somewhat detached from the local detail of decisions on ball clay supply, by unjustified costs. We should defend the rights of enthusiasts, but such enthusiasm does not necessarily equate to sound conservation objectives.

Clearly we need to ensure that rare habitat and species and landscapes are conserved and, where possible, we should increase suitable habitat, but 'rarity' in a locality should never be confused with scarcity in the wider environment. We should also seek to assist greater diversity, but not confuse an objective of enhancing the number of species in a locality on the fringe of their viable range as of being equal in merit or effort with more fundamental conservation of species in their heartlands.

Setting aside the strength of the conservation argument or the potential failure of policy and regulation agencies to manage the risk of harm successfully, evidence shows that extraction and habitat/landscape protection can coexist, and indeed that extraction can enhance conservation objectives. In reality, while the conflict between the development of mineral and conservation in the basin has been conceptually serious over the last 50 years or so, the extent of conflict, or rather the more important issues of the extent of actual harm, has been limited to date. Indeed, despite the perceived seriousness of the 'conflict' restored recent mineral excavations have been included in the designated wildlife sites. In one case a restored mineral working was included by the relevant designating agency in a habitat designation only some 10 years after extraction ceased only in the mid 1980s. The agency was unaware of the position when it made the designation.

The Landscape Case

The AONB landscape designation is of national significance but the relevant policy has been prepared by the local planning authority. Currently the planning policy for ball clay in the designation takes the form of a strategy with the long-term objective of moving ball clay extraction from the designated landscape area while maximising resources in the area outside the AONB by improvements in production and beneficiation and by blending. This would effectively preclude the production of most of the valuable clays and, because it covers all of the southern part of the basin, is a more onerous and restrictive constraint than the international nature conservation designations.

As it stands, this gives rise to a major conflict of interest. The policy was proposed by the planning authority on the speculative presumption that sufficient clay of high quality could be found outside the designated area. However, a recent research project funded by the UK government (in which the authors were contributors) has demonstrated the lack of suitable clay there and the improbability that beneficiation or blending could help to resolve supply concerns. The implications of that research will need to be taken on board by the planning authority when it reviews the development plan.

Currently the planning authority appears to have a negative approach to adjusting its policy and the research has been described as not really relevant because it did not provide what was wanted by the planning authority to support the current perceived essential strategy (although one which was prepared in a vacuum, without any quantification of the merits or necessity). However, when faced with the realities of the situation it is hoped that the authority will want to adopt a more pragmatic approach otherwise it may be sidelined. It is worth pointing out that the policy for aggregate (of only local use) is not so restrictive and that the planning authority proposed allocating land for gravel extraction and has recently granted permissions for such extraction. A proven case justified that permission but it would be rather strange if, on reflection, the authority still proposed a more stringent approach to a mineral of international importance.

Conclusions

The debate in this paper truly reflects the aphorism that 'resources are defined by man, not nature.' Clearly the ball clay resource is valued for economic reasons but equally the environmental resources, be they habitat, species, landscape, cultural or historical, are defined by our interpretation of their value.

Most of the UK habitat and landscape, and hence the numbers and diversity of species present derive to a considerable extent from human actions. Even so, conservationists in the UK have an inbuilt rejection of the concept that the resources they value are not truly 'wild,' that the species present can be anomalous in either range or numbers and, of direct interest to the topic discussed here, that many of the species considered rare either exist because of the anomalous vegetation cover or, of even more significance to mineral extraction, are primarily colonising species. Old quarries, and even active quarries, can provide those particular characteristics (drought conditions, exposure, infertility, highly variable topography, mires, etc.), which can provide essential and otherwise limited refugia for colonising species.

Perhaps the problem is that a large section of society in the UK (and possibly in other parts of the developed world) has lost touch with the notion that the extent of habitat and the type of landscape we see has always been subject to expansion and contraction due to human action. The current environment is seen as fixed and immutable. On the other hand there appears to be an assumption that mineral extraction can be diverted elsewhere, usually an unknown 'elsewhere,' when in fact mineral resources are fixed in place.

The paper suggests that much of the conflict in the Wareham Basin is based on an overly vigorous, narrowly focused application of legislation. This conflict is resolvable if the political will exists to develop and manage all natural resources, within the legislative requirements, in a true sustainable and holistic whole (and in the 'public interest') and if that political will is translated into effective, efficient, and properly integrated institutional arrangements for land use and resource planning.

Unfortunately, historical evidence does not currently indicate a very positive outcome and, as this paper notes, the current institutional arrangements lag well behind in realism, promptness, timescale, and certainty, and there is a real concern that the planning process will not be able to meet this challenge.

However, as perceived conflicts will become real and severe conflicts in the future (primarily because the less contentious options have already been taken), the system will have to respond in a more dynamic and leading manner, otherwise ad-hoc decisions—the very antithesis of planned management of resources and potentially very harmful to either or both environmental or economic objectives-will prevail. It is hoped that no party wishes that situation to arise.

This paper also suggests that the strength of the conservation argument as to the need to protect the landscape or habitat, and thereby restrict mineral extraction, can be, and probably has been, overstated. Even if this is so, there is nothing wrong in protecting species, or providing more of a habitat, or seeking to ensure that the landscape is not harmed as long as such actions do not lay a dead hand on meeting other 'public interest' needs of society, including the international need for ball clay.

How can a less polarised approach to resource development in the basin be achieved in the future? What mechanisms and actions are needed to resolve this situation? Perhaps the answer lies in the general need for a proper balanced and a truly 'sustainable' assessment both of the merits, needs and limitations of each resource, reflecting what we know, not just what we desire, together with an approach to their management which does not polarise the debate. And in support of this both the political will and a proactive planning process are needed to bring balance.

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Sand and Gravel Resource Mapping in Alberta, Canada

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Introduction

The province of Alberta became sufficiently concerned with mineral aggregate resource management in the mid-1970s to invest in the Alberta Geological Survey (AGS) to acquire sand and gravel geology and resource data. Between 1976 and 1983 sand and gravel data for 19% of the province (~32 million acres / ~13 million hectares) was acquired for $3 million ($Can., 1980) (fig. 1). Between 1984 and 1990 another $1 million ($Can., 1987) was spent mapping an additional 39% of the province (~63 million acres / ~26 million hectares) at a reduced level of detail (fig. 1 and table 1, study levels 4 and 5). Information for another 21% of the province was added to the database in 2002: 1% (~1.7 million acres / ~0.7 million hectares) was mapped at level 4 (table 1) for $91,000 ($Can., 2002) and 20% (~33 million acres / ~ 13 million hectares) was derived through office study and interpretation of existing surficial geology maps at a cost of $3,000 ($Can., 2002) (fig. 1).

Aggregate resources are just as important now as they were 30 years ago. The annual per capita demand for aggregate in Alberta, at 14.6 metric tons, is higher than the Canadian average of 11.6 metric tons (NRCan., 2003 and StatsCan., 2003), and is increasing. The production cost of aggregate in Alberta also exceeds the national average (fig. 2) (NRCan., 2003). It was estimated in 1989 that cessation of production at 25 to 50% of sand and gravel deposits that supply aggregate resources to the Edmonton region would add $1 billion ($Can., 1989) over 25 years to aggregate production costs due to increased haul distance alone (Edwards, 1989). Alberta continues to struggle with the aggregate resource puzzle. Appropriate conservation and management of aggregate resources can save taxpayers billions of dollars by reducing haul distance, which in turn reduces haul road maintenance costs, green house gas emissions, and the potential for vehicle accidents. Effective management of aggregate resources requires a sustainable resource development approach. All aspects of the aggregate resource (geological supply, economic, environmental, and social parameters) must be considered and government departments, municipalities, and industry must work together to ensure the future of aggregate resources.

The AGS contributed to this effort by converting spatial and attribute information from 5,489 sand and gravel deposits, in over 150 AGS maps and reports, into digital form. The Sand And Gravel Geology And Resources (SAGGAR) database makes it possible to include aggregate resource data in most electronic land use and resource management plans. SAGGAR also receives all new AGS resource data, supports web distribution of information, and is being used to produce a new 1:250,000-scale aggregate potential map series.

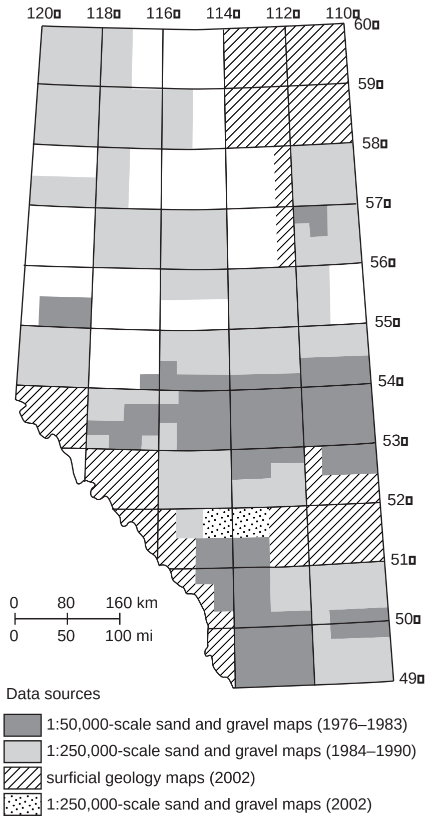

Figure 1. Sand and gravel deposit mapping by the Alberta Geological Survey, 1976 to 2002.

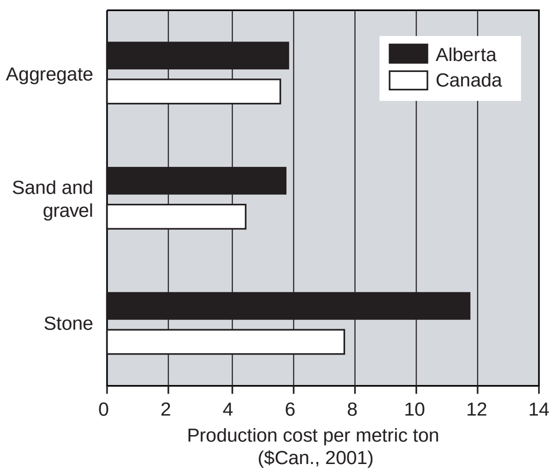

Figure 2. Average production costs for aggregate in Alberta and Canada, 2001 (NRCan., 2003).

Study Level

Alberta Geological Survey sand and gravel resource information is used in a variety of ways including: aggregate exploration programs, detailed deposit delineation, regional land use planning, and resource management. AGS aggregate projects gather data at various levels of detail depending on the purpose, budget, and area of the specific mapping or survey project. It is necessary to ensure that AGS information is applied appropriately over the wide range of potential uses. Study level (fig. 3, table 1) describes the level of detail gathered during an AGS sand and gravel mapping/survey program and provides a way for users to determine if the AGS information is appropriate to their needs. The AGS defines five levels of study (table 1):

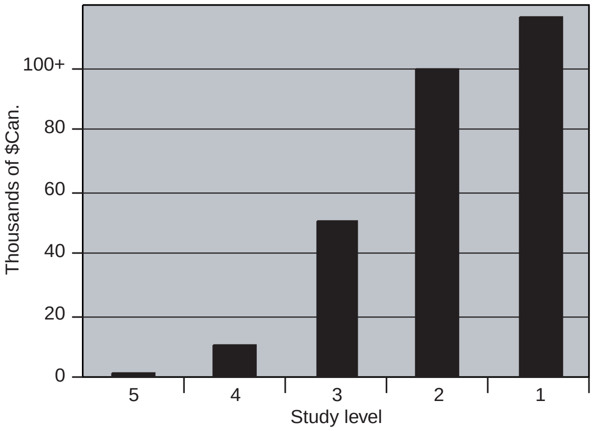

Figure 3. Cost per 1:50,000-scale map sheet of AGS sand and gravel mapping by study level. Average area of a single 1:50,000-scale NTS map sheet is 213,140 acres (86,258 hectares).

Level 1 is the most concentrated level of data gathering. Investigations typically focus on part of a single deposit. Accurate reserve figures and detailed material descriptions are generated from a closely spaced (300 feet / 100 m or less) testing grid with multiple samples per testhole.

Level 2 is a detailed investigation of an individual deposit that includes testing and sampling and provides a reserve estimate suitable for detailed resource management.

Level 3 is achieved through geological mapping supported by limited testing of key deposits and sampling of most deposits. Mapping at this level of detail may not discover all potential deposits in the map area but does confirm the presence of granular materials in all deposits demarcated. This information is useful for comparing the nature, size and origin of deposits over a large area and in developing geological models useful in further sand and gravel exploration.

Level 4 is achieved through air photo interpretation with follow-up field checking of select sites as a control. The limited fieldwork confirms the presence of exposed sand and gravel at some sites.

Level 5 involves the interpretation of soils, water well, or geological data (collected for other purposes), or small-scale air photo interpretation with no field validation. Information at level 5 does not confirm the presence of granular material but may provide a starting point for granular searches or potential in an otherwise unexplored or remote areas.

SAGGAR, and the new AGS 1:250,000-scale aggregate potential map series produced from SAGGAR, are compilations of all existing information. A single map may have data from projects with different levels of detail. The study level for each deposit is identified in an inset map to enable users to determine if the AGS data is appropriate to their needs.

Table 1. Data used in Alberta Geological Survey sand and gravel studies.

Study Level	1 reserve definition	2 reserve definition	3 detailed mapping	4 geological, resource mapping	5 office study
Existing Surficial Geology Data	NA	NA	Y	Y	Y
Water Well Data	NA	NA	Y	Y	Y
Air Photo Interpretation	NA	NA	Y	Y	Y
AGS Site Investigation	Y	Y	Y	limited	N
Drilling/Trenching	detailed grid	wide grid	minimal	N	N
Sampling	many per hole	multiple samples	most deposits	some	N
Product Reliability	very high	high	moderate	low	very low
Mapping Cost per 1:50,000 Scale NTS Map Sheet (approximate, $Can., 2002)*	$100,000 ++	$100,000 ++	$50,000	$25,000	$5,000

***Average area of a single 1:50,000-scale NTS map sheet is 213,140 acres (86,258 hectares).**

Mapping Strategy

The cost of mapping aggregate resources increases with the level of detail to which the deposits are mapped (fig. 3). The AGS considers level 3 as the lowest level of detail required for detailed land use planning and sustainable resource management. It is our intent to complete new mapping and upgrade existing data to level 3 even with reduced funding. We believe this is possible through the following process (fig. 4):

1. Extract data showing sand and gravel potential from existing studies and databases (water well, surficial geology, soils, geotechnical) and input into the SAGGAR database.
2. Prepare an aggregate potential map from SAGGAR. Maps will generally be at the lowest level of detail (level 5).
3. Focus initial fieldwork on areas identified to have sand and gravel potential. Update SAGGAR.
4. Refine aggregate potential areas and evaluate geological data to identify other areas of interest.
5. Investigate and sample (if necessary) new areas with aggregate potential. Update SAGGAR.
6. Prepare a level 3 aggregate potential map from SAGGAR.

The granular materials are classified by the AGS according to the ratio of sand to gravel and the amount of fines (silt and clay) present (fig. 5). Geologists also identify genesis for all deposits. Integrating deposit genesis regionally has enabled development of geological models useful in further sand and gravel exploration. Models of terrace formation in the major river valleys and of the preglacial deposits have proven to be especially useful.

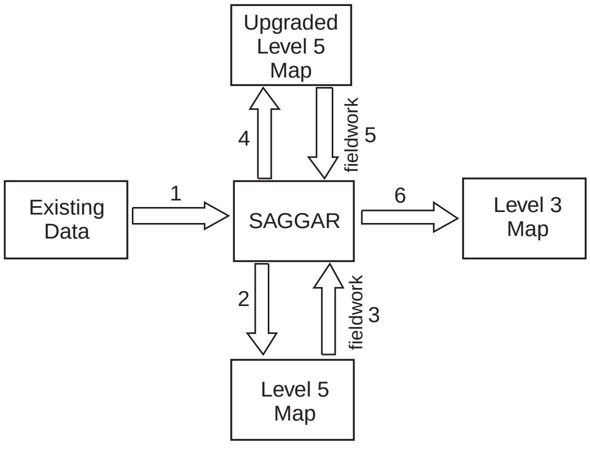

Figure 4. Current Alberta Geological Survey mapping process.

Conclusions

1. Aggregate supply information must be considered during land use planning and resource management activities.
2. The Alberta Geological Survey can provide geological and aggregate resource data to ensure sufficient and affordable aggregate resources for the future.

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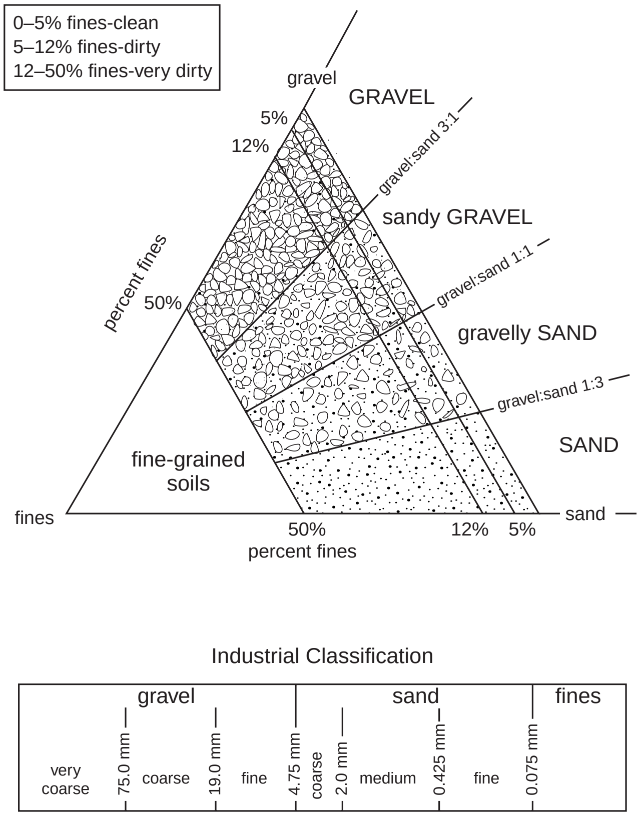

Figure 5. Classification scheme of granular materials used by the Alberta Geological Survey.

World-Class Mineral Specimens From Carlin-Type Gold Deposits in the Great Basin, Western United States

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As a group, Carlin-type gold deposits are noted for the large amount of contained gold, both already produced and as reserves, and for the huge scales at which some have been mined. Hundreds of mineral species have been identified in these deposits (Ferdock and others, 1997, 2003; Ferdock, 2002, 2003); many occur in specimens that range from micromounts to large museum pieces, and are some of the world's finest examples of their species. These are gangue minerals that are economically insignificant when placed in the context of the ore deposits and mines. However, they may be more responsible for the worldwide fame of a mine than the gold it produces. Preservation of specimens from a mine can bring a number of benefits for the mining company, including public recognition of responsibility of the miners for preservation of natural history and as caretakers of the environment. The specimens act as positive reinforcement of what mining produces, and minerals in museum collections are low-cost, goodwill ambassadors between industry and the public. Finally, mineral specimen recovery can actually add to the bottom line, with many specimens commanding prices in excess of $10,000 each.

Carlin-type gold deposits are found throughout the Great Basin physiographic province of the western United States, but are concentrated in northern Nevada (fig. 1). They were identified as a unique type of sedimentary rock-hosted, disseminated, gold deposit following the discovery of the

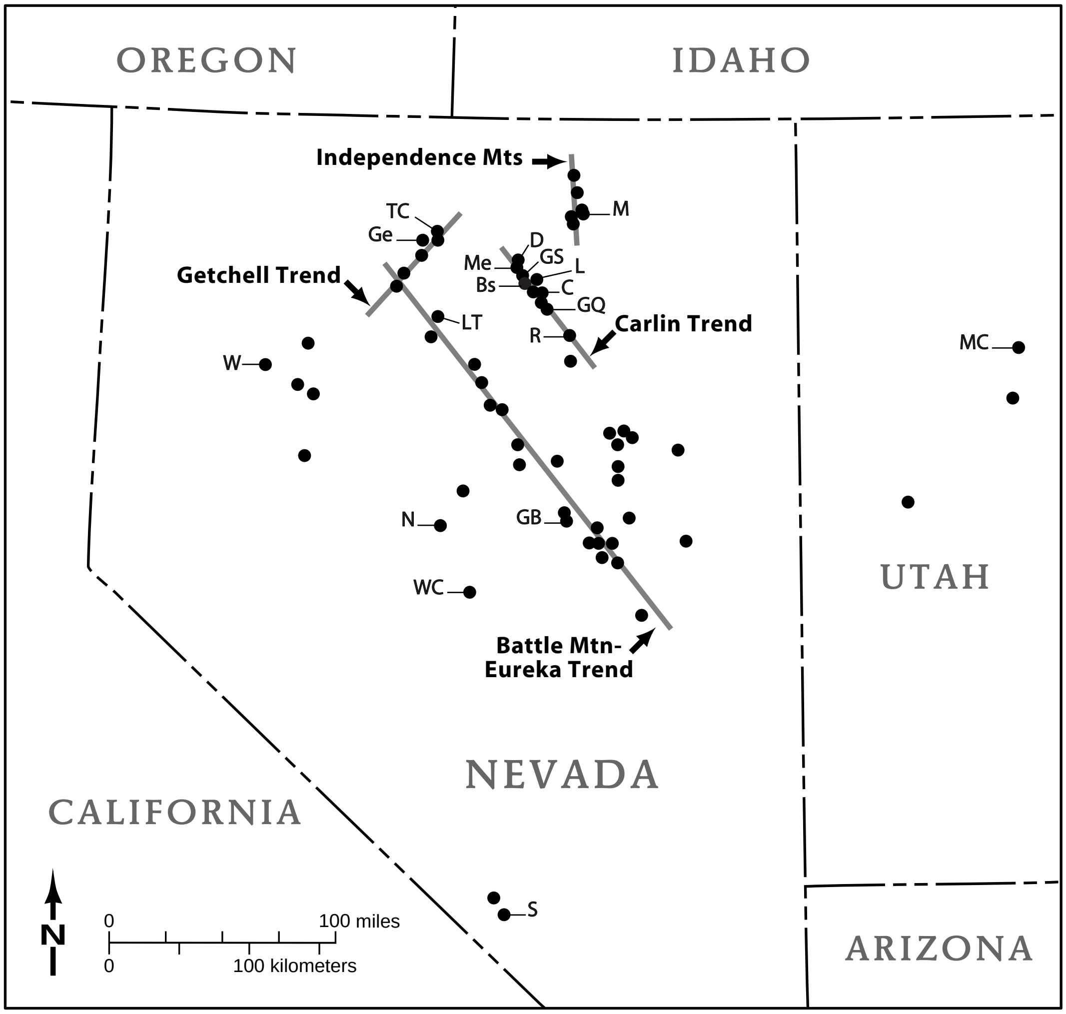

Figure 1. Location of Carlin-type gold deposits in the Great Basin of the western United States. Major trends/alignments of gold deposits are noted. Individual mines mentioned in text: BS - Blue Star; C - Carlin; D - Dee; GB - Gold Bar; Ge - Getchell; GS - Goldstrike; GQ - Gold Quarry; L - Leeville; LT - Lone Tree; M - Murray; MC - Mercur; Me - Meikle; N - Northumberland; R - Rain; S - Sterling; TC - Twin Creeks; WC - White Caps; W - Willard.

Carlin gold deposit, 25 miles north of Carlin, Nevada, in 1964 (Radtke, 1986). However, a number of mines exploited these types of deposits as far back as the latter part of the nineteenth century and the early twentieth century. Almost from the outset of these mining ventures, excellent mineral specimens were recovered and preserved for future generations.

Specimens of many of the minerals found in Carlin-type deposits may be found in museums throughout the world. The W.M. Keck Museum of the Mackay School of Mines, University of Nevada, Reno, has some outstanding specimens from Carlin-type deposits. Further details on collectable minerals from Carlin-type deposits, and other types of Nevada ore deposits, may be found in Minerals of Nevada, a new joint publication of the Nevada Bureau of Mines and Geology and the University of Nevada Press (Castor and Ferdock, 2003). Table 1 lists the notable specimen minerals by mine.

One of the most notable early species recovered from a Carlin-type deposit was a mineral initially identified as "hair orpiment" from the White Caps Mine in the 1920s. This is an attractive yellow-orange species composed of fine, filliform crystals in calcite up to 4 cm long (fig. 2A). This was the first discovery of a species identified over 30 years later in Japan as wakabayashilite. The White Caps Mine occurrence is still the finest location known for the species (Gibbs, 1985).

The Getchell Mine began operation in the 1930s initially as a gold mine and later as an arsenic mine during World War II. Much of the ore contained orpiment and realgar, some of which was found as superb crystals, with many exceeding 6 cm in length (fig. 2B). Realgar specimens recovered from the Getchell Mine are found in most of the world's natural history museums (Berger and Tingley,1985; Stolburg and Dunning, 1985).

Realgar from other Carlin-type deposits is generally crystalline, but crystals seldom exceed those of the spectacular Getchell specimens. Some fine deep red gemmy crystals to 3 cm were recovered from the Goldstrike Mine (in the early to mid-1990s), where realgar occurred in seams and open fissures in silicified ore. Some nice realgar was also found at the Mercur Mine in Utah in the 1980s (Kornze, 1984; Wilson and Wilson, 1990).

Orpiment specimens from the Getchell Mine (fig. 2C) compete favorable with most other worldwide occurrences and were the best from the western United States until large deposits of orpiment were discovered at the nearby Twin Creeks Mine in the late 1990s. Specimens of orpiment from the Twin Creeks locality contain fine yellow to yellow-orange crystals up to 5 cm long, these are commonly translucent to transparent and gemmy (Lees, 2000). The orpiment is generally associated with stibnite and minor realgar. In addition, a few choice specimens with orpiment crystals to 5 cm long were recovered in the early 1990s from the Gold Bar Mine in the Roberts Mountains of central Nevada and the Mercur Mine in central Utah produced some attractive orange-yellow, gemmy crystals of orpiment to 4 cm long. The Mercur Mine orpiment crystals are associated with a "classic" late stage mineral assemblage of fluorite, calcite, barite, stibnite, realgar and rare thallium-bearing species.

Perhaps the most spectacular species recovered from Carlin-type gold deposits is barite. A number of mines (e.g., Goldstrike, Leeville, Rodeo, Dee, Northumberland, Meikle) have yielded exceptional specimens of golden barite crystals. Some of the earliest barite specimen recoveries were from the Northumberland Mine in central Nevada. Here prismatic, gemmy, golden crystals to 13 cm (Forrest Cureton, written commun., 2003) were recovered from large pockets in

Table 1. Carlin-type deposits with collectable minerals; all locations are in Nevada except as noted.

Mine	County	Notable Minerals
Blue Star	Eureka	turquoise
Bootstrap	Elko	calcite
Carlin	Eureka	carlinite, frankdicksonite, weissbergite
Dee	Elko	barite, calcite
Getchell	Humboldt	calcite, galkhaite, getchellite, orpiment, realgar
Gold Bar	Eureka	orpiment
Gold Quarry	Eureka	calcite, faustite, fluellite, goldquarryite, hewettite, kazahkstanite, nevadaite
Gold Strike	Eureka	crandallite, jarosite, stibnite, variscite
Leeville	Eureka	barite
Lone Tree	Humboldt	pharmacosiderite, rhodochrosite
Meikle	Elko	barite, calcite, millerite
Mercur	Tooele, Utah	lorandite, orpiment
Murray	Elko	barite, stibnite
Northumberland	Nye	barite
Rain	Elko	faustite, jarosite, wavellite
Sterling	Nye	calcite
Twin Creeks	Humboldt	barite, getchellite, orpiment
White Caps	Nye	arsenolite, stibnite, wakabayashilite
Willard	Pershing	fluellite, warellite

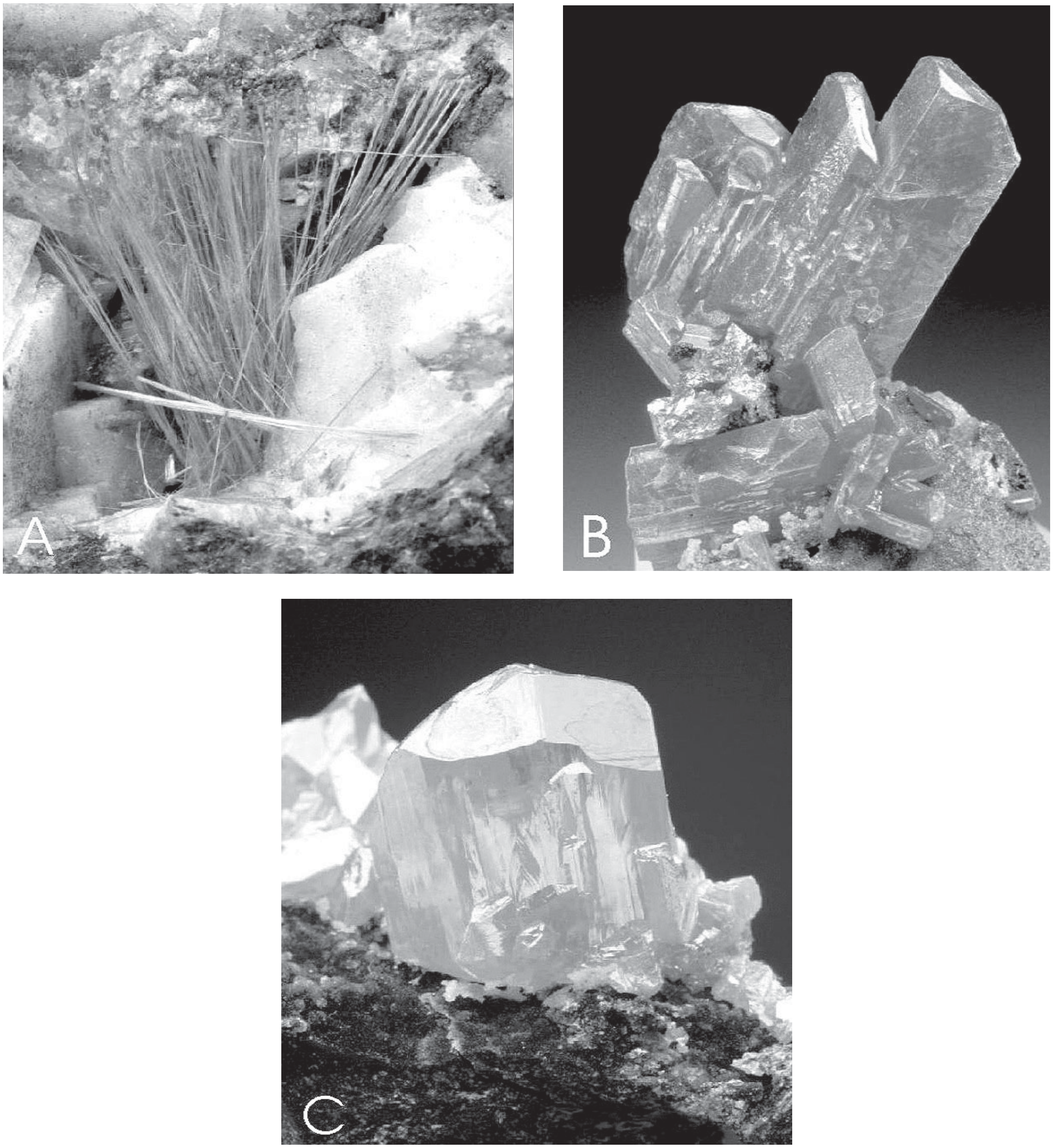

Figure 2. A) Wakabayashilite from the White Caps Mine, 3 cm spray. J. Scovil photo, Barbara Cureton specimen; B) Realgar from the Getchell open pit mine, crystals to 2.5 cm. J. Scovil photo, Bill Moller specimen; C) Orpiment crystal, 1 cm, Getchell Mine, J. Scovil photo, Greg Ferdock collection.

silicified limestone (fig. 3A). This was the first of the "modern" open-pit gold mines to yield such fine mineral specimens, and the amount of crystals recovered was significant over the life of the mine. The Northumberland occurrence was eclipsed by the Meikle Mine in 1995 when platy, gemmy golden crystals to 20 cm were encountered in large caverns on the 1075 level of the underground operation (Jensen, 1999). These crystals first hit the private collectors market in 1998 where they were instantly recognized as the world's finest golden barite crystals, both in size and quality (fig. 3B). The mine has continued to produce large barite crystals, some of even larger sizes, some on crystallized calcite (fig. 3C), and some with bizarre habits from caverns large enough to drive a truck into. A single pocket of pyrite-coated barite crystals was found in 2000 in the lower levels of the mine. About a dozen specimens to 4 cm were recovered; a photograph of one is in Minerals of Nevada (Castor and Ferdock, 2003).

Other barite specimens were recovered between 1996 and 2002 from the Murray Mine in the Independence Mountains in northeastern Nevada. Here, the barite crystals are blocky and can exceed 5 cm in length. They are often coated with 2 to 4 mm milky white quartz crystals forming bright white "sugar cubes" that are extremely attractive when well cleaned. Another occurrence of fine barite came from underground operations at the Dee Gold Mine about 8 km northwest of the Meikle Mine. These crystals, encountered in 1999–2000, are flattened, prismatic, gemmy, yellow to gold crystals up to 6 cm long. They are similar in appearance to those found at the Northumberland site, but differ by having flattened faces. In addition, some exceptional specimens of barite with orpiment came from the Twin Creeks Mine in 1999 (fig. 3D).

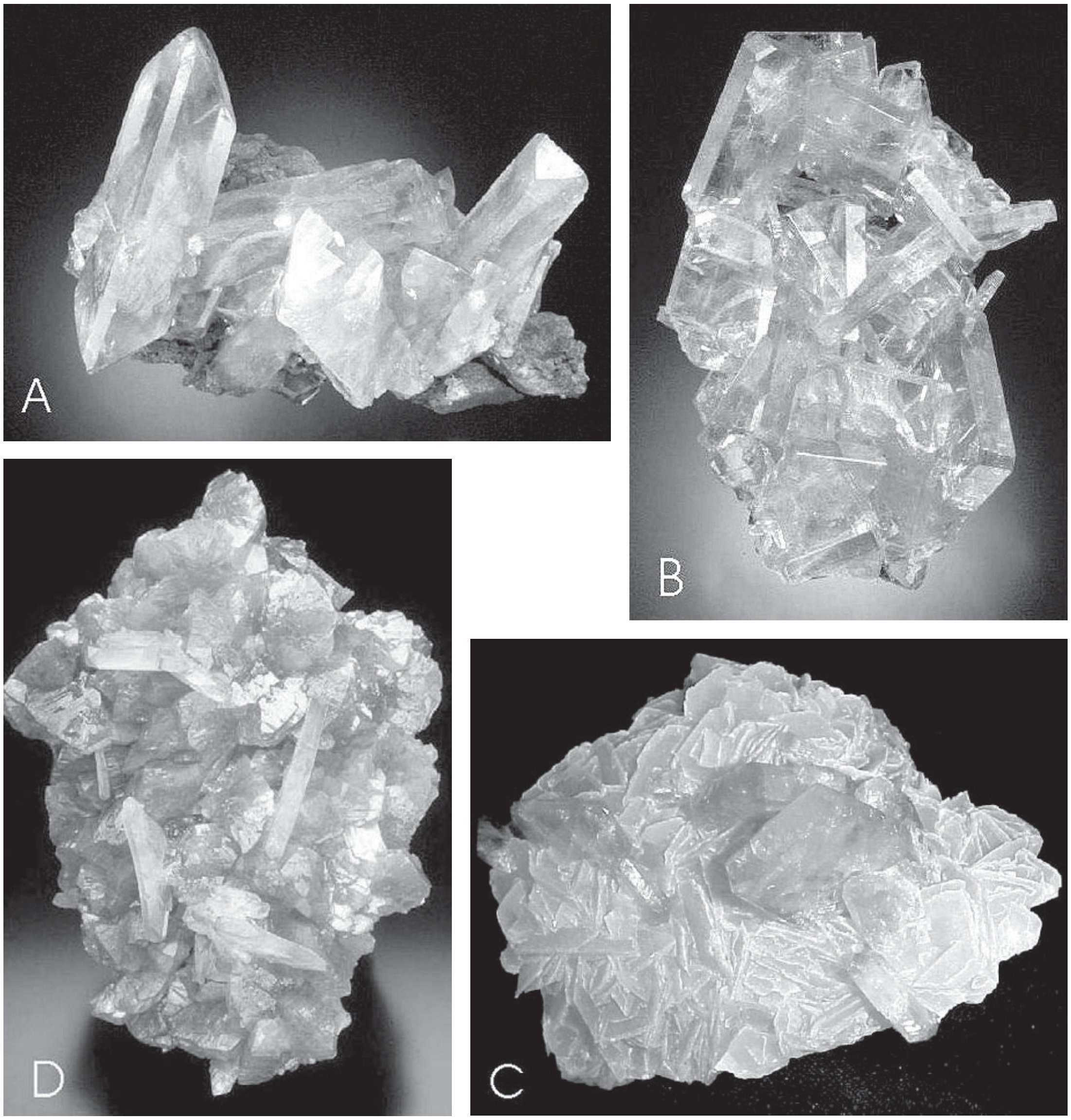

Figure 3. A) Barite crystals to 3.5 cm, Northumberland Mine, J. Scovil photo; B) Tabular barite crystals to 3 cm, 1075 level, Meikle Mine, J. Scovil photo; C) Barite on calcite, barite crystals to 6 cm, 1225 level, Meikle Mine, G. Ferdock photo; D) Barite on orpiment, barite crystals to 2 cm, Twin Creeks Mine, J. Scovil photo.

Stibnite crystals comparing favorably to those found from the classic localities in Romania, Japan, and China have been recovered from a number of Carlin-type gold deposits where stibnite is a common gangue mineral. The earliest such recovery of fine stibnite came from the White Caps Mine, where crystals to 15 cm long were found in sprays and clusters to 40 cm (Gibbs, 1985; Forrest Cureton, written commun., 2003). Many of these clusters have graced the finest mineral displays the world over. When these old specimens (recovered before 1940) reappear on the specimen market, they command high prices on the basis of their rarity and beauty.

Until the 1990s stibnite was noted but not heavily recovered in a number of mines. In 1995, a pocket of fine crystals was struck in the Goldstrike Mine (fig. 4A), producing some of the finest stibnite crystals from North America in individual specimens as much as 6.5 cm long by 2.5 cm in diameter. These larger specimens were discovered with dozens of fine, needle-like, radiating, acicular sprays up to 2 cm in diameter. This discovery was soon eclipsed by even more spectacular crystals recovered from pockets in the Murray Mine (Jones and Jones, 1999). Stibnite crystals from these Nevada mines are the best North America has ever produced. Individual crystals attain lengths to 20 cm and rival stibnite specimens from almost anywhere on the planet (fig. 4B).

Along with barite, stibnite, realgar and orpiment, calcite has been recovered as fine crystals from a number of deposits, including Getchell, Gold Quarry, Bootstrap, Dee and Meikle (figs. 5A and 5B). Calcite specimens from these locations are rare, and usually form masses that are used in the milling process. Specimens range from fine, gemmy, root-beer-colored rhombohedra and modified scalenohedra to lime-green, platy clusters of crystals to 15 cm in length. Groups of calcite crystals that are stained with bright red hematite form beautiful specimens from the Gold Quarry Mine. Clusters of pure white balls and botryoids were recovered from the Bootstrap Mine (Jones and Jones, 1999). Large, delicate, and beautiful clusters of calcite pseudomorphs after aragonite were found in pockets in the Sterling Mine in southern Nevada.

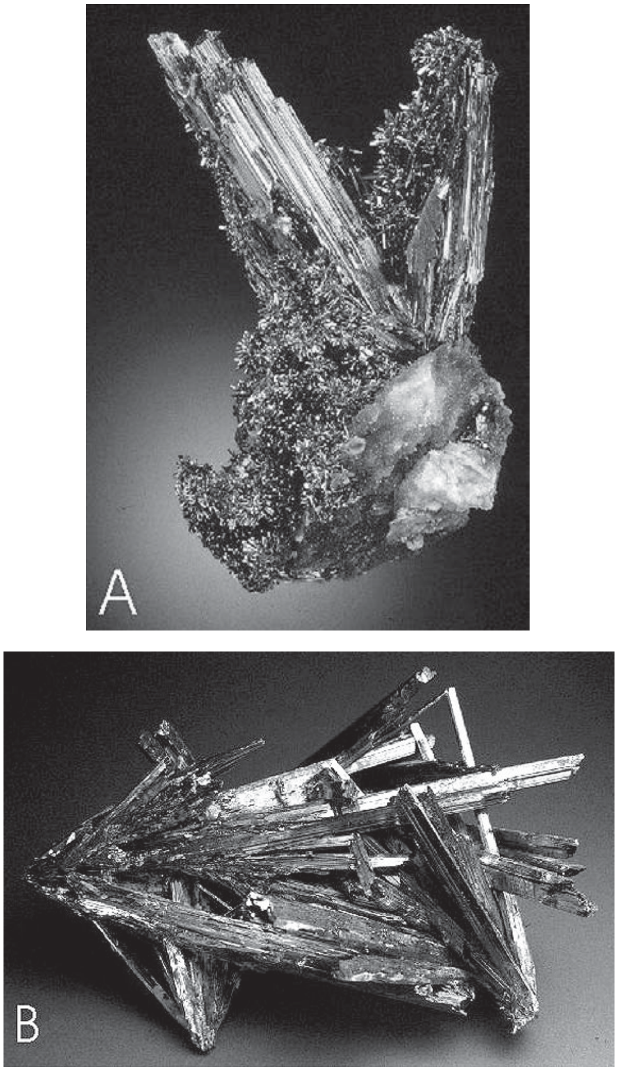

Figure 4. A) Stibnite crystals to 3.5 cm, Goldstrike Mine, J. Scovil photo; B) Cluster of stibnite crystals to 7 cm, Murray Mine, S. Castor photo.

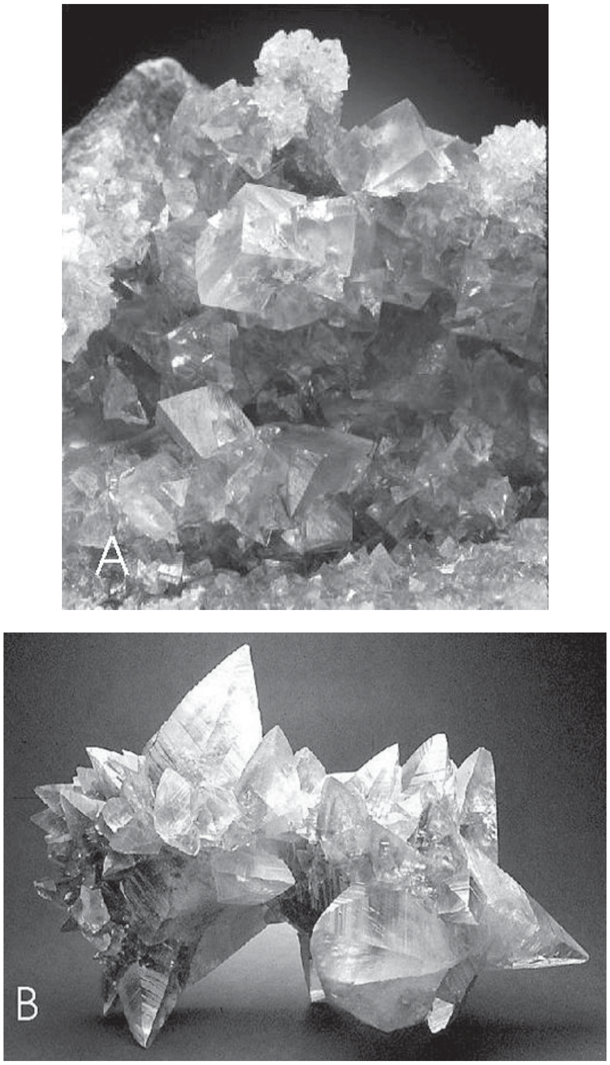

Figure 5. A) Yellow calcite crystals to 3 cm, Getchell Mine, J. Scovill photo; B) Calcite cluster, 12 cm long, Meikle Mine, S. Castor photo.

Superb crystals and crystal clusters of millerite have been found in the Goldstrike, Gold Quarry and Meikle Mines. The Meikle Mine occurrence produced the finest millerite found in the United States, with some crystals attaining 4 cm in length.

Notable occurrences of small but rare phosphate, oxide, and sulfate minerals have been found at many Carlin-type deposits. They include faustite, jarosite, and wavellite from Rain (fig. 6A); faustite, fluellite, nevadaite, goldquarryite, kazahkstanite, hewettite and numerous others from Gold Quarry (figs. 6B and 6C; Jensen and others, 1995); transparent, emerald-green variscite, white crandallite and transparent golden-brown jarosite from Goldstrike (figs. 6D and 6E); pharmacosiderite from Lone Tree; and arsenolite from White Caps (fig. 6F) and the world's largest crystals of fluellite from Willard (Jensen, 1999). World famous spider-web turquoise came from the Blue Star Mine as recently as 1991.

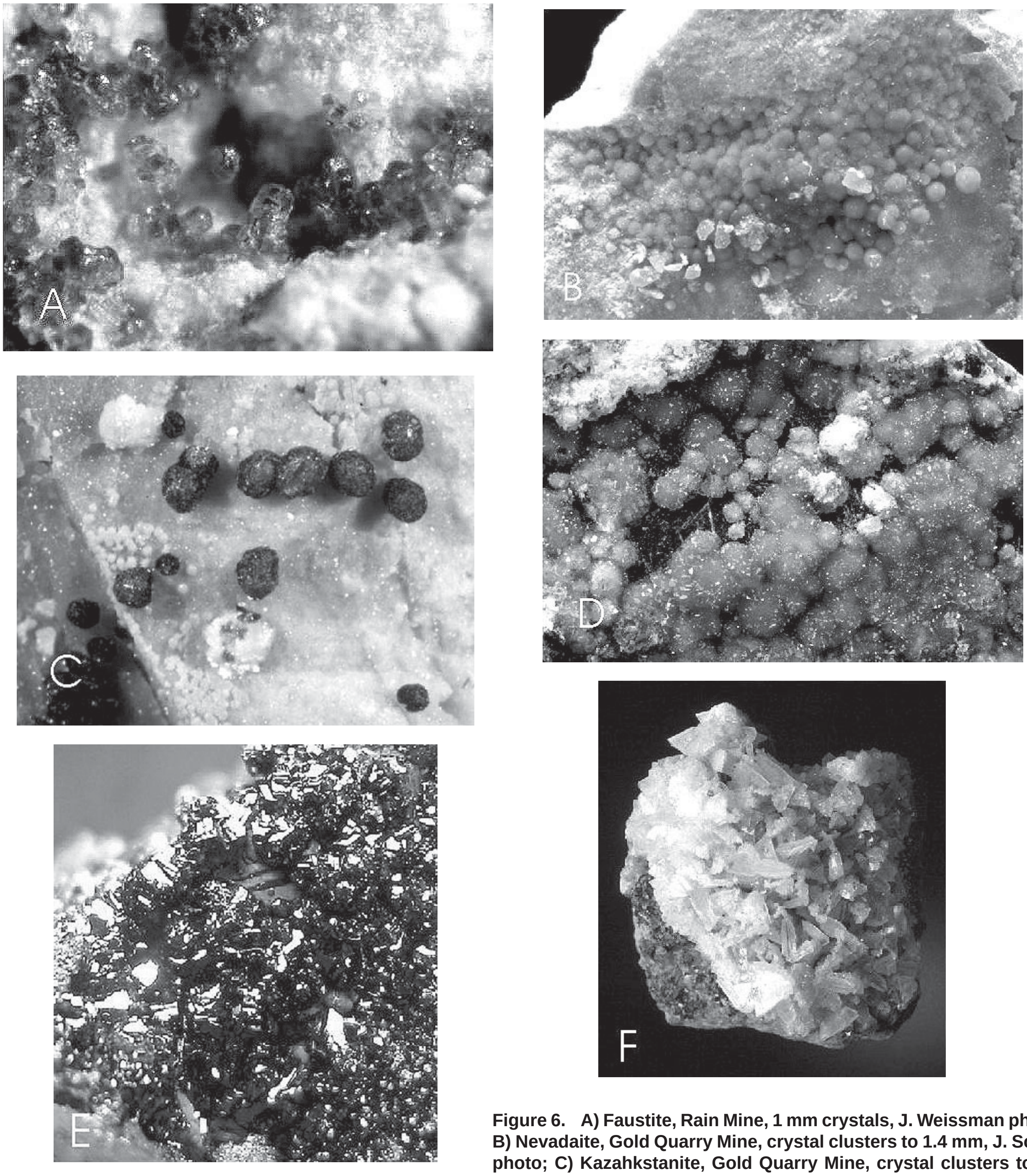

Figure 6. A) Faustite, Rain Mine, 1 mm crystals, J. Weissman photo; B) Nevadaite, Gold Quarry Mine, crystal clusters to 1.4 mm, J. Scovil photo; C) Kazahkstanite, Gold Quarry Mine, crystal clusters to 1.2 mm, Jeff Weissman photo; D) Variscite with crandallite, Goldstrike Mine, crystal clusters to 4 mm, J. Scovil photo; E) Jarosite crystals to 3.2 mm, Goldstrike Mine, G. Ferdock photo; F) Arsenolite crystals to 1 cm, White Caps Mine, J. Scovill photo.

Other exceedingly rare species have been found in Great Basin Carlin-type systems and few, if any other, places on Earth. This includes species such as frankdicksonite, weissbergite, and carlinite from the Carlin Mine (Dickson and Radtke, 1978; Dickson and others, 1979). Very fine specimens of galkhaite have been recovered from the Getchell Mine, where crystals to 1.7 cm occur in quantity and gemmy cherry-red cubes cover specimens to 15 cm long (fig. 7A) (Botinelly and others, 1973; Stolburg and Dunning, 1985). The Twin Creeks Mine recently yielded the world's finest crystals of getchellite, as much as 2.2 cm across. These were found associated with massive stibnite, small orpiment crystals, and minor carlinite masses (fig. 7B). Unfortunately, these crystals were originally misidentified as small and insignificant realgar crystals, resulting in the removal and subsequent destruction by mining processes. A recent discovery of the world's finest lorandite crystals up to 5 cm long at the Mercur Mine in Utah has provided specimens of this extremely rare mineral. A single, doubly terminated crystal of lorandite, 3.2 cm long, on barite, was recently described as the world's finest specimen of the species (fig. 7C).

To conclude, many Carlin-type gold deposits are large orebodies that are most profitably exploited by large-volume, open-pit and underground mines. This facilitates the opening of relatively small pockets of gangue minerals that commonly include fine crystallized specimens. In some cases the finest examples known of the species. These specimens, when properly recovered and preserved for posterity, often are responsible for the fame and worldwide recognition of a particular mine or deposit. The benefits of mineral specimen preservation can lead to positive dividends in an industry that is constantly under attack by under-informed groups and individuals.

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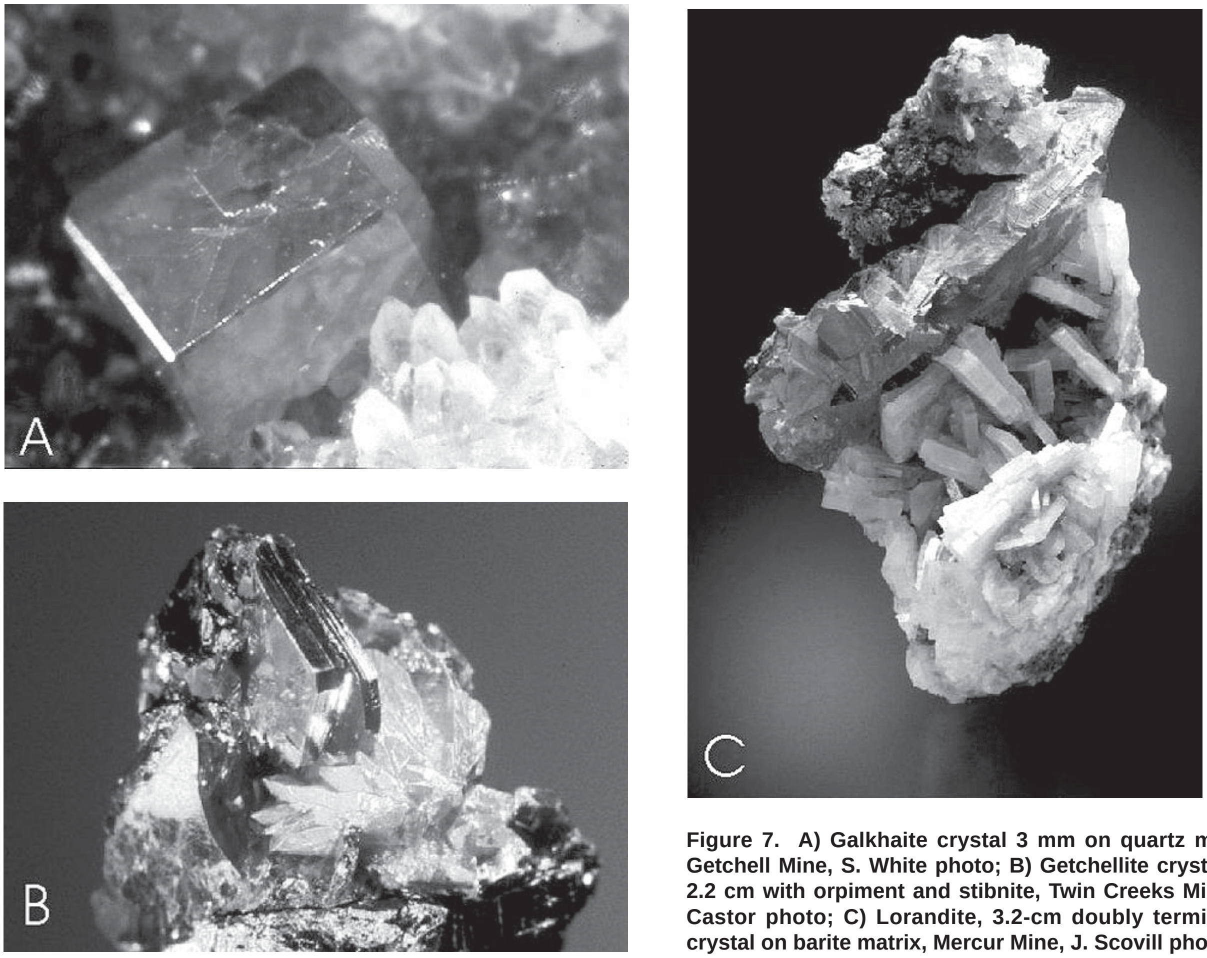

Figure 7. A) Galkhaite crystal 3 mm on quartz matrix, Getchell Mine, S. White photo; B) Getchellite crystals to 2.2 cm with orpiment and stibnite, Twin Creeks Mine, S. Castor photo; C) Lorandite, 3.2-cm doubly terminated crystal on barite matrix, Mercur Mine, J. Scovill photo.

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Gold and the Nevada Economy

Russell A. Fields, Nevada Mining Association

Gold is Nevada's most important mineral commodity in terms of economic impacts on the State and on the local communities near the gold mining areas. Nevada gold production has remained near 8 million ounces per year over the past 5 years, making Nevada the leading gold producing state in the United States. Gold mining in Nevada employs approximately 10,000 people working directly at the mining operations. The average salary for these jobs is $62,000 per year compared to the average statewide salary for all industries of just over $33,000. Indirect employment related to providing goods and services to the industry accounts for another 37,000 jobs.

The gold industry is a substantial payer of taxes to both state and local government. The three major taxes paid are sales and use tax, property tax and a tax unique to the mining industry-the net proceeds of minerals tax. Mining tax payments have averaged in excess of $100 million per year over the past 5 years. It is estimated that about two-thirds of these tax dollars stay with local government as opposed to the state government. A large percentage of the revenues received by local government are used for schools and local infrastructure.

While gold mining in Nevada has faced significant challenges over the past 5 years due to a relatively low commodity price, Nevada's mines have focused on improving efficiency at their operations. The resulting decrease in production cost has kept the mines in business, if not prospering. As of early 2003, there are signs that the gold price will improve and hold at relatively higher levels than in the previous several years. This is welcome news to the industry and the Nevada communities that are dependent on a healthy mining industry.

The history of gold and silver mining in Nevada is, in many ways, synonymous with the early history of the state. Would-be miners and prospectors first traveled through western Nevada in 1849 on their way to the creeks and mountains of California's "mother lode" some 100 miles to the west of Reno. By the mid to late 1850s many of those individuals found that the "easy pickens" were gone - to find and develop gold in the placers and lodes was hard work, it was dangerous and competition among the miners was fierce. Some actually decided to head back over the mountains to return to their homes in the Midwest or beyond. Naturally, these individuals intended to prospect along the way. That is what led to the initial important discoveries.

In 1859 gold was discovered in a dry creek bed below what was soon to be called the Comstock lode. A troublesome blue clay was determined to be rich in silver and indeed silver is the metal of the Comstock's fame, but gold was also important in the rich veins beneath what became Virginia City. The silver and gold discoveries and ensuing development and production from the mines at Virginia City set the stage for numerous advancements in Nevada. The heyday of the Comstock Lode was from 1860 through 1880, with production falling off dramatically in the last two decades of the 19th century. This represented only two decades of massive mineral production, but consider what that led to:

- Statehood in 1864 (population and politics, together with money),
- Technology advancements in mine dewatering (Cornish pumps) and ground control (square-set timbers),
- Mining Law of 1872 introduced and championed by Nevada Senator William Stewart,
- Engineering/Surveying: Sutro Tunnel designed to dewater the deep levels of the Comstock,
- Mine finance: publicly held corporations were formed for the first time to finance mines,
- The infrastructure and incentive to motivate new prospecting throughout Nevada.

This last point set the stage for the growth of new mining activity in the state. As in California a decade earlier, large numbers of prospectors and seekers of riches arrived on the Comstock too late to participate in the great generation of wealth there. The most promising ground was already taken, the mines were deepening and any new development took the financing capability of major consortiums or corporations. The chances for the "little guy" appeared to be past.

As prospectors fanned out across the neighboring and even distant lands of Nevada in search of the "next Comstock," a number of significant pieces of mining history took shape. The discovery and development of gold in places now known as Austin, Eureka, Tuscarora, Goldfield, Tonopah, Hamilton, Battle Mountain, and others led to the establishment of towns, roads, railroads, electric infrastructure (in the early 20th century) and brought more population to the state. As these mines played out, many of the mining towns died and became ghost towns, but some live on today and mining has played an important role throughout their history—in some cases to the present time.

Obviously, Nevada's economy has diversified since those early gold and silver mining days. Nevada is now the fastest growing state in the Nation with approximately 2 million people. The gaming and entertainment industry, which had its roots in the 1930s, has grown to become the undeniable economic engine of Nevada. Agriculture and tourism are important in some of the rural areas of the state. Urban Las Vegas and Reno/Sparks are growing in areas of light manufacturing, warehousing and a wide variety of service industry businesses.

Today, mining is certainly not what it was to Nevada's economy, but it remains a vital industry in many of the rural parts of the state. For 2002, the Nevada Division of Minerals estimated that the total value of mineral production in the state was $2.8 billion. This includes the value of gold, silver, and industrial minerals-aggregates, barite, clays, diatomite, dolomite, gypsum, lime and limestone, lithium compounds, magnesium compounds, opals, perlite, potassium sulfate, salt, silica sand, and turquoise. Gold production in 2002 totaled 7.73 million ounces with a value of $2.4 billion. Gold represented 86% of the value of Nevada's mineral production in 2002. This large contribution of gold mining to the total mineral value has been the case since the mid-1980s.

This proportionately large gold mining component is reflected in all the economic statistics and statements and is assumed in this paper. Despite these significant numbers, mining represents only about 1.9% of the Gross State Product. However, outside of Clark (Las Vegas) and Washoe (Reno/Sparks) Counties, mining represents 13% of that portion of the Gross State Product.

There are about 17 major gold operations in Nevada today. All mining in Nevada employs about 10,000 people working directly in the mines. There are another 37,000 jobs in Nevada associated with providing goods and services to the mining industry. As stated above, the majority of these mining jobs and support jobs are attributable to gold mining activity. The average wage in the Nevada gold mines is $62,000 per year with full health benefits. This compares extremely favorably to the statewide average of $33,000. Other economic impacts of the Nevada mining industry in 2001 were:

- Increased state output by $4.5 billion,
- Contributed $1.4 billion to Nevadan's personal incomes,
- Paid $92 million in state and local taxes (average over the period 1998–2001: $106 million per year).

Gold prices, set in world markets and usually represented by the London PM fixing, have been relatively low over the past several years. The average price per troy ounce was $294 in 1998, $279 in 1999, $279 in 2000, $271 in 2001, and $309 in 2002. Today, in early May 2003, the London PM fixing for gold is $348 per troy ounce, some 22% higher than the average for 1998–2002. While many things influence the price of gold, and it has been quite volatile so far in 2003 (low of $321 and high of $382), the improvement in gold prices is certainly welcomed by the gold mining industry. The economic impacts derived from the industry will be positive for Nevada and the local gold mining communities. Because cost is the only thing that gold mining companies can control in their profit and loss statements, the past few years of low gold prices has caused these operators to become quite efficient.

Some results of the higher gold prices in 2003 are already starting to be seen. Several major mining operations have expansion plans in progress. Rehiring of workers laid off during the challenge of low prices is occurring at one major mine. Exploration for new gold resources is definitely on the upswing. All of these things have positive implications for Nevada's economy: more high-paying jobs, greater expenditures on tangible goods, improved property valuation, more professional services employed, and more economic activity in both rural and urban Nevada. Some economic effects of increased exploration activity are:

- Geologists are in the field exploring,
- Government permits are written and inspections are made,
- Contract drillers are hired, and contract drill pad construction is done,
- Laboratories are engaged to analyze samples,
- Local motels house drillers and geologists,
- Local restaurants, fuel vendors, and grocery stores sell supplies,
- Results are evaluated, perhaps by consultants,
- Reclamation of drill roads and plugging of holes.

If a viable discovery is made, the activities multiply. This activity, while seemingly small, can have a very substantial impact on a small rural Nevada community. A relatively few new dollars in a small town makes a difference.

The future impacts of gold mining on Nevada's economy promise to continue to be important for many years to come. Existing reserves at several major Nevada gold mines exceed 10 years of mine life at current economics without further drilling. The renewed exploration activity resulting from higher gold prices also is positive for future economic impacts of Nevada gold mining.

The Geology and Development of the Tucker Hill Perlite Deposit, Lake County, Oregon

Gregory McN. French

Introduction

The Tucker Hill perlite deposit of Cornerstone Industrial Minerals Inc. (Cornerstone) is located in south-central Oregon. The mine is 35 miles north of the processing facility, which is located in the town of Lakeview, Oregon (fig.1). The ore is transported to customers by truck or rail from the Lakeview plant or the Henley trans-loading facility located near Klamath Falls, Oregon.

The mine property consists of 800 acres of unpatented mining claims located on land administered by the Bureau of Land Management. Within the mining claims, drilling and sampling have delineated a perlite reserve of 5.3 million tons. Test work on core and bulk samples indicates that the Tucker Hill perlite exceeds industry standards for expanded density, furnace yield, and compacted density. The processing facility is located on an industrial park in Lakeview; it is served by a good highway and is on a rail spur operated by a county short line carrier that is linked to the Union Pacific Railroad System at Alturas, California.

Cornerstone also owns and operates a trans-loading terminal in Klamath Falls on the Burlington Northern Railway system, with service to customers throughout the Pacific northwest and Canada. Processed perlite is trucked from the processing facility to the trans-loading terminal. The company sold approximately 90,000 tons of perlite in 2002. It presently ships to customers in 16 states and provinces throughout the United States and Canada as well as by ship to customers along the Pacific Rim.

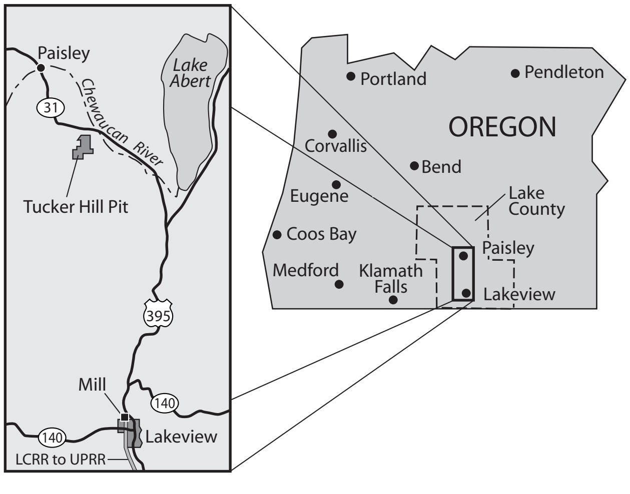

Figure 1. Location of the Tucker Hill pit and the Lakeview mill.

History

Interest in the Tucker Hill area goes back to 1949 when a group of local Oregon prospectors staked claims on perlite outcrops in the northwestern part of the present property. A bulk-sample expansion test was favorable, and small-scale mining was done until 1954 in an area that was easily accessible but contained a high percentage of obsidian nodules. Adjacent areas of high-purity perlite went unrecognized.

In 1980, geologists for Houston International Minerals Corporation (HIMCO), later acquired by Tenneco Minerals in 1982, made a reconnaissance of the area and identified high-quality perlite south of the old mine workings and staked what is now the main Tucker Hill perlite deposit. After continued evaluation by core drilling and bulk sampling, Tenneco confirmed the presence of a significant resource of commercial grade perlite on the property.

In July 1987, Atlas Precious Metals Inc. (Atlas) took an option on the property and subsequently acquired it from Tenneco Minerals in 1988 (Atlas Corp., 1988). Atlas evaluated the property by additional bulk sampling, drilling, and extensive expansion and mineralogical testing that led to a decision to move forward with development. A public company was formed, construction of the processing plant began in 1996, and production commenced in February 1997.

Plant design problems and the deteriorating financial condition of Atlas Precious Metals forced its sale. Seven Peaks Mining Co. purchased the operation in early 1998. Cornerstone, then a subsidiary of Seven Peaks Mining Inc., embarked on a program to renovate and expand the processing plant.

Geology

Regional Geology

The Tucker Hill perlite deposit is in the northeastern part of the Devils Garden lava field (fig. 2), situated at a transitional zone between the Cascade Range to the west and the Basin and Range physiographic province to the east. The lava field is late Miocene to early Pliocene in age (5 to 10 million years old). It is composed largely of olivine basalt flows, minor andesite flows, and related rhyolitic domes, flows, and pyroclastic rocks.

Northwest-trending Basin and Range faults are the predominant structures in the region. The Brothers fault zone, about 50 miles to the north of Tucker Hill (fig. 2) is interpreted as a right-lateral strike-slip fault zone that forms the northern edge of the Basin and Range province (Lawrence, 1976). The less distinct Eugene-Denio fracture

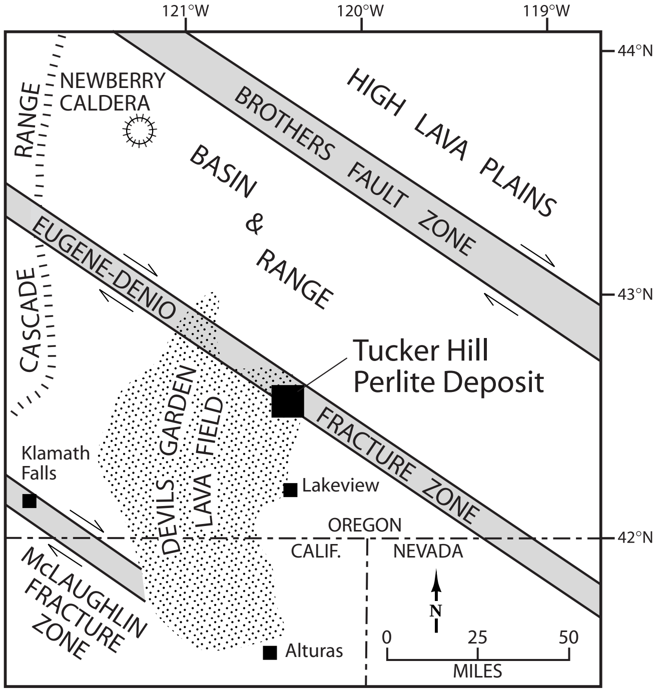

Figure 2. Regional structural trends in the Tucker Hill area.

zone and McLaughlin fracture zone, about 50 miles southwest of Tucker Hill, are interpreted as similar structures. The Tucker Hill perlite deposit occurs within the Eugene-Denio fracture zone.

Rhyolite is fairly abundant in the northern part of the Devils Garden lava field, but is nearly absent in the south. Tucker Hill is one of the late Miocene composite rhyolitic lava domes within the field (fig. 3). An obsidian sample from the Tucker Hill dome has been dated at 7.41 ± 0.19 Ma by the K-Ar method (McKee and Walker, 1976).

Local Geology

The Tucker Hill rhyolite dome complex is a package of flat to shallow-dipping cooling units from several rhyolitic vents that originated during a single eruptive event. Flow foliation and vent breccia veins have revealed three main vents in the dome complex (fig.4).

As a result of differential cooling, the Tucker Hill dome demonstrates distinct lateral and vertical zonation (Wilson and Emmons, 1985). Two major cooling units were recognized, an outer chill margin and an inner rhyolitic core

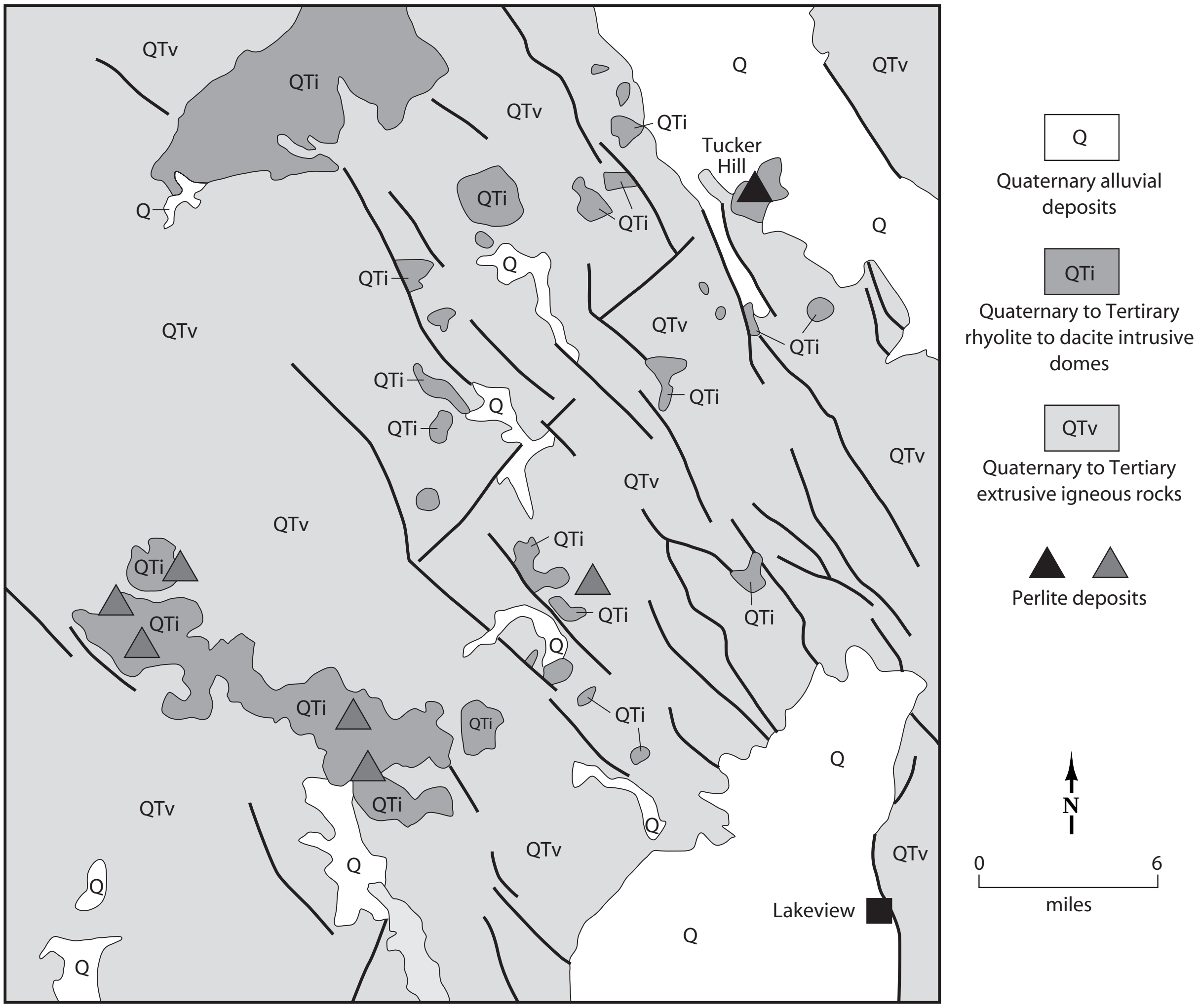

Figure 3. Perlite deposits and intrusive domes in the northern part of the Devils Garden lava field.

(figs. 5 and 6). Vesicle abundance within the rock increases outward from the rhyolite core through the chill margin as a result of degassing of the once molten lava. Conversely, the abundance of feldspar crystallites decreases progressively outward.

The chill margin consists of an outer and inner glass envelope and contains various sub-units of perlite. Classification of these perlite sub-units is based on textural differences that resulted from variable degassing. The textures of the sub-units are: onionskin (classical) perlite, granular perlite, vesicular perlite, and pumiceous perlite. Auto-brecciation is locally common within all of these perlite types. The chill margin was originally obsidian that was converted to perlite as the result of secondary hydration by continued contact with meteoric waters. Spherical fractures (the classical perlite onionskin texture) within chill

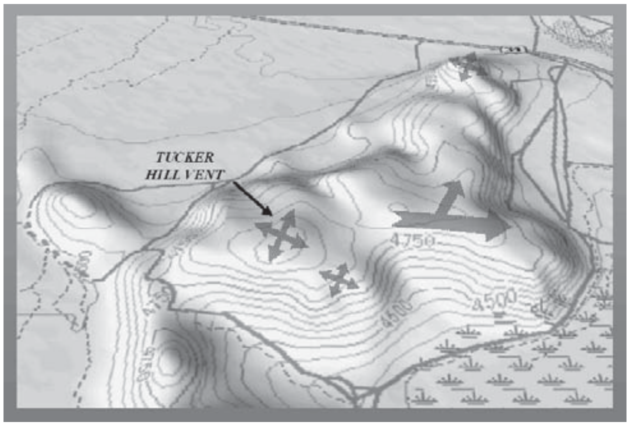

Figure 4. Interpreted vent flow directions at the Tucker Hill deposit.

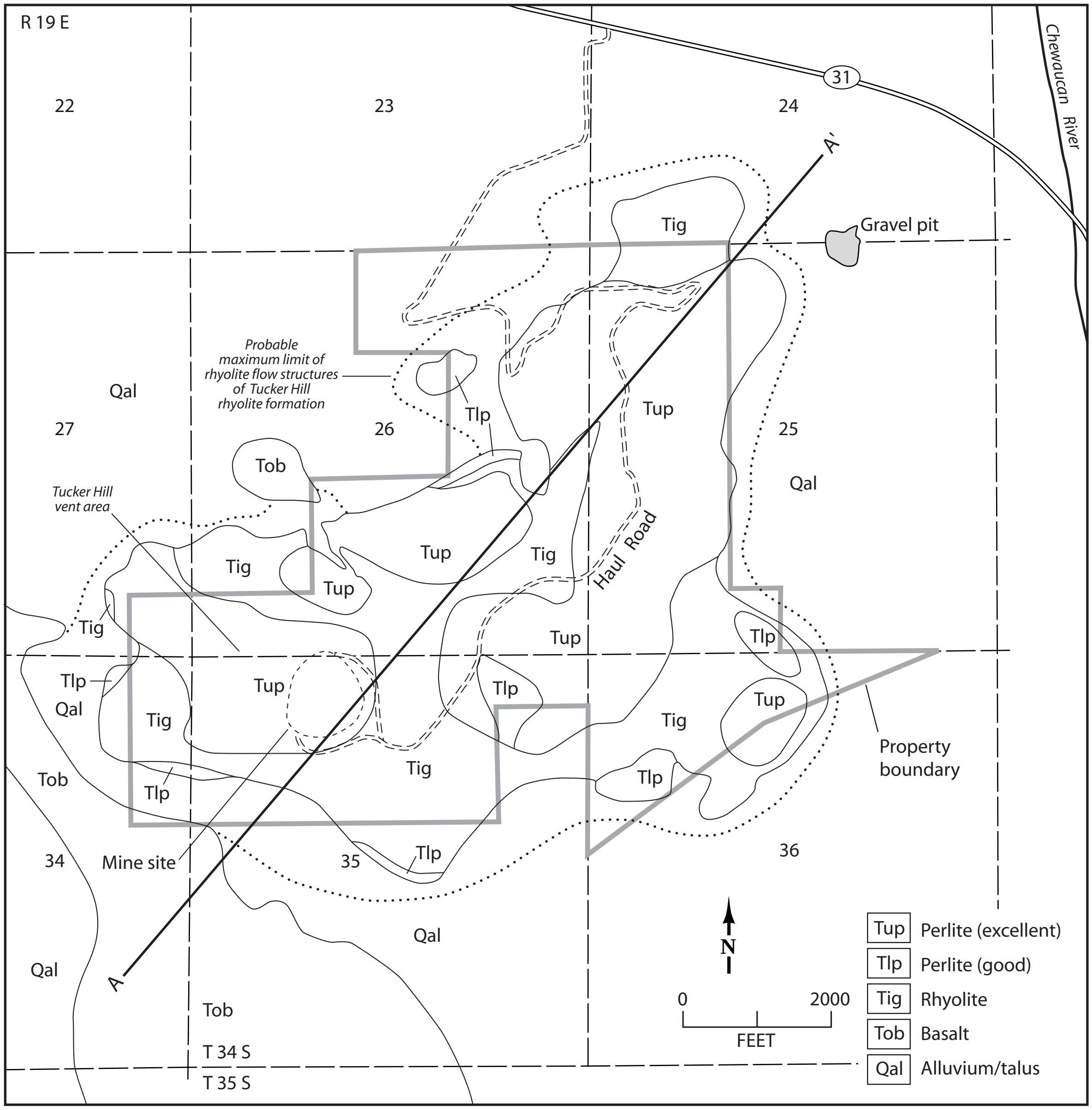

Figure 5. Simplified geology of the Tucker Hill area.

margin perlites are thought to be caused by strain developed by rapid cooling or developed by a volume increase during secondary hydration.

Differential erosion of the Tucker Hill lava dome has removed portions of the outer glass envelope, exposing the rhyolite core (figs. 6 and 7).

Deposit Evaluation and Testing

General

Tenneco Minerals geologists made the first detailed geologic map of the Tucker Hill in 1983, resulting in the identification of significant tonnages of perlite. Atlas conducted additional drilling and bulk sampling in order to determine the economics of the property. Ongoing geological mapping and pit sampling is conducted by Cornerstone in order to characterize the ore and maintain quality control.

Mapping and Sampling

In 1983, 62 surface samples were collected at 1,000-foot intervals along the Tucker Hill area in conjunction with the initial detailed mapping. The Colorado School of Mines Research Institute (CSMRI) conducted expansion tests on 30 of these samples for potential product applications. This work confirmed that the low expanded densities made the Tucker Hill material suitable for most end use perlite markets.

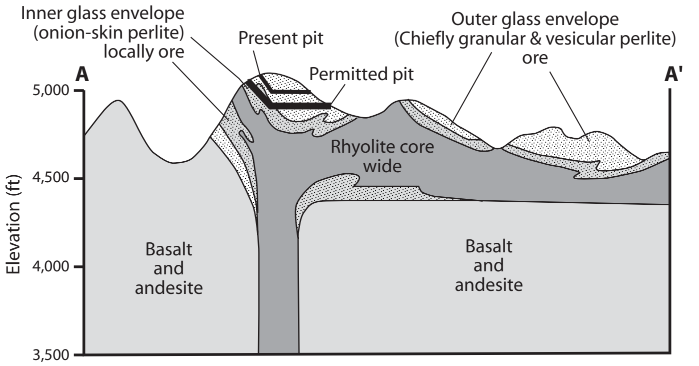

Figure 6. Cross section A–A' through the Tucker Hill deposit.

Drilling

A total of 42 holes (40 core and 2 reverse circulation) totaling 4,525 feet have been drilled on the property. The first six core holes were drilled in 1985 by Western States Minerals Co. Twenty core samples from these holes were submitted to Johns-Manville Research and Development Center (JMRD) for testing. The results indicated that the best overall perlite was found in holes THD85-1 and THD85-2, located in the area of the Tucker Hill Vent (fig. 4), the area of the present permitted pit and proven reserves. All other samples showed good expansion properties.

In 1986, another six core holes were drilled in the area of the Tucker Hill Vent to better determine the expansion properties and determine the thickness of the perlite. In 1987, Atlas Precious Metals Inc. had 31 samples tested for expanded density, compacted density, yield, sinkers, and brightness. The samples generally exceeded the "Grefco Standard" for density and furnace yield.

After taking an option on the property in August 1987, Atlas completed 16 core holes primarily to define additional perlite resources in the immediate and surrounding areas. In 1994 an additional 12 core holes were drilled mainly in the Mine Plan area for detailed mine planning.

Most of the drilling has been concentrated in the southwestern part of the property in the area of the present pit at the Tucker Hill Vent, the largest of the three identified vents. Good quality perlite has also been found in drill holes in the other vent areas, but only a limited amount of detailed work has been completed in these other areas.

Bulk Sampling

Since 1982, 13 bulk samples have been taken from the property for analysis. The first three of these samples (THS-1, 2, and 3) were loaded into fifteen 55-gallon drums and shipped to four different expansion plants where chemical, physical, and optical analyses as well as basic expansion tests were carried out. The perlite was found to be readily expandable at low temperatures, having a high product brightness and low density. Review of the results showed that samples THS-1 and THS-2 consistently had the highest overall quality. THS-1 was taken from a location that is now within the present pit.

Figure 7. Exposed perlite, looking south toward the mine site.

In 1983, another nine bulk samples were taken and shipped to Persolite Products (six 3- to 5-ton samples) and CSMRI/JMRD (three 2- to 3-ton samples). Persolite found that samples Bulk 4 and Bulk 6 had the best overall expansion performance for both the horticultural and loose fill applications. The other samples had acceptable performance, with Bulk 5 being the best of these.

In 1991 in the same location of Bulk 4, Atlas mined and screened a bulk sample, prepared to Georgia Pacific's specifications for testing at its Canby, Oregon expansion plant. The 10-ton sample was shipped and processed in late 1991. Due to internal difficulties experienced at the plant no final report was issued by Georgia Pacific. However, subsequent conversations with the plant manager revealed that the Tucker Hill material met all requirements and successfully produced the Georgia Pacific end product, which is fire-door insulation.

Environmental Testing

Both whole rock and crystalline silica analyses were completed on drill core samples as part of the ore evaluation and the operational permit Environmental Impact Statement. Earlier analyses were completed by the New Mexico Bureau of Mines & Mineral Research (NMBM) and later by Schueller Laboratories. Asbestos testing was later added to the ongoing quality control program. Free silica is less than 1% and the ore contains no detectable asbestos.

Geologic Resources

In October 1983, Houston Industrial Minerals Corp. (1983) made an estimate of "Inferred Perlite Resources - Vesicular and Granular Only." This report included resources within six areas on the property. The estimate was done prior to any drilling on the property; presumably, the areas were selected solely on outcrop mapping and measurements. The thickness of perlite was assumed to be between 25 and 40 feet for the areas in this estimate. The total tonnage of inferred resource perlite was reported as 32,700,000 tons.

In January 1991, Manville Industrial Minerals (1991) completed a detailed resource/reserve evaluation for the Tucker Hill deposit (fig. 8, table 1). Manville's estimate incorporated all available geological information, drill hole data and results from test-work. The estimate yielded a combined resource/reserve of 50,600,000 tons. Of this total, 2,600,000 tons was classified as probable (indicated) reserves in an area well within the permitted pit.

In April 1996, Micon International Ltd (1996) prepared a "Review of the Tucker Hill Perlite Deposit." They reviewed prior resource/reserve work and calculated resources/reserves independently. The evaluation focused on the area delimited by the permitted " Mine Plan."

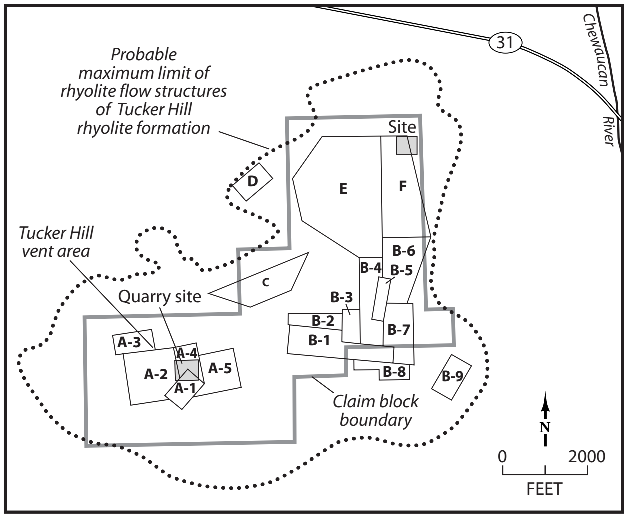

Figure 8. Manville reserve and resource blocks, 1991.

Table 1. Tucker Hill Prospect—Manville Resource and Reserve Estimate, January, 1991

Block no.	Area (ft^2)	Thickness (ft)	Volume (ft^3)	Tonnage*		
				Probable	Possible	Resource
A-1	440,000	90	39,600,000	2,600,000		
A-2	1,255,000	55	69,000,000		4,600,000	
A-3	450,000	40	18,000,000			1,200,000
A-4	375,000	40	15,000,000			1,000,000
A-5	750,000	40	30,000,000			2,000,000
A-1	1,080,000	90	97,200,000		6,500,000	
A-2	360,000	40	14,400,000			960,000
A-3	322,000	40	12,900,000			900,000
A-4	900,000	40	36,000,000			2,400,000
A-5	300,000	40	21,000,000		1,400,000	
A-6	1,005,000	40	40,200,000			2,700,000
A-7	799,000	40	31,960,000			2,100,000
A-8	366,000	40	14,640,000			1,000,000
A-9	495,000	40	19,900,000			1,300,000
C	1,000,000	40	40,000,000			2,700,000
D	4,500,000	40	180,000,000			12,000,000
E	2,100,000	40	84,000,000			5,600,000
Total				2,600,000	12,500,000	35,860,000

*Tonnage factor 15 ft^3/ton

Of the 42 total drill holes on the property, 20 have been drilled within the area designated as the " Mine Plan." All holes were logged in detail and most were sampled in a consistent fashion and analyzed for quality and expansion characteristics. Much of the pre-1994 lab test work was done at the NMBM.

The results of Micon's evaluation are measured plus indicated resources of 5,270,000 tons of perlite in the proposed mine area, the Tucker Hill Vent. Micon also stated that very little internal waste is expected and only relatively minor amounts of pre-stripping would be necessary.

Regulatory Issues

Cornerstone Industrial Minerals Inc. has all operating permits in hand and is on good terms with the government agencies. An Environmental Impact Statement completed for mining activities in September 1996 resulted in a Finding of No Significant Impact. Mining operations are permitted through a Plan of Operations and Reclamation Plan.

Cultural and archeological values were identified during the permitting process. Minimizing the impact to archeological values was set as a goal in the Plan of Operations. A Memorandum of Understanding was signed with the affected Native American tribes.

During the NEPA permitting process, an issue regarding raptors was also identified. Raptors are reported to nest in the vicinity of Tucker Hill. As a consequence, blasting schedules have been modified. Raptor monitoring is currently on going in order to increase the flexibility in blasting schedules. Processing operations are permitted under a use permit issued by Lake County, Oregon and an air quality permit issued by the state of Oregon. The facility is permitted for an annual production rate in excess of 150,000 tons.

Skilled craftsmen are abundant in the Lakeview labor force. The local economy is based on agriculture, ranching, and timber. Severe cutbacks in the timber business and ranching have resulted from major changes in public land management philosophies. Thus unemployment in the area is quite high and there is a surplus of highly motivated skilled labor available.

The process facilities in Lakeview are located in an Oregon state enterprise zone. Enterprise zones encourage new businesses development by providing property tax exemptions for three years. Cornerstone Industrial Minerals Inc. has been certified for an Oregon enterprise zone tax exemption.

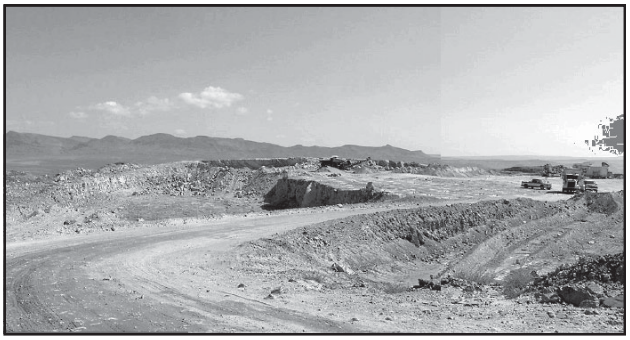

Figure 9. Tucker Hill open-pit mine.

Mining

Conventional open-pit mining is conducted at the Tucker Hill pit (fig. 9). Topsoil and organic matter are stripped from the surface and stockpiled for post mining reclamation. Drilling and blasting loosens the perlite. When necessary, a contractor under the supervision of Cornerstone is does the drilling, blasting and crushing. All blast areas are mapped and drill holes sampled for expansion testing. Ore mining plans are based on the perlite ore types and test results.

At present the ore is crushed to minus 1/2" at the quarry site and stockpiled. The crushed perlite ore is loaded by Cornerstone personnel into over-the-road trucks operated by a local contractor. The trucks haul the perlite to the processing facility in Lakeview where is delivered to the ore stockpile located at the mill. Now that mining has reached below the weathered zone, blasting and possible ripping and crushing operations are currently undergoing an operational review in order to improve rock breakage, material handling, and moisture content.

Processing

The Cornerstone mill (fig. 10) currently produces 11 standard mesh sized product streams, TH-10 through Th-110. More information on specifications is available at www.Cornerstonemineral.com.

Crushed perlite is transferred from the mill stockpile to the first of two scalping screens, and then transferred to a rotary drier operating at 225 to 300ºC. The ore is transferred to the second scalping screen at which point the oversized material is sent to a VSI impact crusher to be sized and recycled. The ore is then sent to five primary deck screens for sizing. The various grades of processed perlite are stored in silos with a total capacity of 1375 tons. An extensive dust collection system recovers fines from all transfer points within the plant.

Figure 10. Lakeview processing facility.

The processing facility went thorough a reconstruction and expansion in late 1999. The addition of four state-of-the-art separating screens and five new silos has increased the operational flexibility needed to provide custom sizing and blending for Cornerstone's customers.

Transportation

Silos with a total capacity of 900 tons and a trans-loading facility are located at Henley, 90 miles to west of Lakeview. Processed perlite is hauled by truck from Lakeview to Henley and off-loaded into silos for transferring into railcars, or loaded directly from trucks into railcars. This facility is available to provide perlite to customers served by Burlington Northern Railroad with connections to the Canadian National Railroad (fig. 11). Processed perlite can be loaded and shipped from the Lakeview processing facility using the local Lake County Railroad, which connects with the Union Pacific Railroad, or it can be loaded on into trucks.

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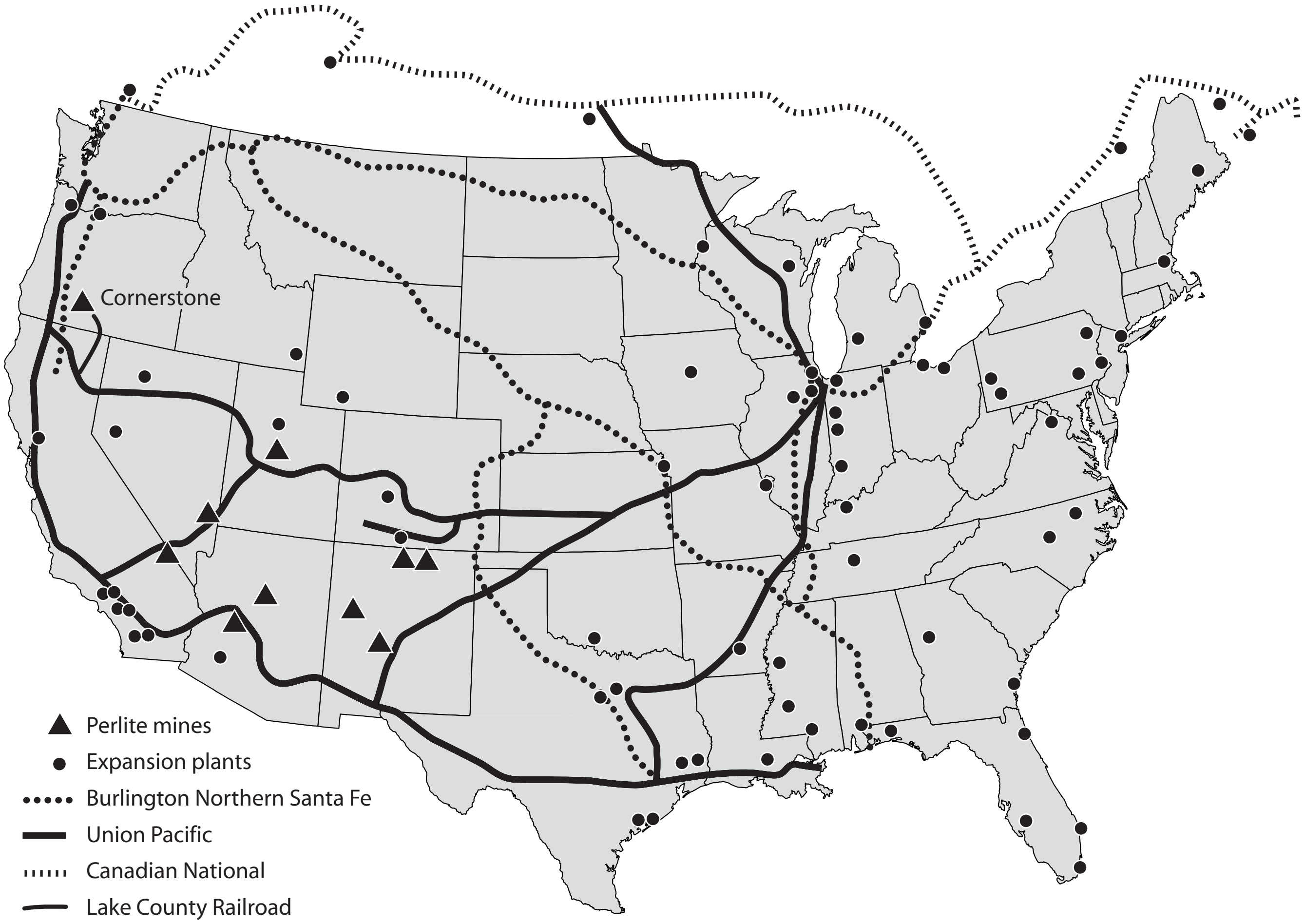

Figure 11. Rail routes, perlite mines, and expansion facilities.

Nevada Cement Company Plant and Raw Materials, Fernley, Nevada

Scott Hardy, Mine Development Associates
Bo Elgby, Nevada Cement Company
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Abstract

Nevada Cement Company operates the only cement plant in Nevada. The plant began production in 1964 with a single rotary kiln, and a second kiln was put into production in 1970. Current production is approximately 560,000 tons of cement per year, the majority being Low-Alkali Type II. The plant is a dry process facility and the kilns are fired by coal from Utah. About 60% of the cement goes to the California market and the remaining 40% is sold in Nevada.

Kiln feed averages 90% limestone, 6.5% clay, and 2.5% iron ore. Gypsum is added to the clinker prior to grinding. The primary raw material is limestone from a deposit located 8 miles south of the plant, and is unique in that it includes sufficient clay and secondary silica to classify it as “cement rock.” It is freshwater Tertiary sedimentary rock interbedded with marl, sandstone, mudstone, and gravel. Tertiary volcanic rocks surround the sedimentary rocks and the entire area has been extensively faulted. The limestone is a discontinuous, massive to thinly bedded unit that appears to be the result of algal activity, similar to that of the Holocene tufa formations at nearby Pyramid Lake. There are abundant bioherms, which are indicative of a warm, shallow, freshwater depositional environment.

Mine planning and characterization are important considerations when mining the limestone because of its variable chemistry and the need for consistent kiln feed. Variable parameters include calcium, silica, magnesia, and alkali contents. Other raw materials utilized include halloysite clay from northwest of Pyramid Lake; iron in the form of waste ballast from sources in Utah; and gypsum from Empire, Nevada, north of Pyramid Lake.

Introduction

The Nevada Cement Company plant is located in Fernley, Nevada, 30 miles east of Reno, off Interstate 80 at Exit 46 (fig. 1). It is the only cement plant in Nevada. Construction of the plant began in 1962 and the production of high quality portland cement began in November 1964. Original design capacity was 540 tons/day. Today Nevada Cement produces and distributes over 560,000 tons of cement annually. Nevada

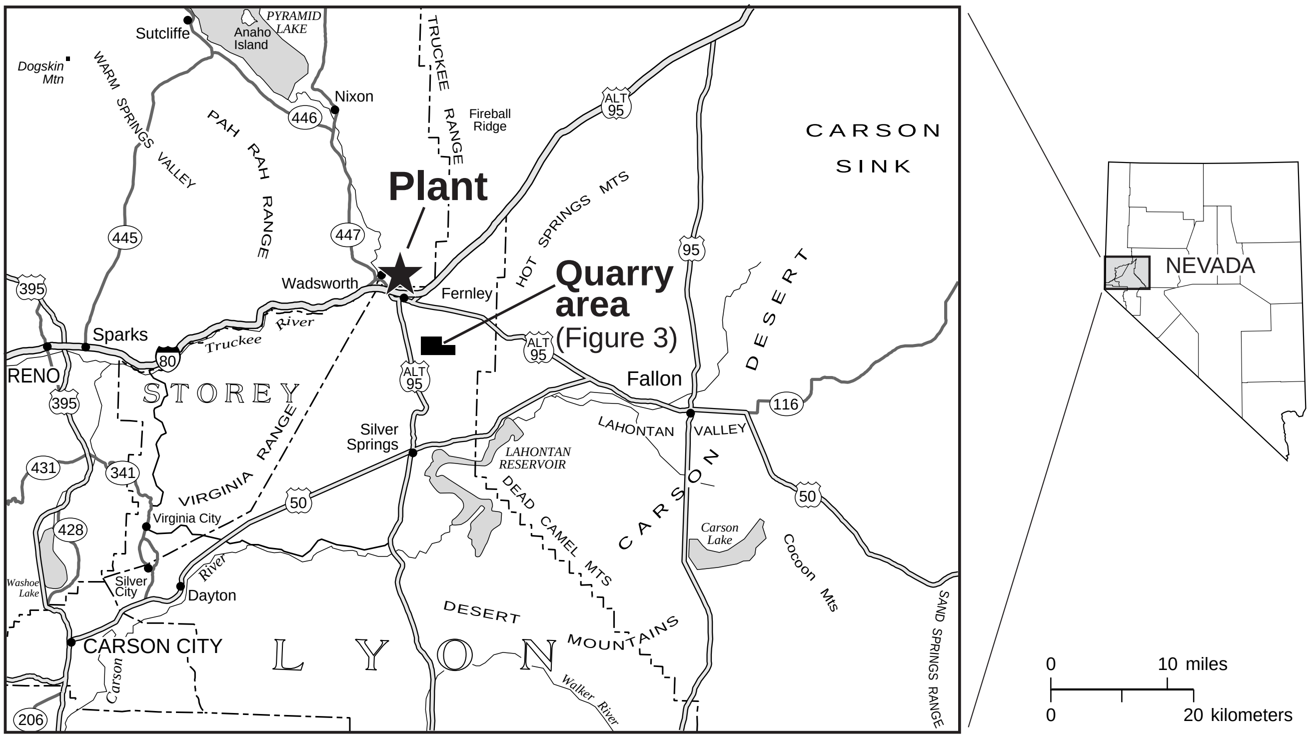

Figure 1. Map showing the Fernley area and locations of the Nevada Cement plant and quarries.

Cement manufactures an all-purpose ASTM-C-150 type II low-alkali, moderate sulfate resistant cement and a 1P cement. The plant is one of four cement plants owned by Eagle Materials, Inc. (formerly known as Centex Construction Products). The other plants are located in Buda, Texas; LaSalle, Illinois; and Laramie, Wyoming.

The current market includes all of northern Nevada, and a rail transfer terminal supplies the Sacramento, California market. These facilities distribute products to ready mix concrete producers, concrete product manufacturers and building material supply dealers.

Major raw materials for the plant are limestone from the quarry 8 miles south of the plant, clay from a quarry northwest of Pyramid Lake, gypsum from a quarry in Empire and sources in California, and iron slag from Utah.

Plant Description

Major facts about the plant are summarized in table 1. The plant is a dry-process plant with two kilns. Kiln feed averages 90% limestone, 6.5% clay, and 2.5% iron ore. Yearly clinker production capacity is 500,000 tons. Originally the plant had one kiln, one raw mill, and one finish mill. Construction of a second kiln, second raw mill, and two finish mills began in 1969, and the new equipment went online in 1970. A Fuller single-stage preheater was added to Number 2 kiln in 1986. Figure 2 shows various views of the plant.

Rock from the limestone quarries is reduced in size by

Table 1. Plant statistics

Location	Fernley, Nevada
Built:	1964
Initial Capacity:	185,000 tons cement /year
Expanded:	1974 to 400,000 tons cement/year
Current production:	500,000 tons clinker/year
	560,000 tons cement/year
Plant:	dry process
	two rotary kilns
	three finish ball mills
	two raw feed ball mills
Fuel:	coal (Utah)
Market:	California (60%)
	Nevada (40%)
Delivery:	rail (50%), truck (50%)
Products:	type II (low alkali) (90%)
	type 1 P (10%)

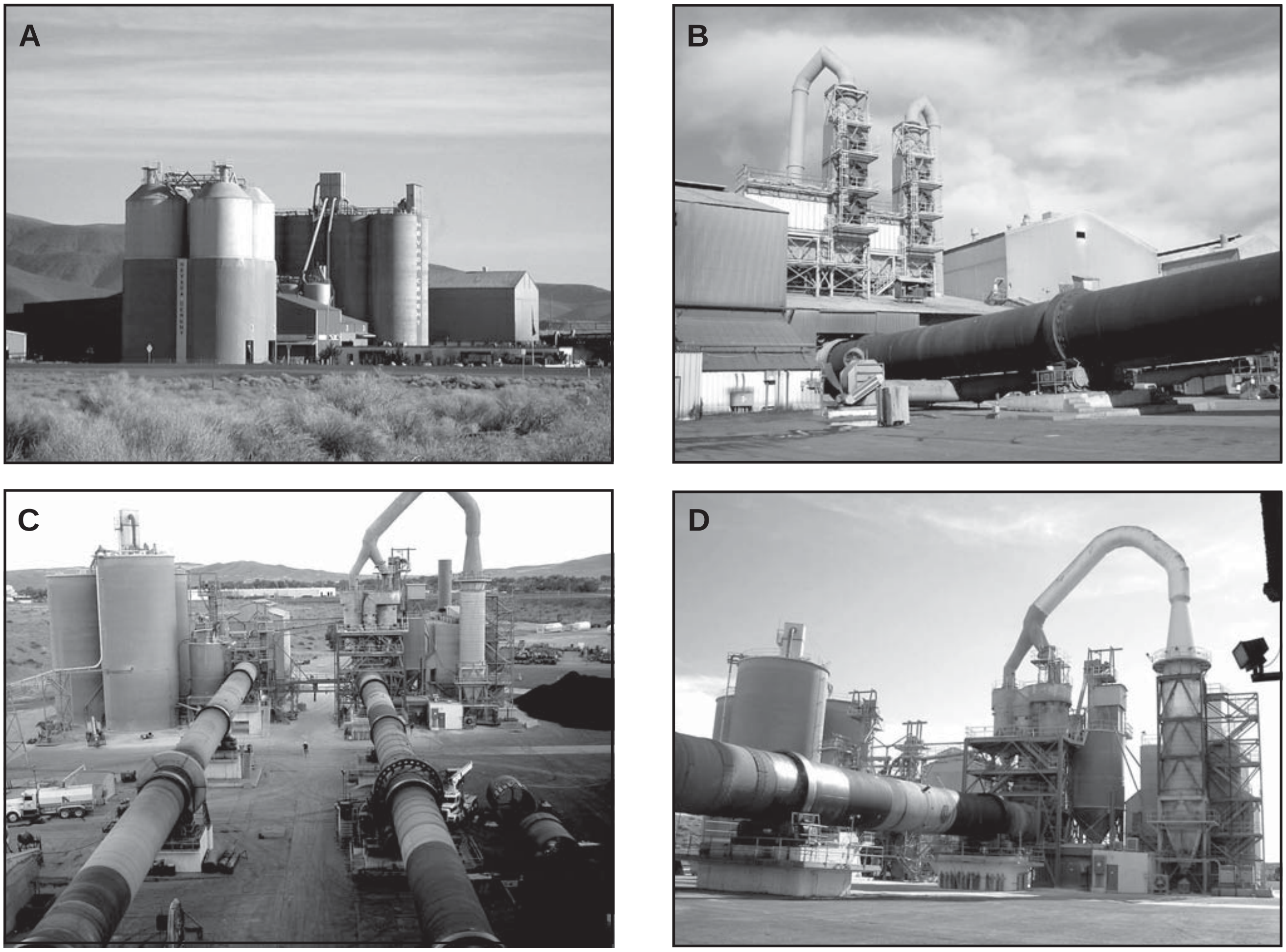

Figure 2. Views of the Nevada Cement plant: A. View of the plant from the southwest; B. View of the number 2 kiln; C. View of both kilns looking south (limestone quarry is on the ridge in the center background.); D. Number 2 kiln showing preheater.

the primary and secondary crushing system to -3/4 inch and conveyed into a covered storage building with a capacity of approximately 20,000 tons. Two raw mills with a combined capacity of 110 tons/hour reduce the raw feed to 80% of -200 mesh material. The two kilns are 11 feet in diameter and 400 feet and 388 feet long, respectively. The finish grinding system consists of three ball mills. The raw mills are also ball mills.

All raw materials, quarry samples, raw grind, fuels, clinker, and finished cement are sampled at regular intervals and analyzed in the plant laboratory. The laboratory is equipped with an Oxford Model QX1287 X-Ray Fluorescence spectrometer to determine Si, Al, Fe, Ca, Mg, S, Na, K, and Ti. Sample preparation equipment includes a Spex 8500 shatter box laboratory mill for fast efficient reproducible grinding of samples, and a Spex X-press (3624B) motorized hydraulic press to produce pellets for X-Ray analysis. A Perl'x3 unit is used for fusing raw feed pellets. For cement testing there is a compression testing machine and a controlled humidity storage cabinet.

Cement is shipped from the plant in both bulk trucks and railcars. There are three scales with 80-ton capacity for trucks and one with 150-ton capacity for trucks or railcars. The maintenance department and machine shop have the capabilities to repair and maintain most of the equipment. Electrical repairs and engineering functions are also included in the maintenance program. A truck shop performs most repairs on mobile equipment.

Geology of the Fernley Limestone

The principal ingredient in cement manufactured at Nevada Cement, the Fernley limestone (informal), is mined about 8 miles southeast of the plant (4 miles south of Fernley) and about 1 mile east of U.S. Highway 95 Alternate. This low range of hills is the eastern terminus of the Virginia Mountains. The deposit is on property owned by Nevada Cement, most of which is private land and patented mining claims, as well as a small number of lode mining claims (Bryan and Kraatz, 1988). The limestone is part of a sequence of late Tertiary freshwater sedimentary rocks deposited in an isolated basin. The geology of the limestone being mined is complex in two respects: the limestone varies greatly in quality, and the structure is very complicated due to abundant faulting.

Late Tertiary Freshwater Basins

There were abundant freshwater basins formed in down-dropped fault blocks throughout Nevada and the Great Basin in the late Tertiary, a result of the onset of basin-and-range faulting and associated deformation (Stewart, 1980). The sedimentary rock sequencess in these basins can be several thousand feet thick and primarily consist of tuffaceous sandstone and clastic materials from rapidly eroding adjacent highlands. Volcanism during this time added material to these enclosed basins leading to the deposition of air- and water-laid tuffs and some interbedded flows. Quieter interludes were also present as evidenced by occasional carbonates and other non-clastic sedimentary rocks. The carbonates tend to be algal-origin limestone, thinly bedded and limited in extent. Some Tertiary basins in western Nevada also contain extensive deposits of diatomite, which indicate a stable, relatively quiet freshwater environment. The diatomite deposition was perhaps influenced by nearby regional silicic volcanism. These early basin-and-range debris-filled basins were themselves subsequently raised by later basin-and-range tectonics and are now undergoing erosion.

Fernley Limestone

The Fernley limestone appears to be the largest deposit of limestone in any of the isolated western Nevada freshwater late Tertiary basins. Figure 3 is a geologic map of the Nevada Cement quarry area showing the Fernley limestone and associated marls. Other sedimentary rocks in the basin include sandstone, mudstone, terrace gravel and interbedded tuffs and tuffaceous sedimentary rocks. Figures 4 and 5 are cross sections of the major mining areas, referred to as the main quarry and the east quarry.

Stephenson (1966) was the first to describe the Fernley limestone in a paper shortly after the cement plant went into operation. He described the formation as consisting...

> "....of light tan to brown fresh-water limestone interbedded with marl and water-laid tuff..... The individual beds or masses of limestone range from a few inches to many feet in thickness, and typically the thicker beds form prominent bluffs on the steep slopes. In places marl and tuff make up the greater part of the formation."

Nevada Cement mined the limestone for over 20 years before any additional geologic work was undertaken. During that time only the western portion of the deposit (main quarry) was mined where three large topographic highs contained many millions of tons of limestone. Toward the end of the 1980s, additional reserves to the east were investigated further and a detailed geologic study was conducted for the purpose of patent on additional mining claims held by the company. At the same time more detailed geologic work on the existing western quarry was undertaken to better characterize reserves. It had become apparent during mining that the geology of the limestone was more complex than originally thought, due to faulting. Several thousand feet of reverse circulation drilling was done the late 1980s through 1992, which helped better characterize the limestone, refine reserves, and led to the development of the east quarry area. Additional reverse circulation drilling was conducted in 1994 and 1998 to further define the deposit and refine the mine plan. The drilling showed that the limestone chemistry varies considerably over short distances and has abrupt facies changes.

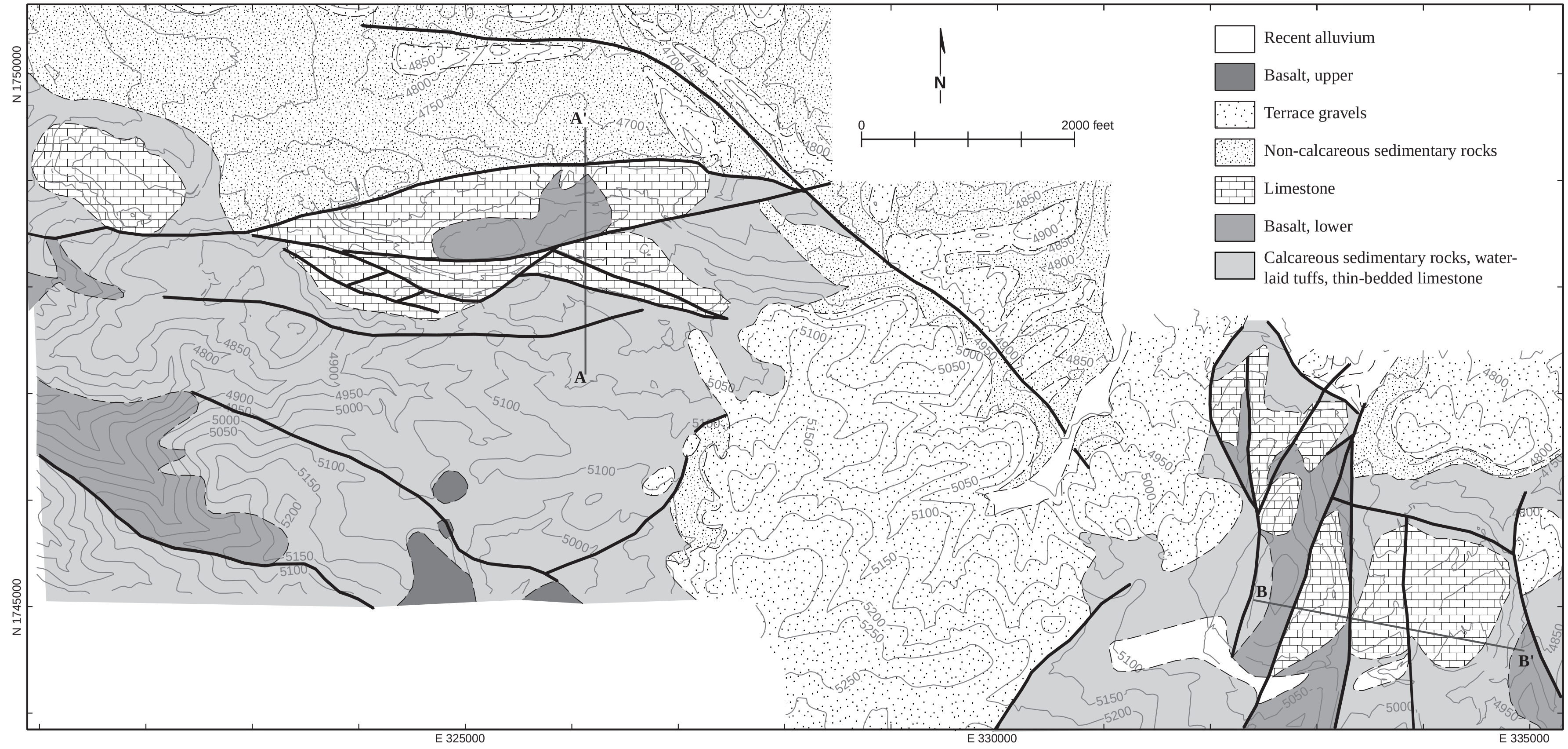

Figure 3. Geologic map of the Nevada Cement Fernley limestone quarry area showing location of cross sections shown in figures 4 and 5. Geology by Dennis Bryan and Peter Kraatz, 1990. Modified by Dennis Bryan and Bo Elgby, 2003. Tics along border at 1,000-foot intervals are Nevada State grid.

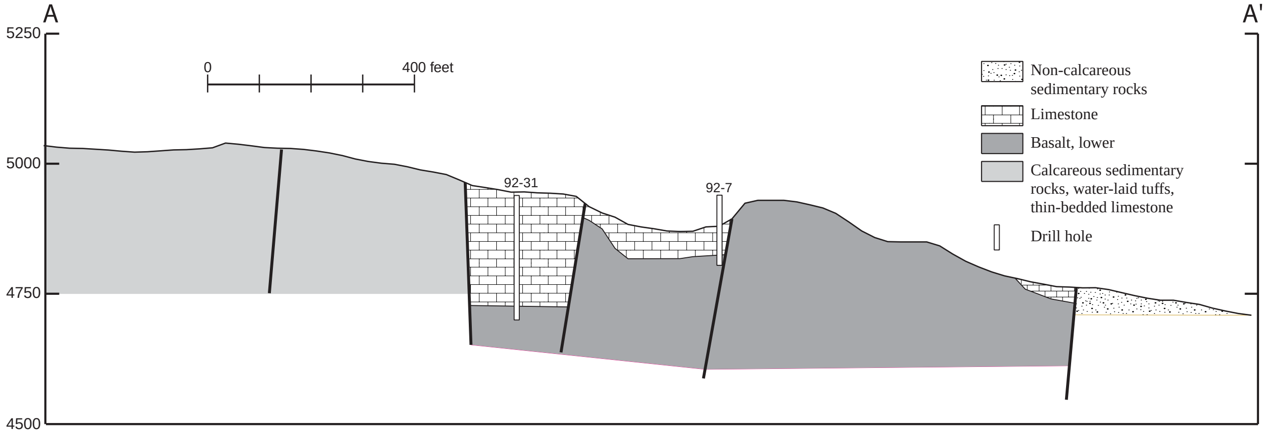

Figure 4. Cross section A–A’, Main quarry area, looking west, showing drill holes.

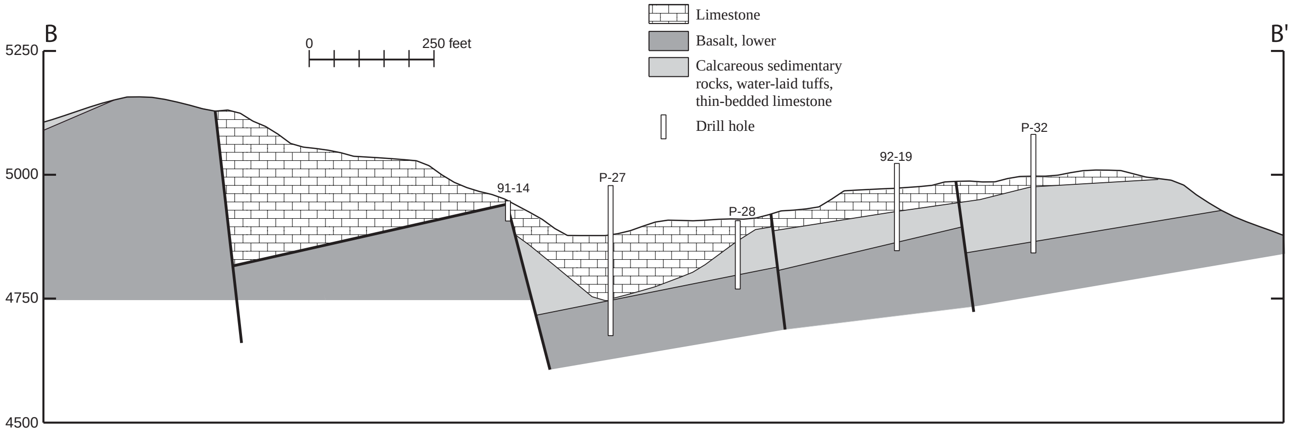

Figure 5. Cross section B–B’, East quarry area, looking north, showing drill holes.

The limestone is concentrated in two areas along a narrow band of ridges and outcrops about 3 miles long, running generally west-northwest to east-southeast. It is the most erosion resistant unit within the basin sedimentary rocks and therefore forms resistant ridges and outcrops (fig. 6). Two distinct concentrations of limestone are about 1 mile apart, both with sufficient reserves for mining. The western area is referred to as the main (west) quarry and the other as the east quarry. The main quarry has been in production from the time the cement plant was built in the early 1960s while the east quarry has been producing material since 1993. The limestone outcrops range from about 4,800 feet to 5,100 feet elevation. The limestone is up to 300 feet thick but thickness rapidly diminishes laterally due to facies changes and faulting. The sedimentary lithologies present range from high-calcium limestones to marls to sandstones, and their distribution and physical and chemical characteristics change rapidly from place to place, both vertically and horizontally. No distinctive identifiable marker beds were recognized during drilling. The highly variable nature of the sedimentary rocks indicate an environment of deposition that may have been dynamically active and changing as evidenced by the presence of abundant volcanic rocks underlying, interbedded with, and overlying the sedimentary rocks.

The Fernley limestone is an algal limestone indicative of a shallow, near-shore depositional environment. Close inspection reveals abundant algal depositional features suggestive of spring-related activity, including crustiform texture, radiating structure including radiating and concentric structures central around hollow pipes, tufa-like textures, and abundant bioherms (figs. 7A–D). The extensive mapping and drilling program revealed that thicker limestone units are very localized and rapidly change to marl and thinner limestone beds within a short lateral distance. These thicker limestone units have weathered out of the surrounding softer marl beds and therefore form very discernible erosion-resistant hills. There are no sizable limestone units found buried outside the boundaries of the known visible limestone outcrops. The thicknesses of these more massive outcrops are somewhat surprising as well. In the east quarry, drilling revealed a limestone mass with a rounded base with a thicker central core that extended downward into the marl and lower-grade carbonate units. The deposition of this limestone,

Figure 6. Resistant limestone ridges in the east quarry area; looking northwest prior to mining.

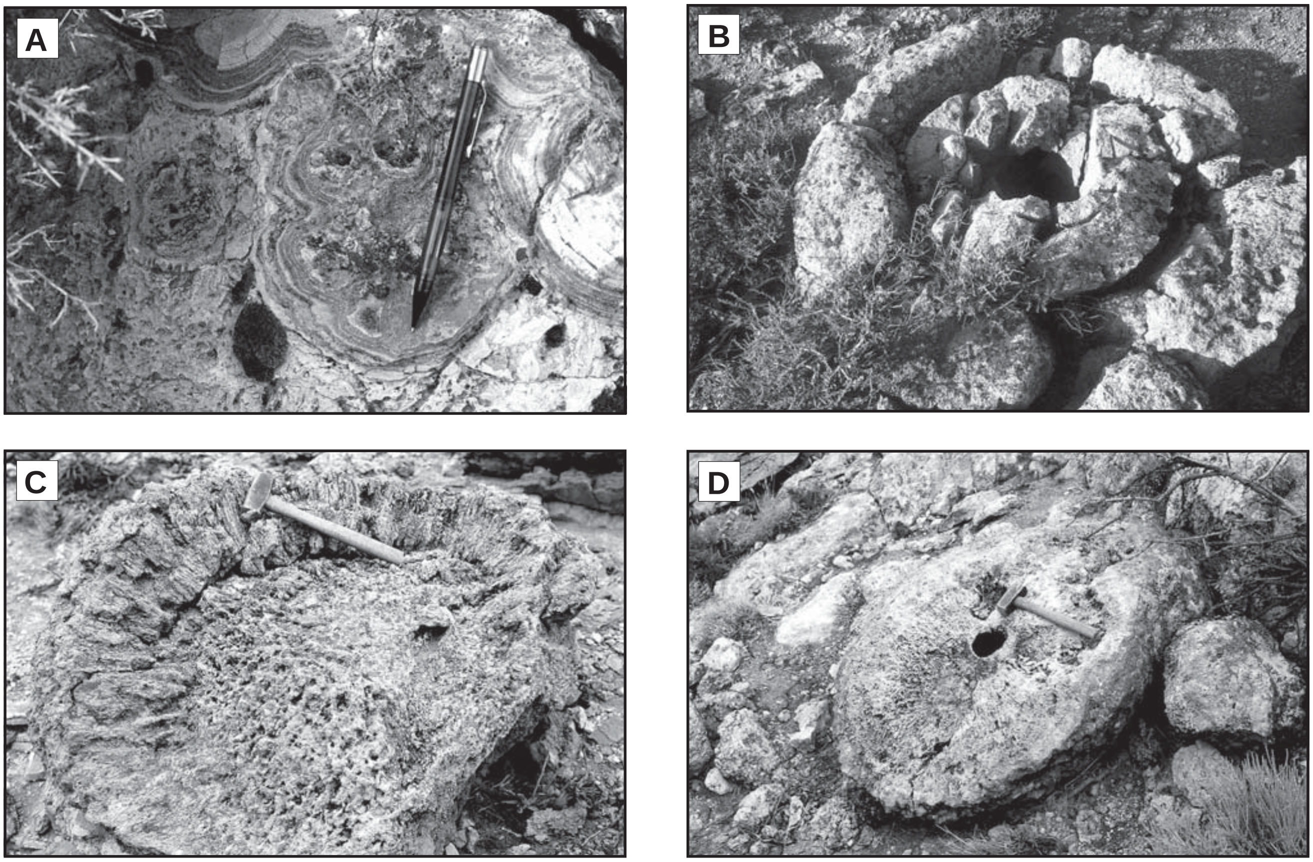

Figure 7. Limestone textures, Nevada Cement quarries: A. Crustiform algal texture; B. Concentric texture around hollow pipe; C. Radiating texture in bioherm; D. Radiating texture around hollow pipe.

Figure 8. Tufa formations at Pyramid Lake; note hot spring steam to right of the formation.

where it is the thickest, appears to have been initiated in one location perhaps by spring activity as described below.

In part, the algal limestone of the late Tertiary Fernley limestone resembles the much younger Holocene tufa mounds at nearby Pyramid Lake (fig. 8). Pyramid Lake is a remnant of Lake Lahontan and is known for massive tufa mounds, which were deposited in warm shallow waters. Many of the large tufa mounds were, and still are, associated with springs, some of which are hot springs. Spring activity, perhaps rich in calcium-bearing fluids, evidently enhanced algal growth and resulted in the large tufa mounds such as the 300-foot-tall "pyramid" along the east side of the lake from which Pyramid Lake gets its name. An active hot spring still exists at the base of this pyramid. The similarities between the Fernley limestone and the tufa of Pyramid Lake suggest similar depositional environments. Both were deposited in warm, shallow, freshwater environments, and the deposition of the larger, more massive concentrations of limestone may have been influenced by thermal waters. The large massive limestone hills of the Fernley limestone may consist of late Tertiary tufa mounds or algal domes (bioherms or collections of bioherms) concentrated partly by hot spring activity that were subsequently eroded out of their enclosing Tertiary sedimentary rocks. There are also abundant crystalline calcite structures believed to be thinolite crystals within the Fernley limestone (fig. 9), very similar to those found at Pyramid Lake. Thinolite, first described by Dana (1884), is a unique form of doubly terminated calcite crystal, which he described as being somewhat unique to Holocene Lake Lahontan and occurring as a product of warm, shallow water in an enclosed basin and calcium-rich environment.

Associated Rock Units

The other rock units that are present but not utilized as kiln feed are briefly described from oldest to youngest below.

Basement basalt—The basement rock within the late Tertiary basin appears to be primarily basalt. The basalt is dark gray to black, underlies the sedimentary rocks of the basin and is probably contemporaneous with the development of the basin. However, the basalt does not exhibit characteristics typical of underwater emplacement. The top of the flow, where exposed in outcrop below the limestone, is often blocky and scoriaceous. Where basalt-carbonate contacts are found, a transition zone exists where abundant basalt boulders are incorporated into the base of the limestone, indicating that sedimentary rocks were deposited on either a scree slope or on a very young, irregular, flow surface. The limestone appears to have precipitated in the voids within and surrounding the basalt cobbles and boulders of an upper rubbleized, irregular flow surface of the basalt (fig. 10). Some basalt boulders appear to float as much as two to three feet into the lower portion of the limestone unit, indicating that basalt cobbles and boulders literally rolled into the calcareous ooze as it was forming.

Associated volcanics—Locally basalt, volcanic tuff, or tuffaceous water-laid sandstone are interbedded with some of the outlying marls on the property. These and other volcanic rocks attest to the volcanic activity of the late Tertiary in western Nevada.

Non-calcareous sedimentary rocks—These units contain little or no calcium carbonate and primarily consist of weakly indurated sandstone, mudstone, and local diatomite. They are typically capped by the terrace gravels and appear to conformably overlie the limestone and marls.

Terrace gravels—Young terrace gravels appear to conformably overlie the marl sediments and probably represent the last depositional stage of the local freshwater lake as it filled with clastic materials from continuously rising adjacent highlands. The gravels are composed of subrounded to rounded primarily volcanic sandy gravels and cobbles that are loosely consolidated and occasionally cemented with calcareous material. These gravels cap several hills in the area and vary considerably in thickness.

Younger volcanics—The youngest unit in the area as depicted on figure 3 consists of basalt and related volcanic cinder capping some of the hills and surrounding the basin sedimentary rocks to the south and east.

Figure 9. Thinolite texture in limestone at a Nevada Cement quarry.

Figure 10. Basalt rubble cemented by limestone.

Structural Geology

The Fernley limestone and surrounding sedimentary basin are located in a tectonically active environment as evidenced by the abundant faults found on the property. This faulting has severely fragmented the sedimentary rocks and complicated the calculation of limestone reserves. This faulting is obviously basin-and-range extension in age and may be closely related to the northwest-trending Walker Lane shear zone, a large structural trend in western Nevada that includes recent movement along a wide shear zone encompassing the entire Fernley area. Faulting in the main quarry, as shown in figure 3, is predominantly east-west while faulting in the east quarry, approximately 1 mile to the southeast, tends to be north-south. The majority of the faulting appears to be dip-slip but there is a component of strike-slip as well. There is also thrust faulting exposed in the extreme western part of the east quarry. A major east-west fault cutting the limestone orebody in the main quarry (fig. 11) has offset the limestone at least 100 feet vertically but shows a combination of both lateral and vertical movement. Probably there are other faults that have not been recognized due to the complex structural relationships and lack of adequate exposures.

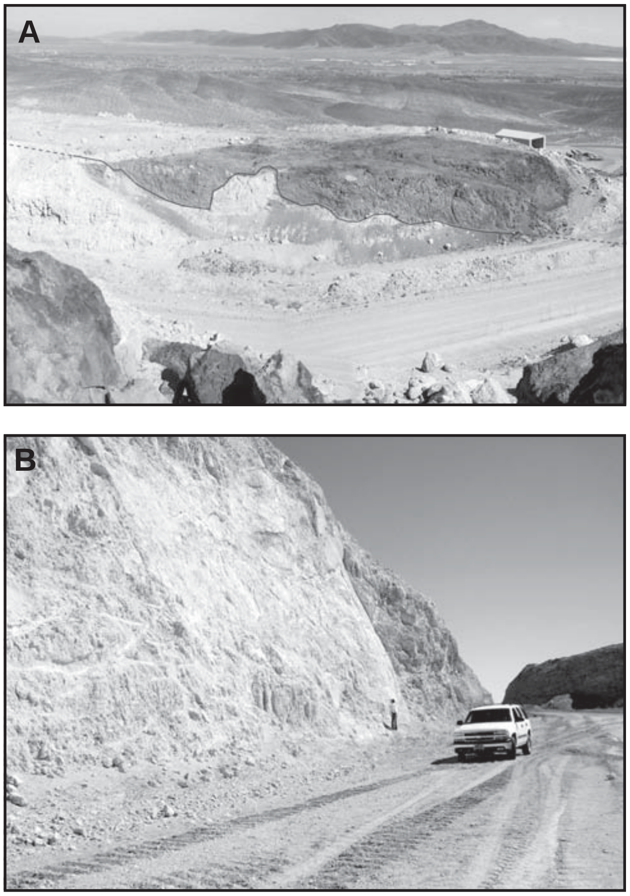

Figure 11. Faulting in main quarry: A. View of a major south-dipping fault looking north; light-colored limestone in hanging wall, dark basalt in footwall. B. Slice of limestone in footwall basalt, looking east along the major fault.

Folding is also observed in the area. In both the main and east quarries bedding attitudes exhibit a general northeast strike with accompanying northwest dip that may indicate the presence of a broad north plunging anticline. Major normal faulting that has exposed the older, underlying basalt flows, apparently disrupts the southern portion of the anticline.

Other Raw Materials

Clay is mined at a halloysite deposit from the Terraced Hills north of Pyramid Lake. A member of the kaolinite family, this aluminum silicate furnishes a high percentage of aluminum and iron to the raw mix. The typical chemical composition of the low alkali clay includes 28% Al_2O_3, 14% Fe_2O_3, and 38% SiO_2.

Basic oxygen furnace slag is also used as a raw material at Nevada Cement. This slag contains alumina, iron, silica, and calcium oxide, which make up the major component requirements of the raw mix. The slag originates from an old steel mill in Utah and is shipped via rail to the plant. There is no need to add additional amounts of silica to the raw mix, because there are sufficient amounts present in both the clay and the limestone to meet the requirements.

Two forms of gypsum are used at Nevada Cement, which are added during the grinding process of the finished cement to control the setting times of the concrete. Natural gypsum is mined at Empire, Nevada, and synthetic gypsum, created at power plants is currently hauled by truck from two sources in California.

Chemistry

The areas mapped as limestone and marl are closely associated, the difference being the amount of calcium carbonate necessary for cement manufacture. A unique characteristic of some reserves of the Fernley limestone is that their chemical composition can be classified as approaching the composition of a “cement” rock. In other words, the rock used as kiln feed contains enough calcium carbonate, alumina, iron, and silica to minimize the import of other materials. Interbedded marls in the limestone unit, as long as they are not too thick or extensive, improve the cement chemistry of the unit.

Limestone is classified as “high stone,” “medium stone,” and “blend stone,” based on chemical compositions. The chemical differences between these classifications are summarized in table 2. The limestone units shown on the geology map and sections (figs. 3, 4, and 5) include these three classifications of limestone. The better quality limestones (high stone with $CaCO_3$ greater than 84%) are buff to beige colored, hard, resistant, thick-bedded high calcium units with a fine to coarse-grained texture. Medium stone ($CaCO_3$ between 75% and 84%) usually includes limestone with higher silica and magnesia. The blendable stone ($CaCO_3$ generally between 66% and 75%) is limestone containing some marl. It has higher magnesia content and must be blended with nearly pure limestone to make a satisfactory kiln feed. High magnesia material such as dolomite is unsuitable for cement manufacture. The marl units generally contain too much clay, alkalis, and other waste materials to be utilized as kiln feed by themselves. Most of the limestone is also very low in alkali (sodium and potassium), which is a requirement for producing low alkali cement. Alkali content increases with increased marl content.

Silica comes from two sources within the limestone. It is found in clays deposited within the interbedded marls and as secondary silica from silicification of the limestone by secondary fluids. This silica is locally abundant as chalcedony and quartz filling of open spaces and may partly be from hydrothermal alteration, since there is nearby oxidized hydrothermal mineralization.

Because the chemistry of the limestone varies so much in the deposit, significant blending is required to produce a quality product. Blending is done on a daily basis by mining appropriate amounts of the three material types, high stone, medium stone, and blend stone. Blend stone and medium stone ratios are kept as high as possible in order to maximize extraction of the overall resource. The chemistry and targeted feed proportions of the materials are summarized in table 2.

The most significant issue is keeping MgO and alkali equivalent (K and Na) values within tolerances. If these constituents are maintained at maximum acceptable levels excellent quality cement is produced.

Nevada Cement and Mine Development Associates built a computer model of the deposit in order to maximize the total extraction of the limestone resource and ensure consistent feed chemistry for the life of the mine. Surface geology was mapped and drilling data interpreted in order to construct the 3-D computer model. This work was done with Surpac software. Limestone chemistry values were estimated into the computer block model from the drilling database. The resulting model contains volumes and locations of the three different material types and their respective chemistries. This model is used as the basis for mine planning, pit design, and blending requirements. Currently work is progressing to generate pit designs and define future mining areas.

Mining

The mining of the limestone in the quarry is by open pit methods (fig. 12). The quarry equipment consist of one Caterpillar 988B loader with a 7-cubic-yard bucket; seven haul trucks equipped with double semi-trailers of 33 ton capacity; one Ingersoll-Rand DM25SP blast hole drill rig; one Caterpillar 12 motor grader, and two Caterpillar bulldozers, a D10R and a D10N both equipped with triple ripper shanks.

Due to the complex geology, abundant facies changes and extensive faulting effective mining is a challenge. Almost all limestone must be blended to achieve a consistently uniform raw feed in the plant.

Most of the limestone in the quarry is drilled and blasted. Earlier in the life of the quarry the majority of the limestone was ripped with the dozers. However, since the latest drilling and blasting program was implemented, and despite the added cost of blasting, downtime on quarry and crushing equipment has been sharply reduced, resulting in improved equipment availability and substantial cost savings. Nevada Cement employees do the drilling, but an outside contractor performs the actual blasting. Blast pattern size varies from 11x11 feet

Figure 12. East quarry, showing benches and mining equipment, looking southeast.

Table 2. Nevada cement raw feed chemistry.

	High Stone	Medium Stone	Blend Stone	Clay	Iron Slag	Gypsum	Pozzolan
C3S	>160	10–160	-140–10	-460			
$CaCO_3$	84–100	75–84	66–75				
CaO	48–56	41–48	33–41	7	48	37	2
SiO_2	<10	10–20	>20	42	20	3	71
$Al2O_3$	<1.0	<2.0	<3.0	30	8	1	14
MgO	<1.0	<3.5	<3.5	1	3	0.3	0.2
Fe_2O_3	<1.0	<2.0	<2.0	16	18		2.5
Alk Eq (K & Na)	<0.3	<0.6	<0.6	1	0.5	0.6	
SO_3				3	2.5	50	2
Raw Feed Blend	50	30	12	5.5	2.5	5*	15–20**

All values in % except C3S (tricalcium silicate crystals in the clinker)
*Added to clinker
**Added to clinker for 1P cement only

in the harder rock, to as much as 13x13 feet in the softer more brittle limestone. Due to the variance in the hardness of the rock in the quarry, tricone bits have been determined to be most efficient for drilling. Drill hole diameter is 5¼ inches, and as the normal bench height in the quarry is 30 feet, the drill holes are drilled with a 4-foot sub-grade to 34 feet for improved fragmentation on the next bench.

The two bulldozer operators in the quarry have the most challenging daily tasks as they separate sandstone layers, impurities, and the odd river and creek channel full of basalt cobbles from the limestone to upgrade the quality of the overall limestone feed. They also push the limestone into easily accessible stockpiles that are loaded into the seven haul trucks by the Cat 988B loader. Normally the quarry operates on a 10-hour, 4-day-per-week schedule. During an average workday, the quarry crew of 12 loads and hauls about 100 loads to the primary crusher located at the plant, resulting in over 725,000 tons of limestone being hauled annually.

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Decorative and Dimensional Stones of Wyoming — Trends and Issues

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Introduction

Most of the State of Wyoming is underlain by the Wyoming Precambrian Province, a province similar in age and lithology to the Superior Province of Minnesota and Canada. This area is characterized by a variety of different colored and textured granites, marbles, gneisses, and other rocks. Uplift and erosion during the Laramide Orogeny, which produced the Rocky Mountains, resulted in their exposure. Exposures of Precambrian rocks at relatively low altitudes are found in southeastern Wyoming and in central Wyoming. Quarriable sandstone, limestone, volcanics, and other rocks are also found throughout the state. With the variety of rocks in a relatively small area and few urban areas, it seems natural that Wyoming could become a center of decorative stone production. For the locations of sites mentioned in the text, refer to figure 1.

History of Wyoming Stone Production

Dimensional and decorative stones have been produced in Wyoming from the first days of settlement when settlers used local stone in the construction of homes, outbuildings, and commercial structures. Larger dimensional sandstone quarries were opened near the towns of Kemmerer, Rawlins, and Laramie. The Laramie quarries were operated by the University of Wyoming for the construction of buildings on the Laramie campus (fig. 2). The Wyoming state capitol was faced with sandstone from Rawlins. The Jay Em Stone Company, located in Jay Em, in eastern Wyoming, produced monument stone, and monument quarries were operated near most Wyoming towns and in Teton Canyon, on the west side of the Teton Mountains. From 1968, when the University Quarry closed, until 1990, no dimensional stone was produced in Wyoming.

Decorative aggregate has also been produced in Wyoming. Red shale produced by the heat from burning coal beds underground, called clinker or scoria, has been intermittently produced from near Buffalo and Gillette, light beige pumice was produced near South Superior, and White marble aggregate, "Wyoming White," has been continuously produced near Wheatland since the early 1950s.

In 1990, Sunrise Stone opened a quarry in a black amphibolite (fig. 3) 30 miles west of Wheatland, Wyoming . The company got its initial contract to produce trim for Bill Gates' house in Seattle. Sunrise Stone changed its name to Raven Quarries (Raven), and named the stone Wyoming Raven (r). Raven also quarried an adjacent stone, a variegated pink and red migmatite, under the name of Mirage(r) (fig. 4).

In 1997 Strid Marble and Granite (Strid) (fig. 5), which cuts block and produces polished slab (approximately 8' x 8' x 5/8"), as well as split stone began producing finished pieces from quarried blocks. This facility is located in Cheyenne. Also in the late 1990s and continuing to today, several companies began harvesting or quarrying moss rock, flagstone, and fieldstone for resale primarily in the growing Colorado Front Range urban areas.

Current State of the Industry in Wyoming

Raven Quarries closed their dimensional stone operations in May 2003 and is looking for a buyer. Raven Quarries ceased existing just after the 39th Forum on the Geology of Industrial Minerals. The quarry owner is selling the quarry site as an individual. Travertine from the Wind River Indian Reservation was quarried in early 2003 and fabricated by Strid for market testing (fig. 6). However, in mid-2003, no dimensional stone is being produced in Wyoming. Several companies and individuals are producing landscape rock, decorative aggregate, moss rock, fieldstone, and flagstone. Imerys Marble produces around 80,000 tons per year of white marble aggregate, including fines, from their quarry and plant near Wheatland. Companies like Wyoming Red Rock in Gillette and Slate Creek Stone in LaPorte Colorado produce significant amounts of these products. Strid Marble and Granite continues to expand and a few other fabricators produce specialized stone products (table tops, counters, etc.) from polished slab and tile in Wyoming.

Four companies are conducting exploration projects for stone in Wyoming. Several potential sites have been identified and are under study for permitting and quarrying. The level of exploration activity is down from the year 2000, when about ten companies were conducting exploration and testing.

Land Acquisition and Permitting for Stone in Wyoming

There are four scenarios for acquiring a quarry site and mining permit in Wyoming; state-owned surface and minerals, federally owned surface and minerals (over 82% of the state); privately owned surface and minerals; and privately owned surface - federally owned minerals. It is the last case mentioned that creates real problems for the developer.

For state-owned surface and minerals the process is the simplest. Stone can be leased for $1 per acre for the first five years and $2 per acre for the next five from the Office of State Lands and Investments. The lessee receives an

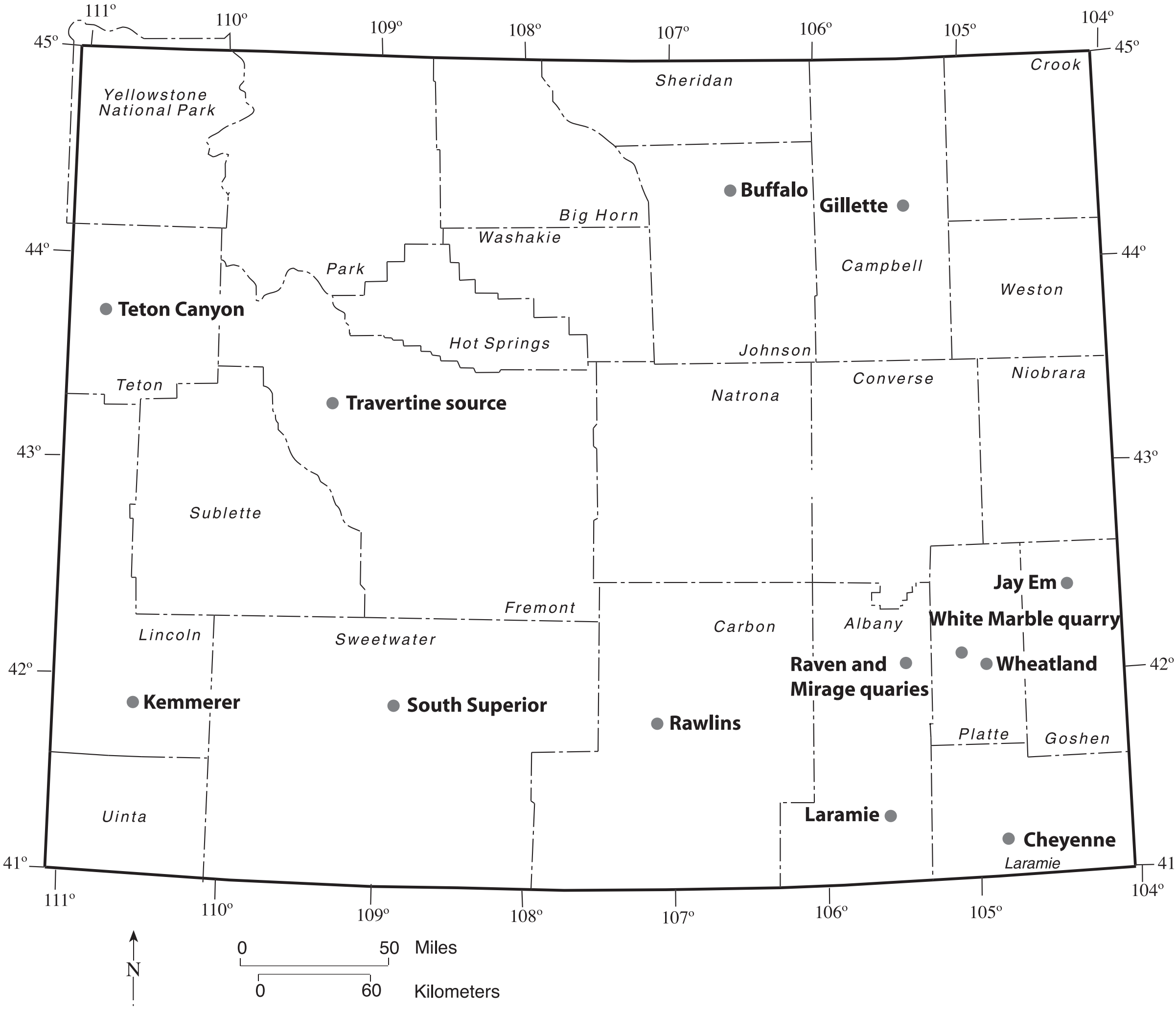

Figure 1. Index map of Wyoming showing localities mentioned in the text.

Figure 2. Geology building on the University of Wyoming Campus. The split-face stone in the wing on the left was quarried 6 miles north of Laramie around 1900. The remainder of the split-face stone is from Utah. The light colored stone around the windows is Indiana limestone, as is the cornerstone (square block right front), the steps are Lyons, Colorado, flagstone, and the trim around the low wall at the left is granite quarried 10 miles southeast of Laramie.

Figure 3. Raven Quarries' black amphibolite quarry.

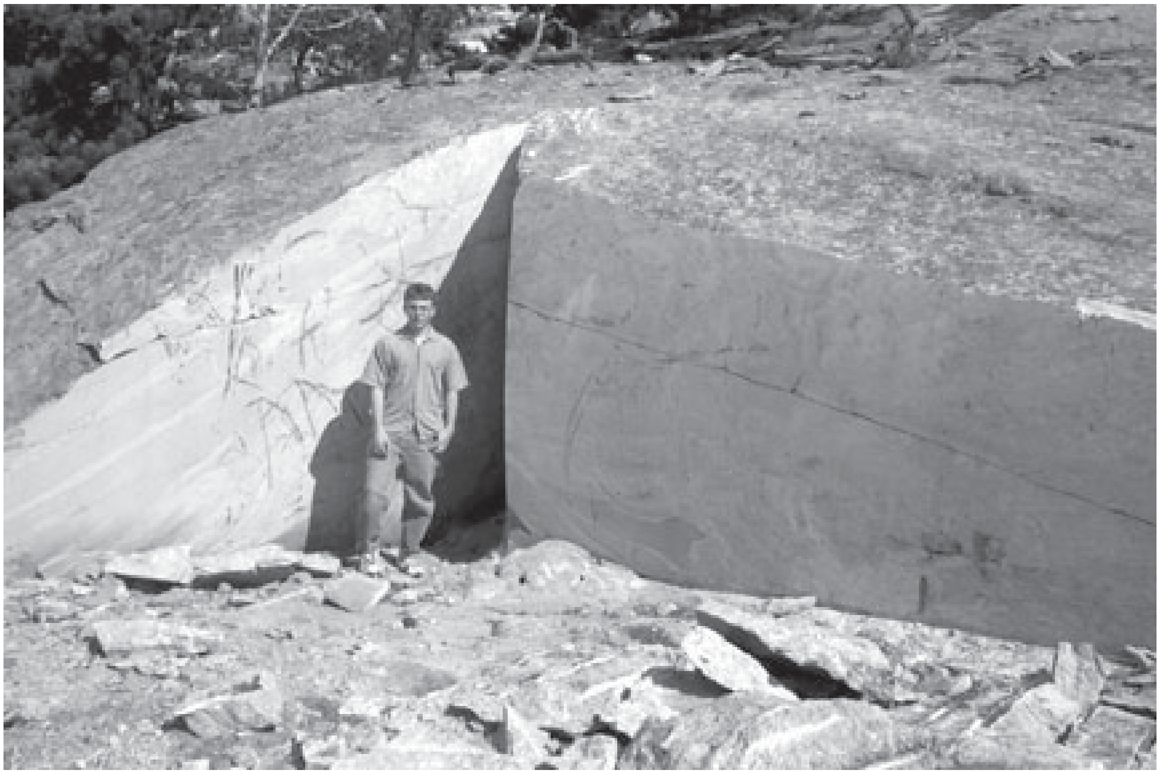

Figure 4. Raven Quarries' migmatite quarry.

Figure 5. Interior of Strid Marble and Granite fabricating plant in Cheyenne. The finished slab on the right is Mirage(r) from Wyoming.

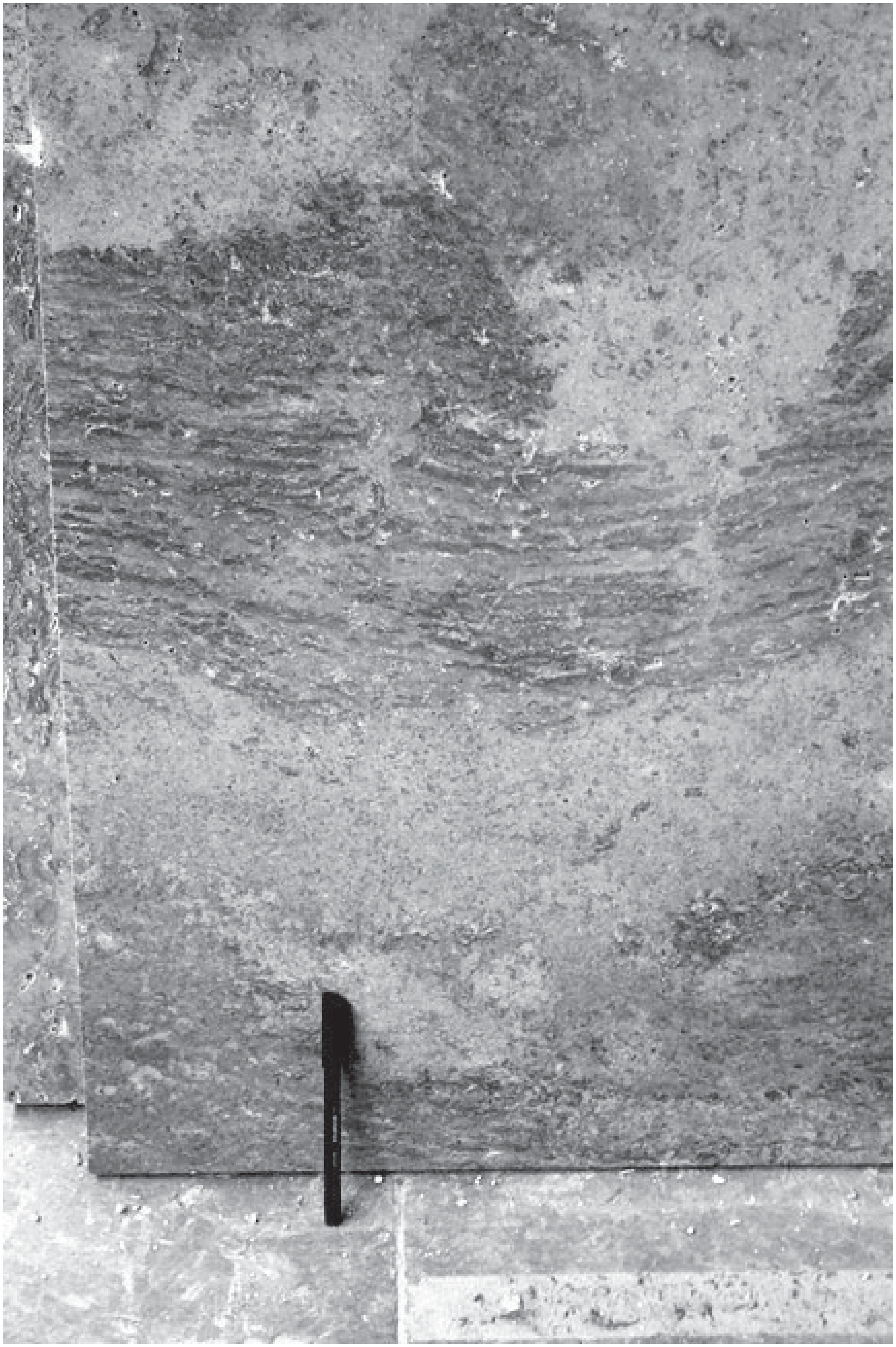

Figure 6. Travertine quarried from the Wind River Reservation and cut and polished by Strid Marble and Granite.

exclusive right to lease and mine for these ten years. Mine permits are handled by the Land Quality Division of the Wyoming Department of Environmental Quality. Necessary permits are Permit to Explore by Dozing or Permit to Explore by Drilling, whichever is applicable. These are inexpensive and simple to fill out. Small Mining Permits are required to quarry dimensional stone. This is for an area of 40 acres and requires extensive form processing and public notification. Attempts to include dimensional stone under a 10 Acre permit have so far been unsuccessful, mostly because the legislation was attached to unpopular bills. Decorative aggregate can be quarried under the 10 Acre permit, which is for a 10-acre-area that includes access roads and requires a relatively simple form and reporting. Also a bonding requirement is set for any permit. State requirements for harvesting from the surface can be obtained from the Department of Environmental Quality (DEQ). The Office of State Lands and Investments maintains mineral development as the highest use and will support the mineral developer in cases of access and grazing rights disputes.

To develop a quarry on Federally owned land (surface and minerals), the developer must negotiate a lease or sale agreement with the Bureau of Land Management (BLM), and comply with their permitting and exploration requirements. Locating stone quarries (claiming) has not been allowed unless the stone has a “unique value.” However, some stone has been acquired by staking claims, having them declared invalid, but receiving a lease or sale agreement afterward. The lease or sale price is determined by a BLM assessor. Mining permits from the state DEQ are the same for all federal lands including national forests as well as BLM managed areas as they are for state lands. Areas of national forests not zoned multiple use are difficult to permit. The developer will have to negotiate access: the BLM may require surface owner permission for access to federal sections if the access route crosses non-public surface ownership. A BLM harvesting permit is necessary for fieldstone, moss rock, and flagstone.

To develop a quarry on private mineral and surface property, negotiate a lease and exploration agreement with the owner. Then state mining permits must be obtained.

A major problem with mineral development in Wyoming and other areas of the western United Statess is the presence of split estates, which are usually privately owned surface and federally owned minerals. Some surface landowners don’t realize they do not own the minerals, and before the late 1970s, an individual or company could stake claims on federal minerals anywhere and develop the property without the surface owner’s consent. However, the BLM requires surface owner consent in most cases and it is up to the developer to obtain it, usually through a damage payment and some other form of remuneration. One way of obtaining consent is to involve the landowner in the developer’s organization, as a partner, investor, or other means. In this case also, the state will require a mining permit.

Advantages and Disadvantages to Developing Stone in Wyoming

In addition to favorable geology and numerous occurrences of many different types of stone, Wyoming has other advantages. These include no corporate or personal income taxes, low sales and business taxes, and a population familiar with mining and its benefits. There is strong support for the mining industry in Wyoming. Disadvantages include its low population (50th of all states), resulting in a lack of nearby markets. Dimensional stone is not classified by statute for severance tax purposes, while other minerals mined in Wyoming are assigned their unique tax rate by legislative action. Dimensional stone comes under the “all other minerals” classification, 10% of the value of the block at the mine mouth, the highest rate charged by the state with the exception of coal. If some major production of dimensional stone is initiated, legislative support may lower the tax rate, as it has in the past for major minerals such as trona and bentonite.

In the current economic situation, foreign competition remains a threat to developing a stone industry in Wyoming as it is to the U.S. stone industry as a whole. Developing quarries and fabricating plants in the United States is at a disadvantage to importing stone produced by subsidized producers with low labor costs. Part of this can be overcome by having the major markets in the country, but it is less expensive to ship stone from Brazil or India to Italy for processing and to ship the processed stone to the U.S. than to ship stone or processed stone from Wyoming to New York or Los Angeles.

Conclusions

Wyoming remains a potential producer of a variety of decorative and dimensional stone products. Land issues, low population, and the transportation costs associated with shipping block to fabricating plants have prevented large scale development. Also, major stone producers seem to be waiting for someone else to construct a plant or large quarry, taking the risk of dealing with permits and regulations that have not been encountered before. However, I believe that the variety of stone in Wyoming will eventually attract investment and development.

Cordierite (Iolite) and Corundum (Sapphire-Ruby): Potential Wyoming Gemstones

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Abstract

Until recently, few gemstones other than jade had been described from Wyoming. However, recent studies by the Wyoming State Geological Survey (WSGS), combined with fieldwork by various prospectors, rock hounds and collectors, resulted in the discovery and identification of several other gemstones, near-gems and lapidary materials.

In particular, some corundum and cordierite deposits have now been identified in the state. One in particular has yielded some high-quality sapphire and iolite. This deposit, known as the Palmer Canyon deposit located west of Wheatland in eastern Wyoming, includes translucent to transparent, facet-grade corundum (sapphire) and cordierite (iolite).

Favorable conditions for the formation of metamorphogenic gemstones within the Wyoming craton occurred during regional amphibolite-grade metamorphism in the Archean. Metapelite in the central Laramie Range containing the index minerals kyanite, sillimanite, and andalusite indicates high pressures and temperatures were achieved. The metamorphic grade along with the presence of favorable host rocks resulted in the formation of some industrial and gem-quality corundum and cordierite in this region.

Within this same general region, undiscovered deposits are predicted based on the presence of corundum recovered in stream sediment samples collected by the WSGS. Other cordierite deposits are also anticipated in this region based on favorable geology and metamorphic conditions.

Introduction

Prior to the 1970s, few gemstones other than nephrite jade were reported in Wyoming. During the past three decades, fieldwork, research, and prospecting by the WSGS and various individuals led to the discovery and identification of some previously unreported gemstone and lapidary material occurrences. Some of the more notable include diamond, sapphire, ruby, star ruby, peridot, aquamarine beryl, green beryl, iolite, pyrope, pyrope-almandine, chromian diopside, chromian enstatite, jewelry grade gold nuggets, labradorite (Norma Beers and Letty Heumier, personal commun., 2000), opal (Scott Luers, personal commun., 2002), variscite and minyulite (Robert Bratton, personal commun., 2002), and several varieties of jasper and agate (Hausel and Sutherland, 2000).

Based on favorable geological environments for certain types of gemstones, near-gems, unique minerals, and lapidary material, further research and field studies should lead to the discovery of additional occurrences. As an example, a research project by the WSGS in the 1980s identified more than 300 kimberlitic indicator mineral anomalies in 1,200 stream sediment sample concentrates in the Laramie and Medicine Bow Mountains in southeastern Wyoming, indicating a potential for widespread diamond deposits (Hausel and others, 1988). Some of these concentrates (<2 mm) also contained grains of gold, aquamarine, and corundum from unidentified sources.

A number of corundum and cordierite occurrences are now known in Wyoming, although many have not been investigated for gemstone potential.

Geological Setting and Genesis

The Wyoming Province consists of an Archean (>2.5 Ga) basement underlying much of Wyoming and large portions of Montana (Hausel and others, 1991). Along the southeastern margin of the province, basement rocks (Proterozoic schist and gneiss) of the Green Mountain terrain abut against the Wyoming Province along a suture zone known as the Mullen Creek-Nash Fork shear zone (also referred to as the Cheyenne Belt) (Houston, 1983; 1993).

The craton was fragmented and deformed during the Laramide orogeny. The style of deformation was brittle and essentially nonthermal. This produced several uplifts that were accompanied by erosion and periodic episodes of renewed uplift.

The basement complex of the province consists of Archean gneiss and schist with scattered greenstone belts and supracrustal terrains intruded by granitic plutons. These include thin successions of metapelite mixed with metagraywacke, metavolcanic rock, and gneiss that has been subjected to regional amphibolite-grade metamorphism with some isolated upper greenschist facies. The regional metamorphism appears to have been favorable for genesis of some metamorphogenic gemstones. Metapelites include sillimanite-garnet-biotite-muscovite-quartz schist, kyanite-biotite-corundum-quartz schist, andalusite biotite schist, sillimanite-kyanite-biotite-muscovite-quartz schist, cordierite gneiss and schist and corundum-kyanite schist.

Corundum- and cordierite-bearing schists and gneisses in these successions are interpreted to represent aluminous shale precursors. One known occurrence of corundum-serpentinite in the Granite Mountains may have also been the result of regional metamorphism imprinted on an aluminous ultramafic magma. The presence of considerable corundum within a narrow zone of the serpentinite suggests the schist may have been subjected to increased local pressure during folding. Other aluminous serpentinites have been identified in the South Pass and Seminoe Mountain greenstone belts, although no corundum was identified in those rocks (Hausel, 1991; 1994).

Estimates for burial depth of metapelite in the central Laramie Range are based on the presence of the three alumino-silicate polymorphs (andalusite, kyanite, sillimanite). These all occur in the vicinity of the Elmers Rock greenstone belt in the central Laramie Mountains. Along the margin of the greenstone belt, Graff and others (1982) identified metapelite with andalusite and sillimanite. A few miles north, at Palmer Canyon, kyanite-sillimanite-corundum-mica schist is found. Thus the presence of all three polymorphs within a narrow region of the central Laramie Range suggests that the metamorphic grade increased to the north, and the highest-grade metamorphism exceeded the polymorph triple point in the vicinity of Palmer Canyon. These data suggest rocks in this region were subjected to lithostatic pressures exceeding 4 kbar (possibly as much as 5.5 kbar) equivalent to a burial depth of 8 to 10.5 miles (12.8–16.8 km) and temperatures exceeding 500°C. The presence of cordierite adjacent to the kyanite-sillimanite-corundum schist supports that those rocks were subjected to relatively high temperatures.

Mineralogy

Several corundum and cordierite localities have been described in Wyoming. Reports of gem-quality corundum and cordierite in the state have been rare until the discovery of the Palmer Canyon deposit, 5 miles north of the Elmers Rock greenstone belt. The possibility of additional undiscovered and unrecognized occurrences of gem-quality material is highly probable.

Cordierite

Cordierite $\{(Mg, Fe)_2Al_4Si_5O_{18}\}$ may form short orthorhombic (pseudohexagonal) prismatic crystals with rectangular cross sections. The common habit of elliptical to rounded porphyroblasts found in many Wyoming specimens is thought to be a result of alteration or resorption under disequilibrium conditions at depth. The mineral is brittle with conchoidal fracture, and may develop poor cleavage parallel to b{010} (on the side pinacoid) and parting parallel to c{001}. Cordierite ranges in hardness from 7 to 7.5 and has a specific gravity of 2.55 to 2.75. It is typically transparent to translucent with vitreous luster (Hurlbut and Switzer, 1979).

According to Sinkankas (1964), the gem variety of cordierite is iolite. The word *iolite* is derived from the Greek word *ion*, meaning *violet*, the common color of gem-quality cordierite. The color of cordierite may vary from yellow to green to blue to violet, but transparent blue and violet-blue grains are sought for gems.

Cordierite is also referred to as *dichroite* due to a strong pronounced pleochroism resulting in gems that appear to change shades of color depending on the angle viewed. In one direction, iolite will appear sapphire-blue; when rotated, it will appear grayish-blue to gray. Wyoming cordierite includes transparent blue nodules, resorbed crystals, rounded black, translucent to opaque grains, and brownish rounded resorbed mineral grains that are partially to entirely replaced by mica and quartz. These latter grains have been referred to as *'peanuts'* or *'almonds'* due to their distinctive, rounded morphology.

Corundum

Corundum $\{Al_2O_3\}$ typically occurs as barrel-shaped, hexagonal prisms or plates with basal terminations. Corundum has no cleavage but often exhibits good rhombohedral and basal parting. Basal terminations often display distinct regular, triangular striations that are expressions of rhombohedral parting, and some prisms may taper to hexagonal pyramids without basal terminations. Corundum may be enclosed by reaction rims of kyanite, sillimanite, zoisite, margarite (a greenish to pink mica) and/or fuchsite (greenish chromium mica). Some Wyoming occurrences are enclosed (or entirely replaced) by reaction rims of zoisite with fuchsite (identified by XRD analyses by Robert Gregory with WSGS).

Corundum has a hardness of 9 and a relatively high specific gravity (3.94 to 4.08), favoring detrital corundum to be concentrated in placers with other minerals of high specific gravity such as gold, magnetite, and garnet. Corundum has an index of refraction ranging from 1.762–1.770, and both the sapphire and ruby varieties of corundum are pleochroic (Schumann, 1997).

Most natural corundum is industrial quality. Transparent to translucent varieties with adamantine to vitreous luster are uncommon, and may potentially yield ruby and/or sapphire. The most desirable color is dark, purplish-red ("pigeon's blood") transparent corundum known as ruby. The most desirable color for sapphire is velvety cornflower blue known as Kashmir blue. Some gemologists refer to other varieties of gem corundum as oriental (i.e., yellow corundum is referred to as oriental topaz, green corundum referred to oriental emerald, violet corundum referred to as oriental amethyst, etc.). However, Hurlbut and Switzer (1979) suggested that gem corundum (other than ruby) be referred to as sapphire with a prefix denoting the color of the stone. Some corundum will luminesce red or orange-yellow under ultraviolet light (Vanders and Kerr, 1967), although Wyoming corundum examined by the author exhibited no detectable luminescence.

Some rubies and sapphires exhibit asterism. These have six-rayed stars of light, which reflect off oriented, needle-like, mineral inclusions of rutile within corundum (Hurlbut and Switzer 1979). The needle-like crystals lie in planes perpendicular to the c-axis. Asterism has been reported by various prospectors in some Wyoming corundum from the Granite and Wind River Mountains.

Corundum may occur as an accessory in some metamorphic rocks such as mica schist, gneiss, and crystalline limestone. It has also been found in silica-poor igneous rocks such as syenite, nepheline syenite, serpentinite and lamprophyre (Hurlbut 1966; Bauer 1968). In Wyoming, corundum has only been found in gneiss, pelitic schist, vermiculite, and serpentinite (Hausel, 2002) and as detrital grains in streams (Hausel and Sutherland, 2000).

Wyoming Localities

The first known report of corundum in Wyoming was by Aughey (1886) who described corundum near the Platte River in the Seminoe Mountains of central Wyoming, and also reported ruby in limestone. Unfortunately, this report appears to be erroneous as there are no known corundum occurrences in the Seminoe Mountains, and no known occurrence in limestone in Wyoming.

Osterwald and others (1966) described some cordierite and corundum occurrences but provided few details. Most Wyoming corundum and cordierite has not been well documented in the past, but those that have been appear to be associated with regional metamorphism.

Corundum has been found in chlorite-biotite schist, vermiculite-biotite schist and mica-kyanite gneiss hosted by Archean orthogneiss within the Wyoming Province. Only one occurrence of corundum has been identified in serpentinite. Following the identification of corundum in vermiculite schist in 1995, a possible relationship between vermiculite schist and corundum was noted, which led the author to investigate other vermiculite occurrences in Wyoming. Following reconnaissance of a few deposits, it was recognized that vermiculites are potential hosts for corundum (at least five vermiculite schists in the state contain corundum) as well as most other metapelite.

Cordierite has been found in metapelite in some supracrustal successions, and has also been described in contact metamorphic rocks along the margin of an anorthosite complex in the southern Laramie Range. One of the more interesting reports of cordierite was by the late mineralogist John Sinkankas. According to Sinkankas (1964), massive Wyoming cordierite was found in the Laramie Range that was capable of being cut. Unfortunately, no location was given. Sinkankas (1959) noted earlier (apparently in reference to the same locality) that gem-quality cordierite was found in the Laramie Range. Sinkankas (1959, p. 475) wrote: “iolite is a widespread constituent of schistose and gneissic rocks in the Laramie Range of Albany County. One estimate has placed the quantity available at thousands of tons. Specimens from this locality examined by the author are glassy broken fragments of rather light blue color, verging towards grayish; small sections are clear and suitable for faceted gems. It is entirely possible that important amounts of gem quality material will be produced from this area in the future.” When contacted, Sinkankas (personal commun., 2000) had no recollection of this occurrence or information on the deposit. But based on size, this might be in reference to the cordierite-gneiss along the southern margin of the Laramie Range anorthosite complex northeast of Laramie.

Laramie Range

Several reports of corundum and cordierite in the Laramie Range make this region attractive for the search for gemstones. More than a dozen stream sediment samples collected in the search for diamondiferous kimberlite in the central Laramie Range yielded detrital corundum (<2mm) (Hausel and others, 1988). The source for the corundum has yet to be identified. There is also a report of purple corundum (0.75 inch in diameter and 4 inches in length) that was found in a granite xenolith in Elk Park northwest of Palmer Canyon in the northern Laramie Range (Ray Harris, personal commun., 1992; Art Snoke, personal commun., 2000). The locality is reported at the NW¼ section 15, T26N, R71W near the Hawks sawmill site on the Laramie Peak 1:100,000. However, the most significant site in the Laramie Range was discovered at Palmer Canyon.

Palmer Canyon—One of the more interesting gemstone discoveries in Wyoming was made in 1995 in Palmer Canyon west of Wheatland (Hausel, 2002). This deposit, located along the eastern flank of the central Laramie Range of southeastern Wyoming, lies about 16 miles (25.6 km) west of Wheatland, a farming community with a population of about 3,500 (fig. 1). This community is located along the northern edge of the Denver Basin 70 miles (112 km) north of Cheyenne. At an elevation of 4,730 feet (1478 m) above sea level, Wheatland has a comparatively mild climate. The Palmer Canyon deposit is located at 5,760 feet (1800 m) above sea level. Nearby peaks reach heights of 6,000 to 7,700 feet (1875–2400 m).

The deposit lies within a narrow inclusion or enclave of Archean pelitic schist and gneiss, quartzofeldspathic gneiss and biotite-chlorite-vermiculite schist within granitic gneiss country rock north of the Elmers Rock greenstone belt. There is no evidence that this deposit had ever been investigated for gemstones in the past, even though a small prospect pit was dug in the schist to test the quality of vermiculite prior to 1944. According to Hagner (1944), this occurrence referred to as the Rolf vermiculite, occurs in a N80°W-trending, 65°SW-dipping, biotite schist that locally contains chlorite, kyanite, and corundum. Hagner (1944) interpreted the deposit to be the result of biotite replacement by vermiculite under the influence of pegmatitic fluids. However, pegmatite is not found in the immediate area. Cordierite schist and gneiss is also found adjacent to the vermiculite, but cordierite was not mentioned or identified during the earlier investigations. Furthermore, no descriptions of the corundum were made by Hagner. In the 1930s and 1940s, vermiculite was sought for fire-resistant insulation.

During field investigations in 1995, only one small prospect pit about 3 feet (1 m) deep and 5–6 feet (1.5–3 m) across was found that indicated there was essentially no production of vermiculite. Samples of vermiculite-chlorite-biotite-corundum schist were found in the pit with as much as 10–20% corundum (much of the schist may only contain 1–5% corundum).

Cordierite was initially discovered in samples collected by the author in 1995 during reconnaissance of corundum-bearing schist. The cordierite was found in quartzofeldspathic gneiss a short distance east of the Roff vermiculite pit, and was confirmed by XRD analysis (Robert Gregory, personal commun. 1996).

The cordierite gneiss crops out over 200 feet (63 m) and has a width of about 10 feet (3.1 m). The gneiss is covered by soil in every direction from the outcrop. The presence of some detrital cordierite found in soil 300 (94 m) feet up-slope from the outcrop, indicates that the deposit is more extensive and has a minimum strike length of 500 feet (156 m). Even so, where explored, the gneiss may contain upwards to 20 to 30% cordierite. Subsequent exploration by Eagle-Hawk Mining in 2002, exposed gneiss with abundant gem-quality cordierite.

Several samples of cordierite gneiss were collected from the property during initial field investigations. These include transparent cordierite grains that weigh 1.5, 6, 11.5, 13.5, 14, 63.5, 109.5, 308.5, 887, 1,715 and 2,948 carats. Another nodule of facet-grade, violet to blue, massive, transparent cordierite was collected that measured 4.25 x 2.5 x 1.25 inches (>3,000 carats), which is the largest gem-quality cordierite found in Wyoming to date. The presence of large gemstone material suggests that the Palmer Canyon deposit could potentially provide a source for large gem-quality iolite stones that are currently lacking in the world market.

The cordierite occurs as rounded to disseminated grains, and as large nodules. A few nodules show intergrowths with quartz. Foliation in the host rock parallels the margins of the nodules, and in a few samples, foliation may also terminate against one edge of the nodule.

The host rock is dark to light gray cordierite-biotite-sericite-quartz gneiss. Kyanite and sillimanite may also be present, but as minor components. Some secondary calcite is found coating some surfaces, and many of the cordierite nodules exhibit a very thin (millimeter-size) alteration halo of chlorite and sericite.

The cordierite was separated into three categories: (1) transparent to translucent, violet to blue cordierite with poorly developed parting and cleavage; (2) dark-gray transparent to translucent cordierite with distinct parting and cleavage; and (3) dark-gray, cloudy, translucent to opaque cordierite with common mineral inclusions and distinct parting and cleavage. In the samples collected by the WSGS, variety 1 dominates.

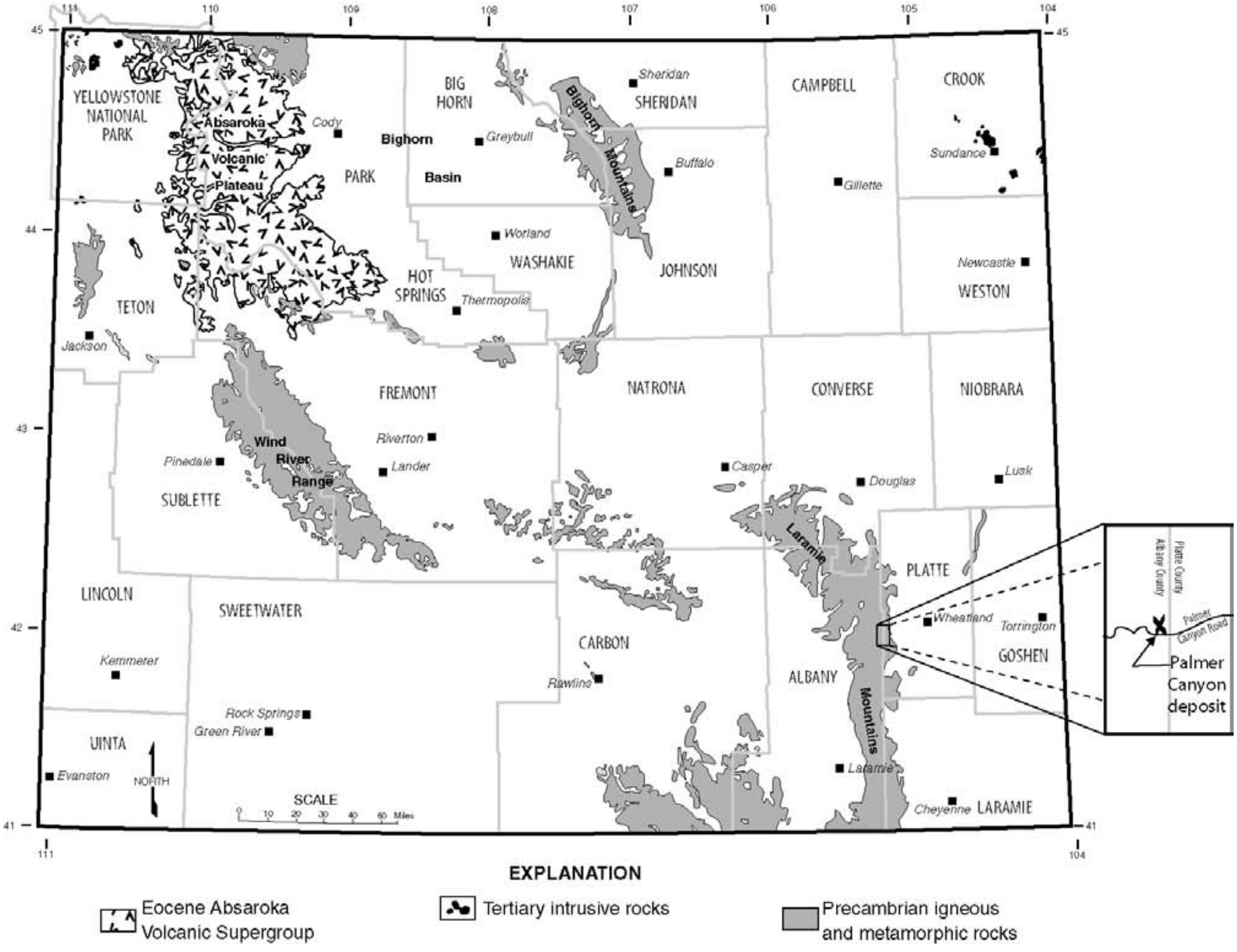

Figure 1. General location map of the Palmer Canyon corundum and cordierite deposit.

Many specimens of variety 1 appear to be suitable for faceting (fig. 2). This material ranges from a pleasing violet to a very light-blue color and exhibits only a hint of cleavage and parting. Some variety 1 cordierite specimens were faceted yielding iolite gemstones with excellent color, transparency and pleochroism. Microscopic examination shows that the gems contain few mineral inclusions, which are for the most part invisible to the naked eye. The mineral inclusions include white, acicular grains (possibly sillimanite) and biotite. The cut gemstones are essentially free of visible cleavage and parting, although one has a visible fracture surface.

Some gray to dark gray cordierite (variety 2) also exhibits good transparency. This variety has well-developed parting parallel to c{001} and cleavage along b{010}. Many variety 2 specimens also exhibit rectangular cross sections: a few with pseudohexagonal habit. A group of cabochons cut from variety 2 cordierite (referred to as "Palmer Canyon black iolite") weigh from 0.27 to 3.02 carats. These are dark-gray to black translucent to opaque near gems with distinct cleavage, parting and some fractures. Placement of the specimens in silver jewelry should greatly enhance their appearance, but otherwise, these are less attractive than variety 1.

Under first approximation, variety 3 cordierite does not appear to be suitable for gem material as the faceted material has many flaws. Two samples of variety 3 cordierite were faceted by Eagle-Hawk Mining and yielded a 3.9-carat lozenge-cut stone, and a 3.4-carat marquise. Both stones were extensively flawed with visible cleavage, parting, and some visible mineral inclusions. However, after these were mounted in gold necklaces, they produced surprisingly attractive jewelry.

Unlike the cordierite, only a small amount of corundum at Palmer Canyon is gem quality. The corundum schist at Palmer Canyon was traced for nearly 1,000 feet along strike. Samples of the corundum-chlorite-biotite schist contain minor kyanite and uncommon sillimanite. Spectacular foliated kyanite-mica-schist located adjacent to the corundum schist, exhibits abundant 1- to 2-inch-long (2.5–5 cm) blades of kyanite, with minor to trace corundum (these remain to be analyzed for potential near gem material). The corundum forms hexagonal prismatic porphyroblasts and plates. The largest prism found by the author is a 1-inch (2.5 cm) prism with 0.3-inch (0.75 cm) diameter. The largest plate measured 0.4 inch in diameter. Larger specimens have been reported by Eagle-Hawk Mining (Vic Norris, personal commun., 2002). The corundum typically averages 0.2 inch (0.5 cm) in diameter.

Figure 2. Faceted iolite from Palmer Canyon, Wyoming. All three stones weigh less than 1 carat.

Three types of potential gem and near-gem corundum occur on the property. These are (1) reddish-pink transparent to translucent corundum (sapphire), (2) light-pink translucent corundum (pink sapphire), and (3) white to light pink translucent to opaque corundum. Microscopic examination of a limited number of corundum specimens shows many to be transparent to translucent with mineral inclusions. Some cloudy to opaque, white to pink corundum is also present.

Several corundums were fashioned into gemstones by Eagle-Hawk Mining. Two of these include brownish-pink opaque corundum fashioned into a 1.4-carat cabochon, and a near-perfect red transparent 1.1-carat marquise with few flaws visible to the naked eye (fig. 3). Other sapphires faceted by Eagle-Hawk Mining include gemstones of 0.75 to 3 carats in weight (Vic Norris, personal commun., 2002). A group of light-pink corundums were also cut for the WSGS: these ranged from 0.17- to 0.45-carats. Two were faceted and two were cut into cabochons. The cabs yielded pleasing, light-pink sapphires, but the faceted light-pink corundum was less attractive due to common mineral inclusions.

The Palmer Canyon occurrence may potentially become a source for some very high-quality gemstones in the future. More important, the deposit illustrates that the potential for colored gemstones has been overlooked in Wyoming.

Anorthosite complex—An extensive deposit of cordierite is described along the southern edge of the Laramie anorthosite-syenite complex and north of the Horse Creek

Figure 3. High quality pink-red 1.1-carat faceted sapphire sits adjacent to a 1.4-carat brown sapphire cabochon. Both specimens sit on hand specimen of corundum schist from Palmer Canyon (Specimens courtesy of the Vic Norris collection).

anorthosite in the central Laramie Range (southeastern Wyoming) several miles south of Palmer Canyon and about 15 miles (24 km) northeast of Laramie. Osterwald and others (1966) reported that widespread lenticular to tabular layers of cordierite occur in metanorite (hypersthene gneiss), gneiss and syenite, along the southern margin of the complex in sections 13, 14, 24, T17N, R72W and 17, 18, 19, 20, T17N, R71W. They indicated at least 500,000 tons of cordierite reserves were found in the region.

The host gneiss is reported to locally contain 50–80% cordierite (this deposit has not been investigated for gemstones, although based on size it is possible that this is the deposit referred to by Sinkankas). The occurrence lies about 0.5-mile west of Raggedtop Mountain, less than 1.8 miles (2.9 km) north of Dirty Mountain and lies in a belt 0.3 to 1.2 miles (0.5–1.9 km) wide and about 6 miles (9.6 km) long. The host gneiss is highly foliated, intensely folded, and contorted.

Subbarayudu (1975) reported the host rock as cordierite-hypersthene gneiss, interpreting the rock to represent paragneiss derived from contact metamorphism of sedimentary rock. The cordierite is fresh and clear and slightly altered to pinite along fracture planes, and may enclose inclusions of zircon and spinel (Subbarayudu, 1975). Formation temperature of the cordierite was estimated at 1000°C by Miyashiro (1957).

Howard (1952) described the weathered cordierite to have dark brown surfaces, but yielded blue or bluish gray (massive) material on fresh surfaces. In thin section, the cordierite forms colorless subhedral to anhedral grains ranging from a fraction of a millimeter to 1 mm across with a refractive index of 1.542 to 1.550. Well-developed polysynthetic twinning is common, but some cordierite is untwined.

Grizzly Creek—Cordierite is reported to occur at Grizzly Creek (section 35, T24N, R71W) with kyanite and sillimanite (fig. 4). The kyanite and sillimanite schist lies in a zone 300 by 5000 feet (94 by 1560 m), just a few miles southwest of Palmer Canyon. Mapping by the late George Snyder of the USGS apparently identified a collector's quarry in the area that contained some corundum and blue cordierite. Some of this cordierite is reported to be light blue and translucent to transparent (B. Ron Frost, personal commun., 2003).

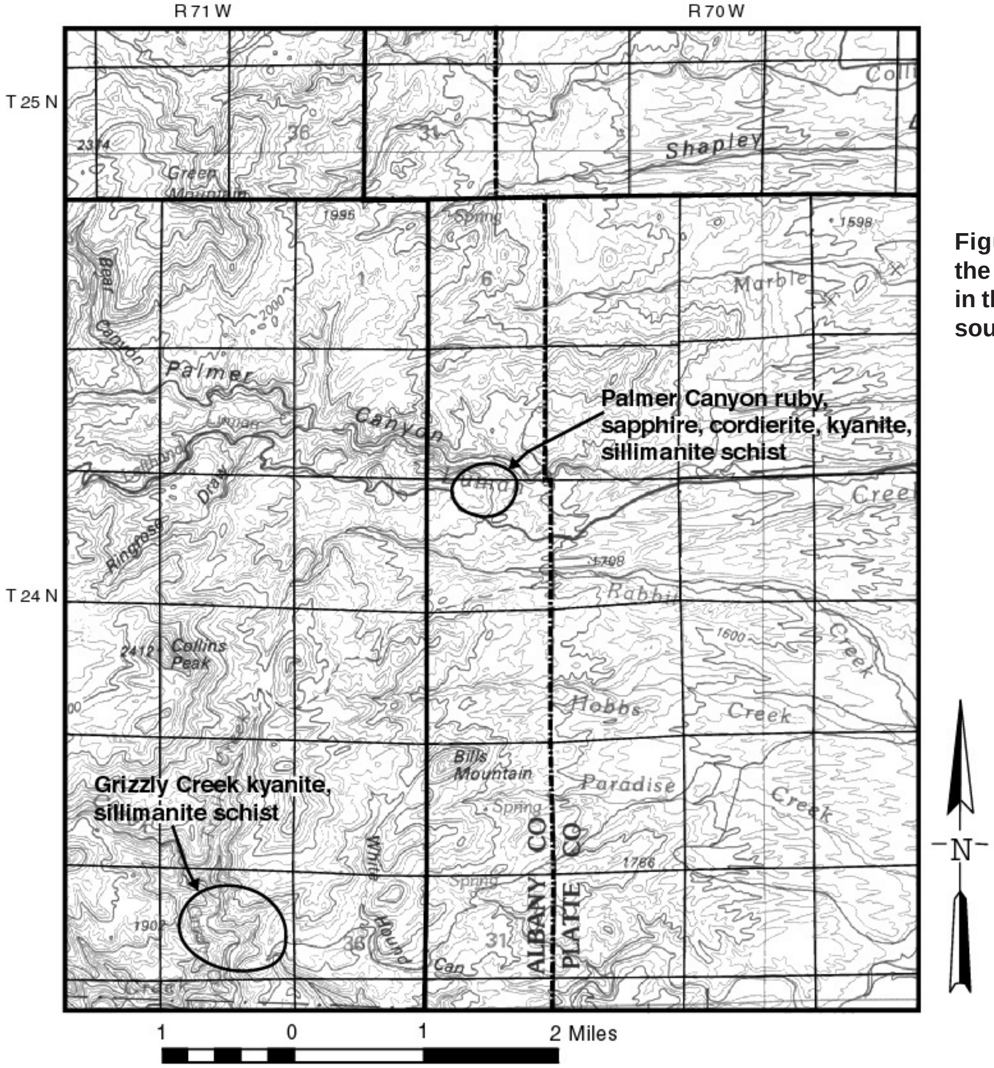

Figure 4. Location map of the Grizzly Creek metapelite in the central Laramie Range, southeastern Wyoming.

Wind River Mountains

Cordierite was also described in the South Pass greenstone belt in the Wind River Mountains of western Wyoming (Hausel 1991), and has also been identified in the Copper Mountain supracrustal belt of the Owl Creek Mountains in northwestern Wyoming (Hausel and others, 1985). Cordierite in these two metamorphic belts forms opaque, black to brown, rounded porphyroblasts typically less than 0.5 inch (1.3 cm) across. Many of the grains are partially to entirely replaced by fine-grained sericite and quartz and no gem material is known from either area.

Abundant placer industrial corundum with some "dark, rich red" rubies (including star rubies) is found in the Big Sandy opening in the southern Wind River Mountains, western Wyoming (Spendlove, 1989). The source of this corundum has not been identified. The detrital corundum has been dredged by hobbyists from Grass Creek (a tributary of the Big Sandy) in section 15, T30N, R104W (Joe Sims, personal commun., 2003), and specimens weighing up to 80 carats have been recovered. The 80-carat specimen shows rounding of the hexagonal prism, which may be due to stream abrasion. Much of the corundum examined by the author is reddish to reddish-brown, opaque to translucent, and gem material was lacking.

Sierra Madre Mountains

Cordierite was also described as almond-shaped grains in schist in the Sierra Madre southwest of Encampment, southeastern Wyoming. One ruby with green transparent beryl was found in the Sierra Madre by a prospector in the recent past. The location of the discovery was not revealed.

Powder River Basin

Cordierite is reported in baked shale and clays above some coal burns in the Powder River Basin in northeastern Wyoming (Osterwald and others, 1966). Descriptions of the material were not given.

Platte Valley

Corundum was found in vermiculite in the Platte River valley along the edge of the Medicine Bow and Sierra Madre Mountains in southeastern Wyoming. One deposit at Baggot's Rock is described as specks of corundum with kyanite and vermiculite in biotite- and hornblende-schist (Osterwald and others, 1966). The deposit was mined on a small scale for vermiculite from 1937 to 1941 (Hagner, 1944).

A few miles south, an open cut in vermiculite hosted by granite-gneiss in the Homestead Draw area contains scattered pockets of ruby. Some have reaction rims of green zoisite similar to those at the Red Dwarf ruby deposit in the Granite Mountains. Rubies were also found in a second vermiculite deposit on the Platte Ranch to the southwest (Ralph Platt, personal commun., 1998).

Granite Mountains

Corundum has been reported at a few localities in the Granite Mountains, central Wyoming. Some gem-quality corundum was described in alluvium along the Sweetwater River both east and west of Jeffrey City. Pinkish red sapphires up to 0.25-inch (1 cm) diameter were found in pelitic schist in NE¼ SE¼ NE¼ section 31, T31N, R89W of the McIntosh Meadows Quadrangle in the northeastern Granite Mountains (Sutherland and Hausel, in press). The corundum is very limited in extent. Deep- to purplish-red rubies were described near Sweetwater Divide. Some specimens of this material were cut and polished, producing star-rubies (Curtis, 1943).

Corundum was found on the Hart Robinson Claim in the Rattlesnake Hills of the northeastern Granite Mountains. One specimen of purple-red, opaque to translucent hexagonal corundum from the deposit was provided to the author and is a little more than 1.25 inches (3.2 cm) in diameter.

Abernathy sapphires—Sapphires were reported from the Abernathy deposit, 40 miles (64 km) east of Lander. The pale-blue to white sapphires were described in a N25°E-trending mica schist enclosed by gray-brown granite near Sweetwater Station. Abundant 1-inch diameter badly shattered, nodular 'sapphires' were found that were altered around the edges (Love, 1970). According to Hagner (1942) poor quality gray to dirty blue, cloudy corundum is exposed in a 5x5x8 foot (1.5x1.5x2.4 m) prospect pit. The biotite-corundum schist is about 4 feet (1.2 m) wide. Pale to bright-red rubies were found in mica schist north of the Abernathy deposit at the Marion prospect. Some of these were cut into gems (Osterwald and others, 1966).

Other rubies were found as float in the Granite Mountains. According to Love (1970), soft green mica schist boulders with dark red rubies were found near Muskrat Creek in the Wind River Formation (Eocene) near Beaver Rim, west of the Gas Hills uranium district, 12 miles (19 km) north of the Red Dwarf ruby deposit. These rubies were up to 1 inch (2.5 cm) in diameter and highly fractured. The source of the schist was not determined.

A nearby placer with abundant, bright red, >1-inch-diameter, fractured rubies was also reported (Osterwald and others, 1966). Chloritic schist float with rubies (similar to the Red Dwarf schist) was also found in the Crooks Gap Conglomerate (Tertiary), along the northern flank of Green Mountain, about 15 miles (24 km) to the southeast of the Red Dwarf deposit (Avon Brock, personal commun., 1982; Hausel, 1986).

Red Dwarf—The Red Dwarf deposit lies a few miles northwest of Jeffrey City (sections 13 and 24, T30N, R93W) in central Wyoming. The host rock is corundum-bearing gneiss with a strike length of 5,000 feet (1560 m) and widths that vary from 20 to 50 feet (6.25–15.6 m) (Hausel, 1997). The gneiss grades from gray biotite gneiss along its northern end, to chloritic schist along its southern end. It typically contains

1–10% corundum porphyroblasts enclosed in fuchsite-zoisite reaction rims (the presence of fuchsite was confirmed by XRD - Robert Gregory, personal commun., 1998).

The largest known specimens of Wyoming corundum are found here. These include a specimen collected by the author that was about the size of a hen's egg, which measured more than 2.5 inches (6.4 cm) across. A specimen collected by J. David Love of the U.S. Geological Survey is a large fuchsite-zoisite pseudomorph after corundum with small (0.25 to 0.5 inch {6–13 mm}) specs of purplish-red corundum. Only half of the original sample remains but measures more than 5 inches (12.7 cm) in length and 3 inches (7.6 cm) across.

A few Red Dwarf specimens were cut into cabochons, but none have been faceted primarily due to the translucent to cloudy nature of the corundum (fig. 5). The fashioned stones are purplish-red rubies (none have been tested by heat treatment). One specimen yielded a 2.77-carat ruby cabochon that shows a couple of parting planes on the stone, but otherwise is an attractive gem. A few specimens of gem-quality ruby cabochons with excellent asterism were produced from this deposit in past years (George Devault, personal commun.).

In addition to the Red Dwarf gneiss, a serpentinite located a short distance west, contains small (average 2 mm diameter), light blue, translucent to opaque corundum (Robert Odell, personal commun., 1998). Locally, this rock contains as much as 20% corundum (Hausel and Sutherland, 2000).

Conclusions

Based on research over the past few decades, several gemstone and near gemstone localities have been identified (Hausel and Sutherland, 2000), and the possibility for discovery of additional gemstone sites is considered high. The discoveries still remain relatively unexplored and essentially all remain unexploited.

The possibility of finding additional gemstone corundum and cordierite deposits in Wyoming is considered very high, as most of Wyoming's mountain ranges are cored by amphibolite-grade schists and gneisses, which include successions of metapelites that are considered favorable hosts for such metamorphogenic deposits.

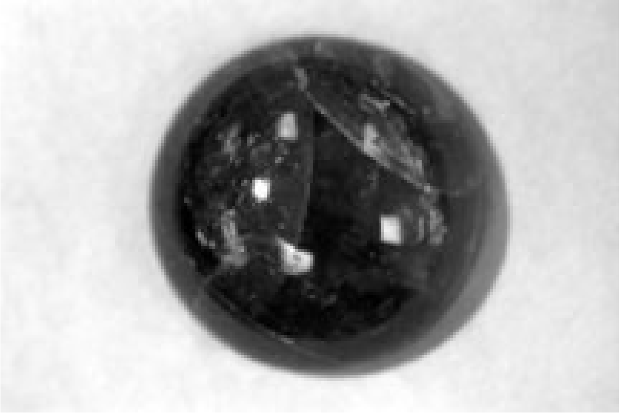

Figure 5. About a 0.5 carat ruby cabochon cut from a Red Dwarf corundum. Note the distinct cleavage.

Recent field investigations have shown correlations among metapelite, corundum, and cordierite, as well as a strong correlation of corundum with vermiculite: about 10–20% of the vermiculite deposits investigated to date contain corundum. Thus, further investigations of Wyoming's vermiculites as well as other metapelites, will undoubtedly lead to the discovery of other corundum and cordierite occurrences.

Acknowledgments

Over the past several years, both Robert Gregory and Wayne Sutherland of the WSGS have provided invaluable assistance on various projects related to gemstones. I would like to also acknowledge and thank Vic Norris of Eagle-Hawk Mining for continued cooperation in the investigation of the Palmer Canyon deposit, and Robert Odell, consulting geologist from Casper, for cooperation and access to his claims on the Red Dwarf ruby deposit.

I would also like to acknowledge my son, Eric J. Hausel for lending me some samples of corundum and cordierite from his collection. The late Dr. J. David Love provided information on various corundum occurrences in the state. Chuck Mabarak also provided pictures of some of the Palmer Canyon gemstones set in gold necklaces from his collection.

The author would also like to thank both Richard Berg (Montana Bureau of Mines and Geology) and Greg Ferdock (CGF Mineral Resources) for their critical comments and review of this manuscript. Their comments greatly enhanced this paper. The author would also like to thank Dick Meeuwig with the Nevada Bureau of Mines and Geology for his editorial reviews.

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The Road to Hungry Valley

Fred G. Heivilin, Oil-Dri Corporation of America

Introduction

Oil-Dri Corp. of America, a Chicago-based company, is the world's largest manufacturer of cat litter and a leading supplier of specialty sorbent products for industrial, automotive, agricultural, horticultural, and specialty markets. Oil-Dri has been mining the fuller's earth in Georgia since 1968 for use in cat litter and other absorbents and adsorbents. The fuller's earth occurs in the Meigs Member of the Hawthorne Group, mostly in southern Georgia (Heivilin and Murray, 1994). Part of the Meigs Member is a high quality white or light tan, low bulk density (22–36 lbs. /cu. ft.), high absorbency (+80%), relatively dust-free clay that contains smectite and palygorskite with minor amounts of amorphous silica as diatoms. The Meigs Member also contains heavier, lower absorption clays composed mainly of smectite.

The company has been attempting to develop a clay deposit in Hungry Valley, north of Reno, Nevada, since Bill Moore showed us the deposit in 1997. However, local opposition to the Hungry Valley project has stymied its development. In December, 2002, Oil-Dri purchased the Taft, California mine and plant built by Excel Minerals and owned by The Clorox Company. The plant is located 120 miles north of Los Angeles and gives Oil-Dri a west coast cat litter operation.

The Oil-Dri Exploration Project

The road to Hungry Valley, 14 miles north of Reno, Nevada, started in 1982 with the request to find a deposit of material similar to Georgia Meigs Member clay, within a few miles of Los Angeles County. The deposit needed enough reserves to supply a major cat litter and oil absorbent plant. Table 1 shows some of the properties that were looked for in a western Meigs Member look-alike deposit. Note that the properties listed in table 1 are listed as exploration guidelines, because it was believed unlikely that we would find a deposit with everything we wanted. The exploration project didn't happen as planned. The search for Meigs Member look-alike material, or similar fuller's earth, widened out to include the area from Northern Mexico to the Columbia River, including most of California, Nevada, Oregon, and Arizona. During this project it became clear that Oil-Dri would have to kiss a lot of "frogs" before finding one with the potential to turn into a "prince" of a deposit.

The western U.S. exploration project, which was part of a larger nationwide search, included evaluations of all deposits and outcrops described in the literature, investigating areas around present plants and old deposits, using local consultants, conferring with geologic surveys, locating new outcrops, checking waste streams from operating plants, and testing samples from prospectors. Oil-Dri searched in deserts and mountains, Wilderness Study Areas, private lands, movie lots, and in areas 100 miles from the nearest supermarket or drug store. Figure 1 shows some of the "frogs" that were evaluated.

The nationwide search resulted in purchases of plants in Ochlocknee, Georgia, Blue Mountain, Mississippi, and Mounds, Illinois, in addition to the Taft, California plant. Many other plants were looked at and eliminated from consideration for cost and quality reasons.

The company looked at clays, diatomite, and zeolites. We tried to mix them together. We looked for parts of larger deposits that would give us the properties we needed in the right location. The exploration trail became littered with deposits of the wrong quality and too little ore. Out of hundreds of sites evaluated, only 14 were found to have the quality that needed. Of these, ten didn't have enough ore, one contained mordenite hopelessly mixed with erionite fibers, one was reported to contain 0.1% erionite on the basis of questionable testing for mineralogy rather than fibers, one is tied up in court, and one is somewhat further from the market and more remote from utilities than we would like.

As a result of this exploration, Oil-Dri now controls the Hungry Valley deposit near Reno, which has some Meigs Member-quality cat litter material; and the Capricorn property, a Meigs look-alike deposit about 85 miles north of Reno. Another result was the acquisition of the Taft operation, which can make some, but not all, of the products that Oil-Dri wants to produce. At Taft, Oil-Dri obtained a deposit of higher density (> 40 lbs./cu. ft.) clay with over 20 years of proven reserves, along with an operating mine and plant with grandfathered rights that are located near the

Table 1. Properties used to evaluate Meigs Member look-alike deposits.

Category	Guidelines
Color	White or light tan
Density	<33 lbs. /cu. ft.
Absorbency	>85%
Dust Content	Low
Hardness	Good granules
Heavy Metals	Low
Asbestos Minerals	None
Crystalline Silica	Low - 10 micron fraction
Erionite	None
Reserves	>20 years
Mining/Transportation Cost	Low or advantageous for a portion of market
Permitable	A must have
Local Zoning Acceptance	A must have
Operating Plant and Deposit	Preferable
Pre-operating Marketability	Preferable

largest west coast market. However, even with the Taft purchase, the company is still missing the west coast production location for a premium, low-density cat litter for which it has been searching.

Nevada Exploration

In 1989, Keith Papke showed us the location of the Capricorn deposit north of Reno. Capricorn was found and drilled by Chevron in the 1920s (Lincoln, 1923) and then its location was lost. This large, premium-quality deposit, which is located in a Wilderness Study Area, consists of calcium bentonite with diatoms (table 2). It was located and claimed in 160-acre group placer claims by Mr. and Mrs. Hill, Mr. and Mrs. Bailey and 4 other locators. Oil-Dri optioned, drilled, purchased, established locatability, and helped the BLM with the patent processing procedure on the Capricorn claims. The patent, prepared by Jim Evans of the BLM, was filed in 1996. However, we knew that Capricorn was years away from patent approval. It was 37 miles from paved roads, 25 miles from utilities, and over 80 miles to Reno making it much more expensive to operate than Hungry Valley. By 1997 we still didn't have what we needed and Capricorn was a long way from patent approval. Even though Reno, Nevada had served as our base of operations for 8–10 years, we had no knowledge of the 5,000-acre-plus Hungry Valley deposit just a few miles north of Reno. In our defense, earlier work on clay deposits in Nevada had failed to turn up the Hungry Valley deposit (Papke, 1976).

By 1999, it was determined that the Hungry Valley deposit had the clay we were looking for. In 15 years of exploration how could we have missed this large, high-quality deposit on our doorstep? The answer is that the much of the clay in Hungry Valley exposed in outcrops and dozer trenches is of poor quality. Good-quality material is under overburden or 18 to 24 inches beneath the surface. Bill Moore, the prospector who collected samples from the area, took weathered material. He sent us samples from the north end of the deposit that were dusty, too heavy, and not absorbent enough even for generic cat litter. This material would not have competed with two operating west-coast plants, which are 350 miles closer to Los Angeles.

In September of 1997, I had a half-day free after checking a large diatomaceous earth deposit south of Yerington, Nevada, and contacted Bill Moore. I picked up equipment to dig into the outcrops so we could get fresh clay. We sampled five locations, getting clay that was harder, had lower density, and better absorbency. It was not premium material, but it indicated that there might be some of it in the Hungry Valley deposit.

Subsequently, Oil-Dri signed an exploration agreement and lease on the first eight 80-acre group placers, and sampled the material using a back hoe because it was right on the surface. The backhoe work and outcrop checks doubled the potential size of the deposit, but it wasn't until the deposit was drilled that we had any idea of the size and the variation of the material in the deposit.

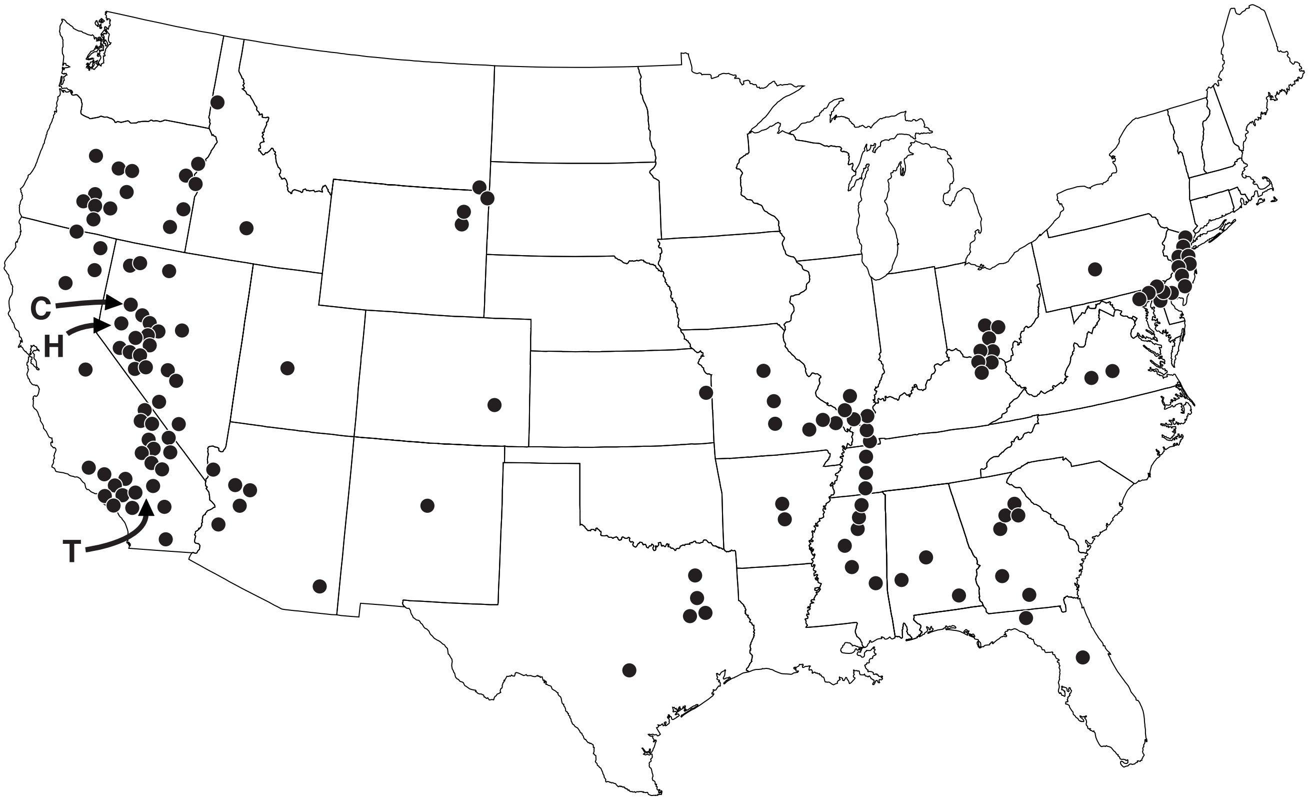

Figure 1. Deposits evaluated during the search for Meigs Member look-alike material. T - Taft, H - Hungry Valley, C - Capricorn

During one day's drilling, seven 100-foot-plus holes on one-mile centers extended the deposit 3 miles further south with a width of 2 to 3 miles in that area. None of those drill holes went completely through the clay deposit, and overburden was found to range between 5 and 25 feet deep that day. Further drilling on the west side of deposit showed clay under more than 70 feet of overburden. The reserves of premium clay were increased around two of the drill holes and then we knew we had enough premium clay to build a plant. None of the premium clay came from the area of the original claims or the initial samples. The deposit was defined with more drilling and backhoe sampling, and ultimately totaled 74 group-placer claims covering 5,824 acres. On a single day during this work, we increased the overall tonnage from less than 80 million tons to over 500 million tons. However, we still needed a lot more drilling to differentiate the premium clay from clay used for generic products. Most of the 500 million plus tons of clay in the Hungry Valley deposit is lower in density and higher in absorbency than clay of the Antelope Formation in the Monterrey Group in the San Joaquin Valley of California. The two major west coast plants near Taft, California, produce from the Antelope Formation. However, premium low-density clay is only a small, as yet unmineable, part of the total clay in the Antelope Formation.

Some of the Hungry Valley clay is premium-quality cat litter material (table 2). It contains 65 to 70% calcium montmorillonite with minor amounts of quartz and feldspar, plus up to 35% diatom tests in places. All of the premium clay found so far is under 3 to 35 feet of cover. Only animal diggings in one location revealed this high-quality material. We discovered the clay in the animal diggings after we had drilled the area. Exposed clay in Hungry Valley did not look like high-quality material, and exposures of the Pliocene lacustrine unit further north consist of siltstone without significant clay or diatomaceous components.

Conclusions

It is very probable that other clay deposits exist where surface material is not of good enough quality, but sampling at depth by drilling or backhoe work could provide evidence of high-quality material. It happened at Hungry Valley, and will happen again with other clays and other mineral deposits. You will have to answer for yourself how many more deposits are out there and how many "frogs" you will have to kiss to find them. Based on the Oil-Dri Hungry Valley experience, if you find such a deposit, other considerations, including permitting and local zoning, may present obstacles to mine development.

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Table 2. Comparison of the Taft, Capricorn, and Hungry Valley deposits with the properties and guidelines desired by Oil-Dri for a Meigs Member look-alike cat litter material deposit. Transportation cost is estimated in comparison to that of competitors, and such cost will vary depending on the marketing area considered. Moderate (Mod.) transportation cost equals slightly higher transportation charges than competitors.

Category	Guidelines	Taft	Capricorn	Hungry Valley
Color	White or light tan	Yes	Yes	Yes
Density	<33 lbs./cu. ft.	No	Yes	Yes
Absorbency	>80%	No	Yes	Yes
Dust Content	Low	Low	Low	Low
Hardness	Good Granules	Good	Good	Good
Heavy Metals	Low	Low	Low	Low
Asbestos Minerals	None	None	None	None
Crystalline Silica	Low	Low	Low	Low
Erionite	None	None	None	None
Reserves - Premium*	>20 years	>20 years	>20 years *	>20 years *
Mining/Transportation Cost	Low/Mod.	Low/Low	Mod./Mod.	Mod./Mod.
Permitable	A must have	Yes	Yes	Yes
Local Zoning Acceptance	A must have	Yes	Maybe	?
Operating Plant and Deposit	Preferable	Yes	No	No
Pre-operating Marketability	Preferable	Yes	No	No

Late Miocene Diatomite Formation Near Fernley, Nevada

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Abstract

Diatomite deposits near Fernley, Nevada, characterize a complex, tectonically active late Miocene lake-basin environment influenced by faulting, westward tilting, and changing lake levels. The diatomite deposition documents two overlapping stages of basin evolution: an early stage characterized by active faulting, tilting, centric diatom formation, and clastic sedimentation (9.8–9.5 Ma), and a later stage of relative tectonic quiescence, and pennate diatom formation (9.5–9.4 Ma). In the middle and late Miocene, extensional faulting produced a topographic and structural framework of west-tilted, half-grabens that, with rising lake levels, formed a series of narrow lake embayments. Early-stage sedimentation in these embayments included a thick sequence of coarse clastic rocks with interbedded diatomite. The diatomite beds are dominated by planktonic, *Aulacoseira* diatoms that accumulated in a near-shore environment between periods of clastic sedimentation. The beds have a westward tilt, but bedding invariably lessens up-section. This shallowing, as well as the persistence of reworked sediments through the lower section, confirms that faulting and westward tilting accompanied basin sedimentation. As the lake basin evolved, tectonism decreased, grabens became sediment filled, and a subdued basin topography developed. Late-stage lake sediments are dominated by extensive benthic, pennate diatom beds that indicate a lake with increasing surface area, but decreasing water depths. The pennate diatomite beds overlapped many of the early graben-forming faults and, at least locally, remain untilted. As such, this sequence is effective in bracketing the end of most extensional normal faulting in the Fernley area.

Introduction

The Fernley diatomite deposits are in an area of approximately 15 square miles of the northeast Virginia Range in Lyon and Churchill Counties, Nevada. Commercial-scale diatomite mining is ongoing in three locations within T19N, R26E. Celite Corp. operates a full-time quarry in Section 17, and Eagle Picher operates seasonal quarries in Sections 6 and 9. The diatomite is used in a variety of filler applications, including agriculture and construction products, as a silica source in the manufacture of calcium silicate insulation, and in high brightness, paint-grade filler applications. Diatomite was first prospected in the area in the early 1950s, and limited commercial production began in the late 1950s. Despite having a significant production history, the area has received little geologic study. Celite Corp. began a program in 2001 to evaluate the diatomite potential of their mine and the surrounding district by geologic mapping and drilling. One outcome of this program has been the opportunity to reconstruct the late Miocene basin history around in the area. Neogene basin-filling sedimentary rocks are widespread in western Nevada, yet poorly understood. It is hoped that this study will improve the general understanding of these sedimentary deposits, as well as the chronology of Neogene volcanism and extensional faulting in the area.

Geological Setting

Western Nevada

The Fernley deposits (also referred to as the Hazen diatomite deposits) are situated near the western edge of the Basin and Range province within a small, northeasterly outlier of the Virginia Range (fig. 1). The area lies immediately east of the Walker Lane, a north-northwest-trending, segmented zone of strike-slip faults that is transitional between the Basin and Range and the Sierra Nevada province to the west. The

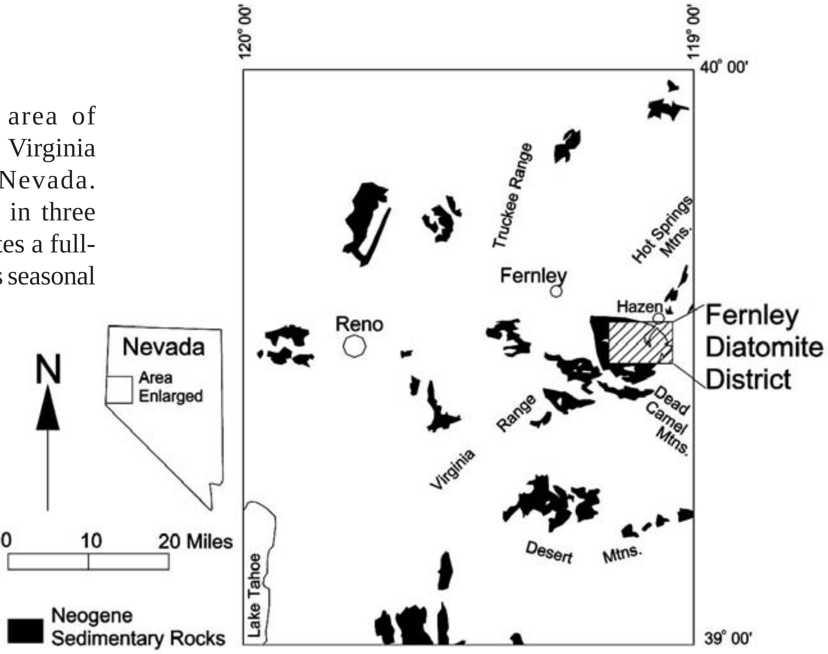

Figure 1. Location of the Fernley diatomite district with respect to Neogene sedimentary rocks in west-central Nevada. Neogene rock locations from Stewart and Carlson (1978).

Fernley area is underlain wholly by Neogene basin sedimentary and volcanic rocks that extend southwest in the main Virginia Range (Rose, 1969; Schwartz, 2001), to the south in the Dead Camel Mountains (Greene and others, 1991), and to the north in the Hot Springs Mountains (Stewart and Perkins, 1999). The Neogene rocks in western Nevada have been grouped into several formations, including the Desert Peak, Coal Valley, and Truckee Formations (Axelrod, 1958; Rose, 1969). The diatomite-bearing sediments near Fernley have been included within the Truckee Formation by several people, including Kelly (1998), and Trexler and others, (2000). This work, however, has shown that all these formations can be linked to several, partially contemporaneous late Miocene basins that often had their own distinct sedimentary and volcanic histories. Extensional faulting likely modified and frequently isolated these basins from one another at various times.

The northeast Virginia Range is a 50-square-mile, roughly circular exposure of late Miocene volcanic and sedimentary rock. The sedimentary rocks are most abundant in the north half, with diatomaceous sediments covering 6 to 8 square miles towards the northeast near Hazen. Possible extensions of diatomaceous sediment to the north and east are covered by Quaternary alluvial and Lake Lahontan gravels in the Hazen and Lahontan Valleys.

Fernley Diatomite District

The district is composed of a series of north-south elongate andesite ridges separated by lacustrine sediments (fig. 2). The andesite ridges are the up-thrown portions of a series of closely spaced normal faults that form several west-tilted, narrow, half-grabens. These grabens became lake embayments and were later filled by diatomaceous sediments. Most of these embayments were remarkably narrow, with widths of 750 to 1000 feet, and lengths of one to one and a half miles. Graben-bounding faults are identifiable today in some areas but others are frequently buried by the younger diatomaceous sediments in the district. The andesite that floors the east side of the district (referred to as the “lower andesite” in this study) consists of at least two flows. In the western third of the district, several thin basalt/andesite flows that originated outside the district interfinger with the lake sediments.

Diatomite

Diatomaceous sedimentary rocks mostly occur as graben-fill deposits that evolved over time from small, narrow, fault controlled sub-basins to larger, less restrictive basins. Therefore, the stratigraphically lower section in the district

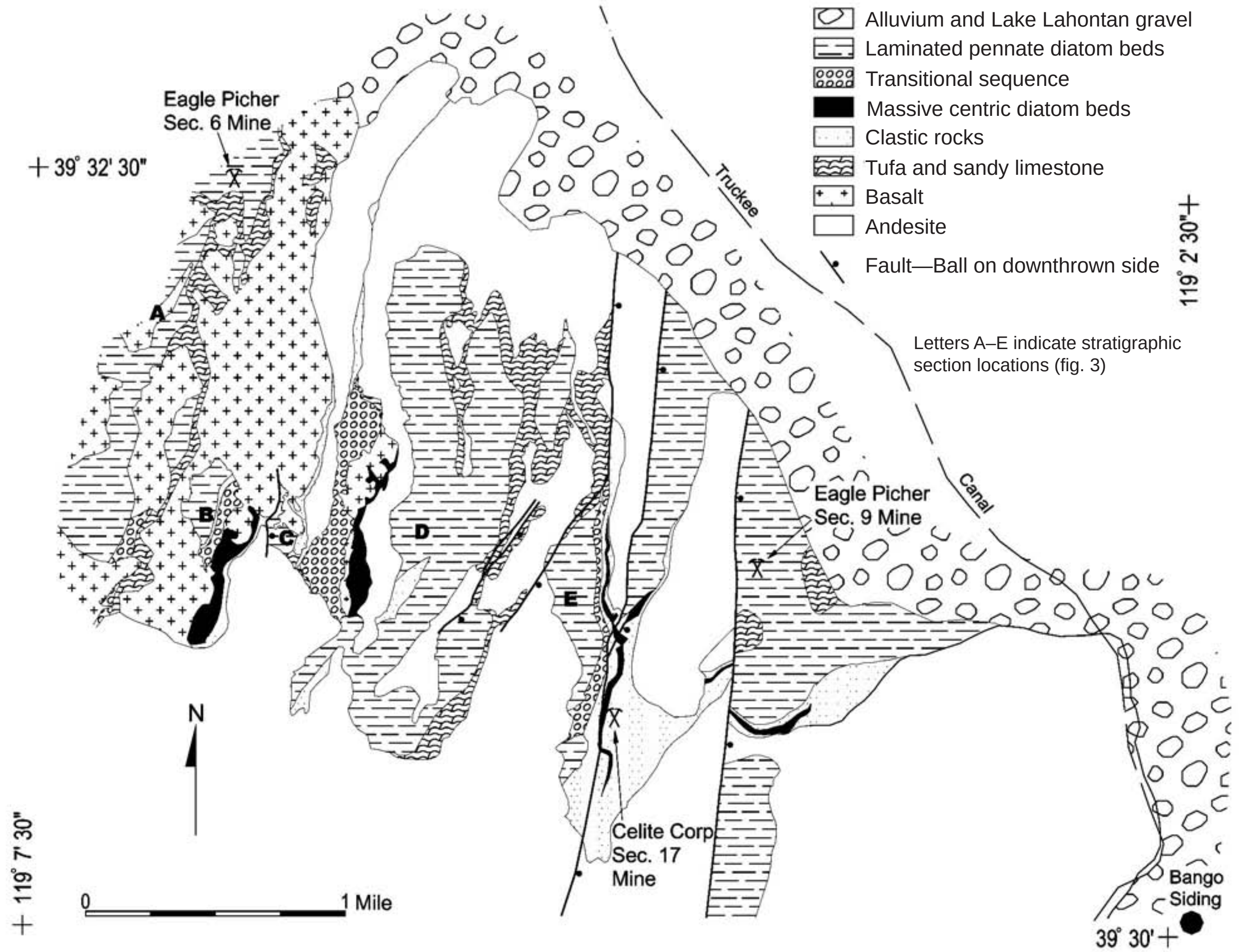

Figure 2. Geologic map of the Fernley diatomite district.

varies somewhat from area to area as each sub-basin initially had its own distinct depositional history. Over time, however, the sedimentary histories of these sub-basins became quite similar. On a district scale, the stratigraphically lower half of the section consists mostly of coarse clastic rocks with interbeds of massive diatomite (fig. 3). The massive diatomite is dominated by the centric diatom genus *Aulacoseira*, and occurs as numerous, thin interbeds that thicken within some sub-basins to economic thicknesses of 5 to 50 feet. The clastic rocks within the lower section consist of weakly to moderately indurated sand, conglomerate, and breccia.

The upper half of the section consists of thinly laminated diatomite dominated by araphate pennate diatoms (*Fragilaria* and *Synedra*) with minor, thin interbeds of clay, ash, silt, and fine sand (fig. 3). The basal portions of this section commonly contain a tufa, or sandy limestone, particularly near sub-basin contacts with the underlying andesite. Some areas of the district have only the upper laminated section.

Throughout the district, the distinction between massive and laminated bedded diatomite is an important one in discerning diatom morphology. Massive diatomite beds are invariably dominated by centric *Aulacoseira* diatoms. Higher aspect ratio, elongated pennate forms of *Fragilaria* and *Synedra* dominate laminated diatomite.

Nearly all of the beds in the district dip to the west. Dips within the lower massive-clastic section are typically 30 to 38 degrees. Dips consistently shallow up-section and are usually less than 10 degrees within the youngest laminated diatomite.

Diatomite and Sedimentary Stratigraphy

Centric Diatomite Sequence

These rocks are characterized by the predominant occurrence of *Aulacoseira* diatoms. It should be noted that most *Aulacoseira* species were previously assigned to the genus *Melosira*. Many earlier diatom studies in the Great Basin often used the designation *Melosira*, but most of these species have now been reassigned to the genus *Aulacoseira* (California Academy of Sciences, unpub. data, 2003).

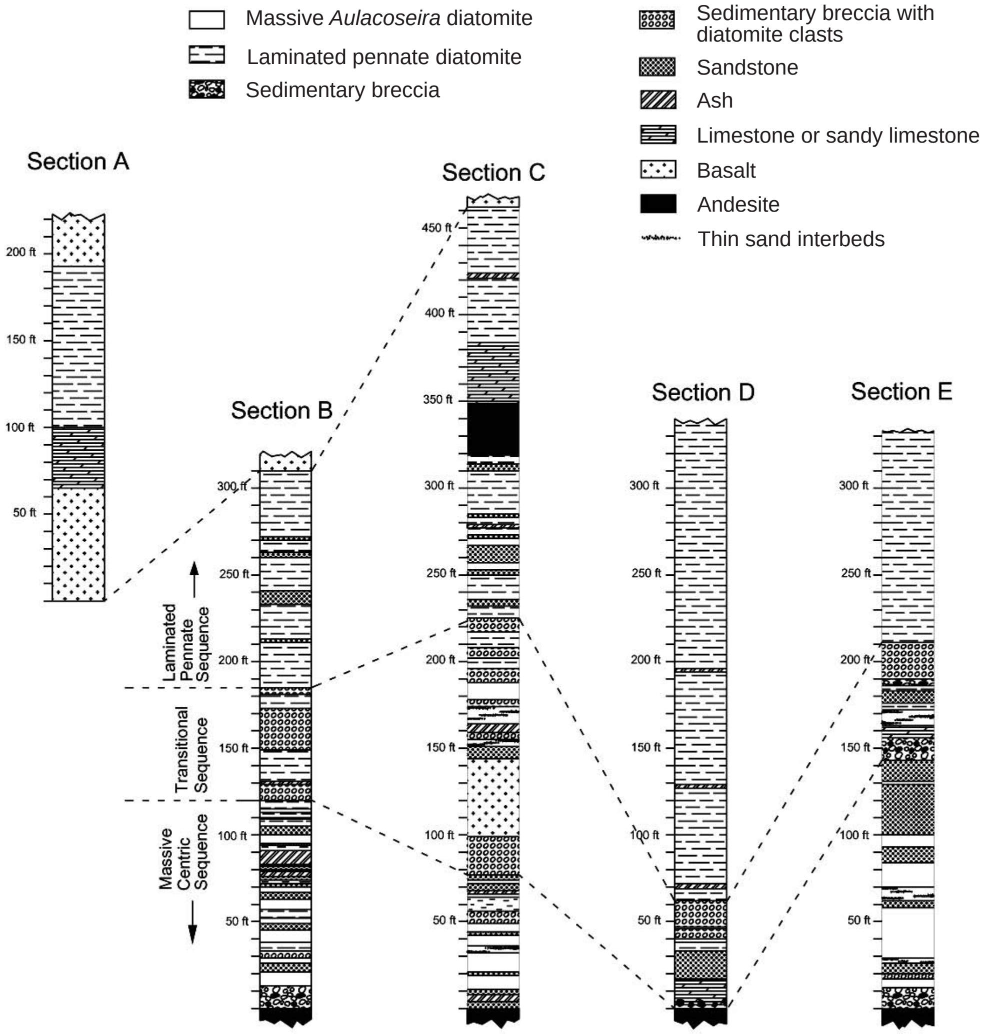

Figure 3. Stratigraphic sections from five locations within the Fernley district. Sections progress from the west side (Section A) to the east side (Section E). Section locations shown in figure 2.

All of the centric beds at Fernley are massive, lacking in bedding features. The centric sequence contains some minor pennate diatomite beds, particularly towards the west side of the district, as accessory pennate diatoms in dominantly centric beds. In general, this sequence contains some of the least-contaminated, high-silica beds in the district (table 1). The sequence contains abundant clastic rocks, which often dominate the section. Spatially, this unit is noticeably subordinate to the overlying laminated section, and its distribution was strongly influenced by the preexisting topographic and structural framework. Centric diatomaceous beds occur on the east and west sides of the district, but they are largely absent in the center suggesting the presence of a central north-trending andesite horst during this stage of basin development. This sequence rapidly terminates against lower andesite to the south reflecting an apparent lake margin and an emergent andesite high ground. The sequence thins on the north edge of the district where the depositional environment changed from a proximal, near-shore environment to deeper, open water. The centric sequence is largely a near-shore facies, and the abundance of both clastic rocks and diatomite interbeds thin noticeably away from this shoreline environment.

Correlation of this sequence from the east side of the district to the west is based on the similarity of diatom morphology (centric), tectonic history (similar degree of tilting), and tephrochronology. Brown (1986) obtained dates on ash beds from two sites: the Celite Corp. quarry in Section 17, dated at 9.79 Ma + 0.12, and the Eagle Picher quarry in Section 18, dated at 9.75 Ma + 0.31.

Fernley District-East Side—The centric sequence on the east side of the district formed in a small sub-basin or embayment with a complex geometry. The western two-thirds of the embayment was cut by several north-striking faults, which produced a series of narrow, west-tilted blocks. These fault blocks formed several elevated, narrow andesite ridges that strongly influenced the depositional history of each sub-basin. Much of the clastic rock in the centric sequence appears to have been derived from these ridges. Fault movement and westward tilting was active throughout the depositional history of the early sequence and the beds show a progressive shallowing in dip up-section. Near the Celite Corp. quarry in Section 17, the sequence appears to be about 150 feet thick, but it thins out both to the north and south.

In the eastern half of the district, diatomite is subordinate to clastic rocks and normally occurs as thin interbeds. Many of these beds are poorly preserved and most contain features indicative of slumping, scouring, and reworking. Diatomite breccias are common and consist of massive diatomite clasts in a diatomite and coarse sand matrix. The thinner beds are usually massive and dominated by *Aulacoseira* diatoms, but a varied subordinate assemblage includes *Synedra*, *Fragilaria*, *Cymbella*, and *Staurosira*. The lower third of the clastic section contains one very prominent diatomite bed that is exposed in Celite Corp. quarries in Sections 16 and 17. This bed is a high brightness, uncontaminated, massive *Aulacoseira* layer up to 50 feet thick. The bed is currently being mined for high brightness filler.

The clastic rocks usually consist of basaltic sandstone, conglomerate, and sedimentary breccia. Drill fences around the Celite Section 17 mine indicate that the clastic beds thickened and became coarser to the south as the sediments lapped against an andesitic lake margin. Drilling has shown that most coarse sand beds grade into a siltstone-diatomaceous mudstone within a distance of about one and a half miles from the andesitic shoreline. Paleocurrent indicators (cross laminations, pebble imbrications) within the coarser beds indicate a predominate south to north current movement. Most clastic rocks, even many of the finer siltstones, contain abundant reworked diatomite grains and clasts that correlate to diatomite beds in the underlying part of the section. These clastic rocks are interpreted as being predominately lacustrine turbidites produced during periodic fault movement and westward tilting.

The transition to the overlying laminated sequence is fairly abrupt in the eastern parts of the district. The transition corresponds to a 60-foot sequence of coarse sandstone, conglomerate, and minor clastic limestone. Rocks above this clastic sequence are dominated by pennate diatom layers. Non-diatomaceous layers are limited to thin (0.25 to 3.0 inch) fine sand and silt layers and clearly indicate a pronounced change in depositional conditions in the basin.

Western Fernley District—On the western side of the district, the centric sequence is exposed in several small quarries and prospects in Sections 7 and 18. These rocks appear to have formed in two narrow, fault-bounded sub-basins. Like the beds to the east, the unit appears to have thinned abruptly to the south against an andesitic high ground, and gradually thinned out to the north to fine siltstone/sandstone and intercalated basalt flows. Mapping of the unit northwards was hampered by younger basalt that partially covers the sequence.

Table 1. Average whole-rock chemistry of Fernley centric and pennate diatomite. Original analyses normalized to 100%.

	A	B	C	D
SiO_2	91.91	90.38	90.91	81.40
TiO_2	0.17	0.20	0.24	0.41
Al_2O_3	3.00	3.82	4.06	8.23
Fe_2O_3	1.48	1.62	1.56	3.62
MnO	0.02	0.02	0.02	0.09
MgO	0.58	0.60	1.02	0.66
CaO	1.03	1.56	1.23	2.42
Na_2O	0.60	0.72	0.49	1.06
K_2O	0.46	0.54	0.34	0.83
P_2O_5	0.06	0.13	0.04	0.21
SO_3	0.12	0.09	0.01	0.35
Cl	0.38	0.27	0.02	1.28

A *Aulacoseira* diatomite, from early lacustrine sequence. Mean of 53 samples.
B Pennate diatomite from early lacustrine sequence. Mean of 51 samples.
C *Aulacoseira*-dominated bed. Section 17, Celite Corp. mine. Mean of 37 samples.
D Pennate diatomite, from late lacustrine, laminated sequence. Mean of 12 samples.

Unlike the centric sequence in the eastern part of the district, clastic rocks to the west are subordinate to diatomaceous beds, comprising no more than a third of the section. Diatomite beds are numerous and typically occur as 5- to 15-foot layers separated by sand interbeds. The diatomite beds contain a more varied diatom assemblage dominated by *Aulacoseira* but containing a larger proportion of pennate diatoms then beds to the east. A few laminated, pennate beds occur in the lower part of the section, but these are much less contaminated than laminated beds in the main pennate section. All the beds strike north-northeast and dip to the west. Drilling indicates that the sequence has an average thickness of about 120 feet.

Transitional Sequence

Throughout the district, a complex assemblage of rocks separates the lower centric beds from the overlying laminated pennate beds (fig. 3). The transitional sequence contains both *Aulacoseira* and pennate diatomite in thin beds separated by thick beds of clastic rock, sandy limestone (or tufa), and one intercalated basalt flow. The most distinct feature of this sequence is the frequent presence of reworked diatomite clasts in the clastic beds, comprising up to 50% of a bed in some places. The transitional sequence ranges from 60 to 145 feet thick, and it has been found throughout the district.

The transitional sequence in the western part of the district contains a thin intercalated basalt flow. The flow thins rapidly to the south where it appears to lap against the lower andesite. The transitional beds indicate a complex history of fluctuating lake levels, tectonism, and changing water conditions. The abundant diatomite-clast breccias and sandstone beds suggest a period of accelerated fault movement and fault block rotation. The diatom assemblage in the beds changes abruptly from bed to bed. Tufa-like clastic limestone is quite abundant and may indicate periodic low lake levels. The absence of pillows and pepperites within intercalated basalt flows indicates predominantly subaerial conditions. The transitional beds show a pronounced shallowing of dip going up-section from about 30 degrees to about 10 to 15 degrees.

Pennate Diatomite Sequence

The pennate sequence at Fernley is a widespread, remarkably uniform sequence found throughout the district. The lower portions of the laminated sequence were deposited in the same sub-basin configuration as the underlying massive unit. Over time, the laminated beds became more extensive, indicating a simpler basin geometry and much less topographic influence on the depositional processes. On a district scale, this sequence, like the early lacustrine sequence, thins to the south and east where it appears to lap against an andesite high ground. To the north the unit disappears beneath Quaternary alluvial and Lake Lahontan gravels. To the west, the unit appears to interfinger with several basalt flows. Drilling shows that the sequence is at least 270 feet thick in the central part of the district (section 8). Mapping and drilling on the west side of the district has shown that the unit is as much as 465 feet thick, including intercalated basalt flows. The sequence has not been dated, but correlations based on tephra chemistry of interbedded ash by Brown (1986), Perkins and others, (1998), and Perkins and Nash (2002) indicate a date of about 9.4 Ma.

The pennate sequence has been extensively mined in the district for lower-quality agricultural filler and absorbents, as well as for more specialized applications such as the calcium silicate insulation markets. Currently, two active quarries in the district produce diatomite products from this unit.

The pennate sequence consists mostly of *Fragilaria* and *Synedra* diatoms with lesser amounts of *Staurosira* and *Cymbella*. Some *Pinnularia*, *Eunotia*, and *Aulacoseira* occur in most beds. Laminations that occur as millimeter and sub-millimeter scale layers are believed by Bell and Haglund (1982) to be varves, caused by seasonal variations in diatom accumulation rates. A larger-scale bedding, typically 0.5 to 2.0 inches thick, also occurs and corresponds to a flattening or compression of elongate diatoms along some layers. Whole-rock chemistry shows an elevated alumina content, indicative of clay contamination (Table 1). Microscopic examination shows relative pure pennate diatom seams separated by clay. This alternating sequence probably represents seasonal diatom blooms separated by periods of low diatom accumulation. The unit contains abundant sand interbeds typically 0.25 to 3.0 inches thick, as well as frequent sand “films” between individual lamina. These sand layers are interpreted as seasonal variations in sediment influx such as by periodic storms. The majority of the sand layers indicate a local origin, derived from nearby andesite. However, some layers contain a more varied assemblage that includes quartz, feldspar, and hornblende indicative of a more silicic volcanic origin. The unit contains numerous thin vitric and crystal-tuff layers.

The laminated sequence is well known for the common occurrence of fossil fish. The fossil stickleback, *Gasteroseus doryssus*, is found throughout the district and was studied in detail by Bell and Haglund (1982). Firby (1995) also noted the frequent occurrence of the fish, *Fundulus nevadensis* from several Fernley localities. Fossil stickleback fish were also found during this study in a few of the pennate layers within the lower, centric sequence, but they are not common. None have been found in any of the centric diatomite layers.

The pennate sequence often contains one or more tufa or clastic limestone beds near its base. Where the underlying transitional sequence is present, these beds occur as extensive, thin (2- to 10-foot) interbeds. Where the laminated rocks directly overlie andesite, the limestone forms a thicker (10- to 45-foot) prominent bed that often seems to be a shoreline marker for higher water levels. Many of the sub-basins appear to have tufa around their margins, but drilling has found that it often thins towards the sub-basin centers. The limestone often forms rounded or radial-like mounds, features strongly indicative of tufa formation.

Bedding in the pennate sequence predominantly dips gently west or is nearly flat. Local steepening or dip reversals are common and are believed to represent bedding attitudes that conformed to an undulating lake floor. On the west side of the Fernley district, pennate beds appear to interfinger with basalt and andesite flows. The younger basalt flows appear to have been emplaced after considerable tilting and erosion and at least one flow now overlies both centric and pennate beds. On a district scale, this flow appears to be tilted to the west about 3 to 5 degrees. This flow is overlain by additional sedimentary rocks that are predominately pennate diatomite, but do have some minor centric interbeds near the bottom of the sequence. All of these younger diatomaceous sediments appear only slightly tilted, with bedding attitudes concentric to the local sub-basin geometry.

Volcanic Rocks

At least six individual basalt or andesite flows were mapped in the Fernley district. In the field, these flows are generally recognizable on a broad scale as either andesite or basalt. Individually, flows are often difficult to distinguish. All are aphyric and usually quite fine grained. A summary of the basalt-andesite major element chemistry is shown in table 2. Classification based on total alkali elements versus silica is shown in figure 4. This classification groups the Fernley volcanic rocks into the basalt, basaltic andesite, and trachyandesite fields. All the Fernley rocks appear to be calc-alkaline but bordering on alkaline. In general, the volcanic rocks can be classified into two groups based on distinctions in SiO_2, K_2O, Al_2O_3 and P_2O_5. This chemistry seems to outline two volcanic suites and suggests a mixing of volcanic flows from two distinct sources.

Table 2. Whole-rock chemistry of Fernley volcanic rocks. Normalized to 100%.

	A	B	C	D	E	F	G	H
SiO_2	57.69	55.27	57.10	53.45	53.34	51.98	54.47	54.89
TiO_2	1.36	1.40	1.47	0.97	0.94	1.02	0.89	0.90
Al_2O_3	17.99	17.46	18.45	20.28	19.69	20.63	20.22	20.37
Fe_2O_3	6.85	8.57	6.06	8.01	8.31	8.63	7.72	7.50
MnO	0.08	0.13	0.07	0.13	0.13	0.15	0.15	0.14
MgO	2.05	3.52	2.09	3.57	2.31	3.88	2.85	2.74
CaO	6.15	7.02	6.52	7.97	8.29	8.61	7.80	7.53
Na_2O	3.64	2.90	3.76	3.73	3.18	3.47	3.82	3.79
K_2O	2.87	2.58	2.88	1.32	1.62	1.14	1.48	1.56
P_2O_5	1.29	1.01	1.54	0.57	0.56	0.44	0.54	0.51

A Lower andesite, upper flow.
B Lower andesite, lower flow.
C Andesite, intercalated flow in lower laminated sequence.
D Basalt, intercalated flow in transitional sequence.
E Basalt, intercalated flow in laminated sequence.
F Basalt, intercalated flow in upper laminated sequence.
H Basalt, upper capping flow.
G Basalt, intercalated flow in upper laminated sequence.

Lower Andesite

Based on major element chemistry, the lower andesite includes three flows within the Fernley district. These flows include the underlying basement to the centric diatomite beds, as well as one intercalated flow within the lower part of the pennate sequence. The andesites are pyroxene bearing, fine grained, and aphyric. They have a well-developed, vesicular flow top that typically grades downward into a thin, platy-jointed rock with noticeable flow banding. When freshly broken, the andesite commonly has a pronounced, trachytic flow foliation.

Mapping tentatively correlates the Fernley lower andesite with a similar rock immediately east of the Fernley district, near Bango Siding. There, Stewart and others (1994) reported a K/Ar date of 9.6 Ma +0.30. This date is problematic as it is slightly younger than tephra dates reported by Brown (1986) from the centric sequence overlying the andesite. This discrepancy has yet to be resolved, however it is reasonable to assume that both the centric sequence and the underlying andesite will be found to have fairly similar ages.

Basalts

Basalts occur on the west side of the Fernley district. They occur as either intercalated flows within sediments, or as capping to partially capping flows. All have a similar major element chemistry and these flows can probably be grouped into a single volcanic suite. All of these flows are augite olivine basalts. They are fine grained, aphyric, and occasionally glassy. Chemically, they correlate well with the Clark Mountain Basalt described by Schwartz (2001) from the Chalk Hills basin to the southwest. The Clark Mountain Basalt, however, is plagioclase-phyric, unlike the aphyric basalt flows found in the Fernley district. Schwartz (2001) reported an age of 9.64 Ma +0.04 for the Clark Mountain Basalt. This age may be slightly older than the Fernley basalts, but this has not been verified.

Structural Geology

All the sub-basins at Fernley that host either the centric or pennate sequences show a prominent decrease in westward tilt up-section. This phenomenon of tilt-fanning is indicative of continued faulting and rotation during the depositional history of the basin. Tilt-fanning also produced a pronounced asymmetry within each sub-basin. Older sediments were restricted to the east sides of the sub-basins and now appear to dip into the apparent floor. Younger sediments are found in the western sides of the sub-basins and become increasingly conformable up-section with respect to the basin floor.

The tilting of individual blocks was the direct result of progressive normal faulting along predominantly north-striking faults. Several of these faults are mappable and show evidence of recent movement forming prominent scarps. However, the majority appear to have been buried by the youngest pennate sequence, indicating that most fault activity subsided before the end of diatomite formation. The presence of these faults is often clearly indicated by the apparent displacement seen in the pre-lacustrine andesites.

Most faults at Fernley strike to the north, but there is also a younger secondary set of faults striking N30–45°E. The northeast-striking faults appear to offset all of the sedimentary rocks in the district and clearly postdate all but a few of the north-striking faults. The northeast faults show limited offsets (5 to 50 feet) and both normal and right-lateral strike-slip movement. Most of these faults are aligned in an east-trending belt through the center of the district and many of the larger north-striking faults that remained active show a distinct northeast flexure as they cross this belt.

Basin Formation in the Fernley Area

Pre-Lacustrine Events

The oldest rocks in the Fernley area are the lower andesites. These rocks underlie the entire district and floored the lake basin prior to the onset of clastic sedimentation and diatomite deposition. Andesites floor many if not most of the middle and late Miocene basins in western Nevada, and the majority of these rocks have been collectively grouped into the Kate Peak Formation. Kate Peak volcanic rocks to the west and southwest of Fernley from the Verdi basin and Chalk Hills basin have been dated at 12.11 and 12.43 Ma (Trexler and others, 2000, Schwartz, 2001), and they are generally described as strongly plagioclase-phyric. The Fernley area andesites appear to be younger, aphyric, and more alkali enriched than typical Kate Peak andesites. While not directly correlative, the Fernley andesites and Kate Peak andesites are likely both the product of similar, widespread and voluminous andesitic volcanism that covered much of western Nevada. Regional tectonism, expressed by north-striking, high-angle faults, affected the andesite almost immediately after their emplacement. This faulting produced a series of uplifted horsts and gently west-tilted grabens that had a pronounced influence on the developing lake basin.

Early Stage Lacustrine Sedimentation

The earliest sedimentation at Fernley began with the deposition of an alternating sequence of clastic rocks and diatomite (fig. 5). In an east-west direction, clastic deposition was highly variable and few, if any, clastic beds in the various sub-basins are directly correlatable. This variability suggests that initially, much of the district consisted of several north-south, elongated sub-basins that may have only been partially connected.

Diatomite deposition during this early lacustrine stage formed some of the cleanest, high-silica beds in the district. Paradoxically, these diatomite beds are invariably associated

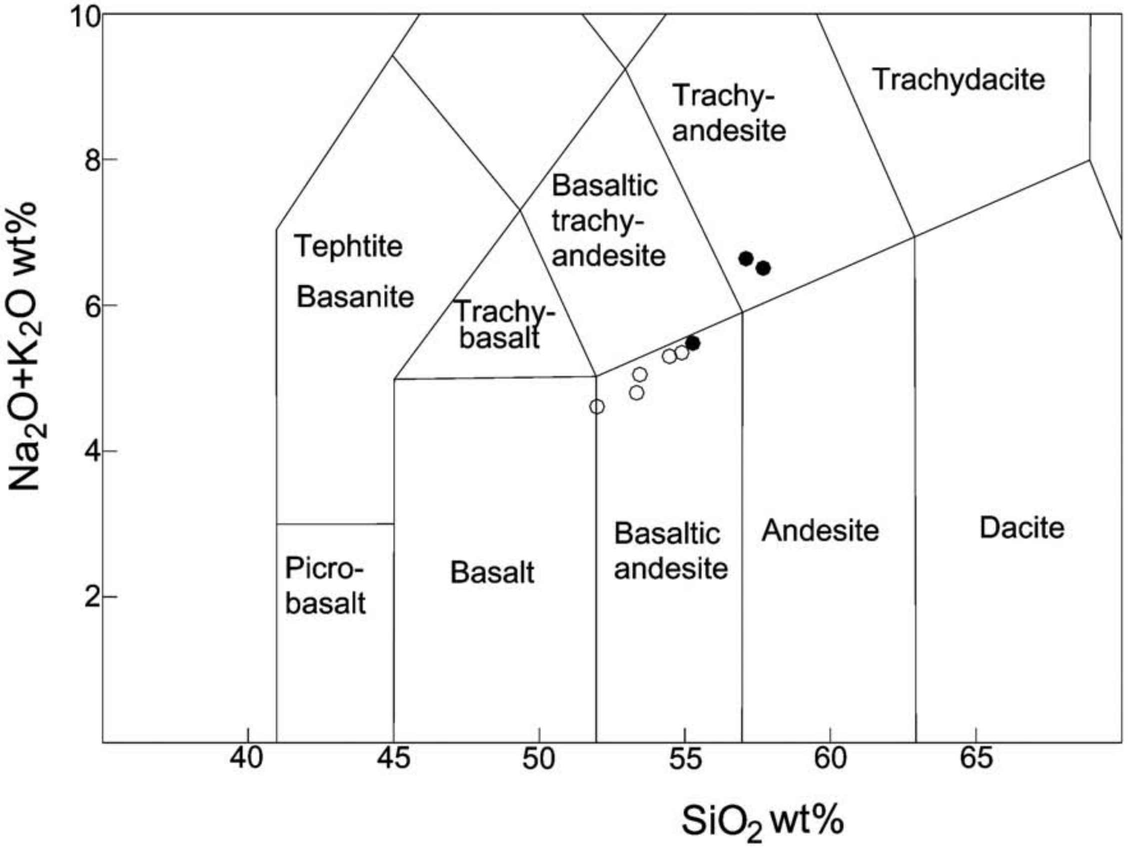

Figure 4. Total alkalis versus silica plot (TAS) for volcanic rock. Open circles are basalts, filled circles are andesites, as used in the field and text.

with coarse clastic interbeds and seemed to show an affinity to the higher-energy, littoral or near-littoral environment that hosts coarser sedimentary breccias and sandstones (fig. 6). This diatomite formed in an east-trending, 1/2-mile-wide belt. The belt is immediately north of, and closely parallel to the probable lake margin. On the north edge of the belt, thinning of the diatomite beds corresponds to the fining seen in the clastic interbeds. North of the belt, drilling shows that the early lacustrine sediments are largely high-clay, diatomaceous mudstones, and siltstones.

Early lake conditions can be inferred from the prevalence of *Aulacoseira*. Bradbury (1999) reported that *Aulacoseira* is a planktonic diatom characteristic of a nutrient-rich, low-turbidity/high sunlight environment. Additionally, Wolin and Duthie (1999) pointed out that *Aulacoseira*, because of its high mass to volume ratio, needs relatively high- energy, turbulent lake conditions to stay suspended in the water. These conditions would have existed in the near-shore environment in the early history of the Fernley district. This area received significant sediment input (abundant clastics), water throughput, and it was probably rich in nutrients. North of this environment, water depths increased, and suspended sediment and nutrient levels may have decreased as distance from the shoreline increased. Diatom accumulation decreased as well, and what little occurred was dependent upon current transport of diatoms from the proximal shoreline environment to the south.

The concentration of economic-grade diatomite in an environment dominated by coarse clastic sedimentation may be unusual. Traditional views of diatomite deposition usually place maximum diatomite accumulations in a quiescent environment lacking in sediment input. Yet all economic concentrations of *Aulacoseira* at Fernley occur as interbeds in a section dominated by clastic rocks. Under such conditions, significant diatom accumulations would have to be during brief periods of greatly reduced clastic sediment influx or greatly accelerated diatom accumulation rates. At Fernley, clastic rock deposition can be closely linked to faulting and subsequent uplift and tilting. This tectonism appears to have continued unabated through the early basin history with no recognizable hiatus to allow for diatomite accumulation. Actual transport of this clastic material into the lake could, however, be subject to periodic changes in precipitation and runoff. During periods of lower rainfall,

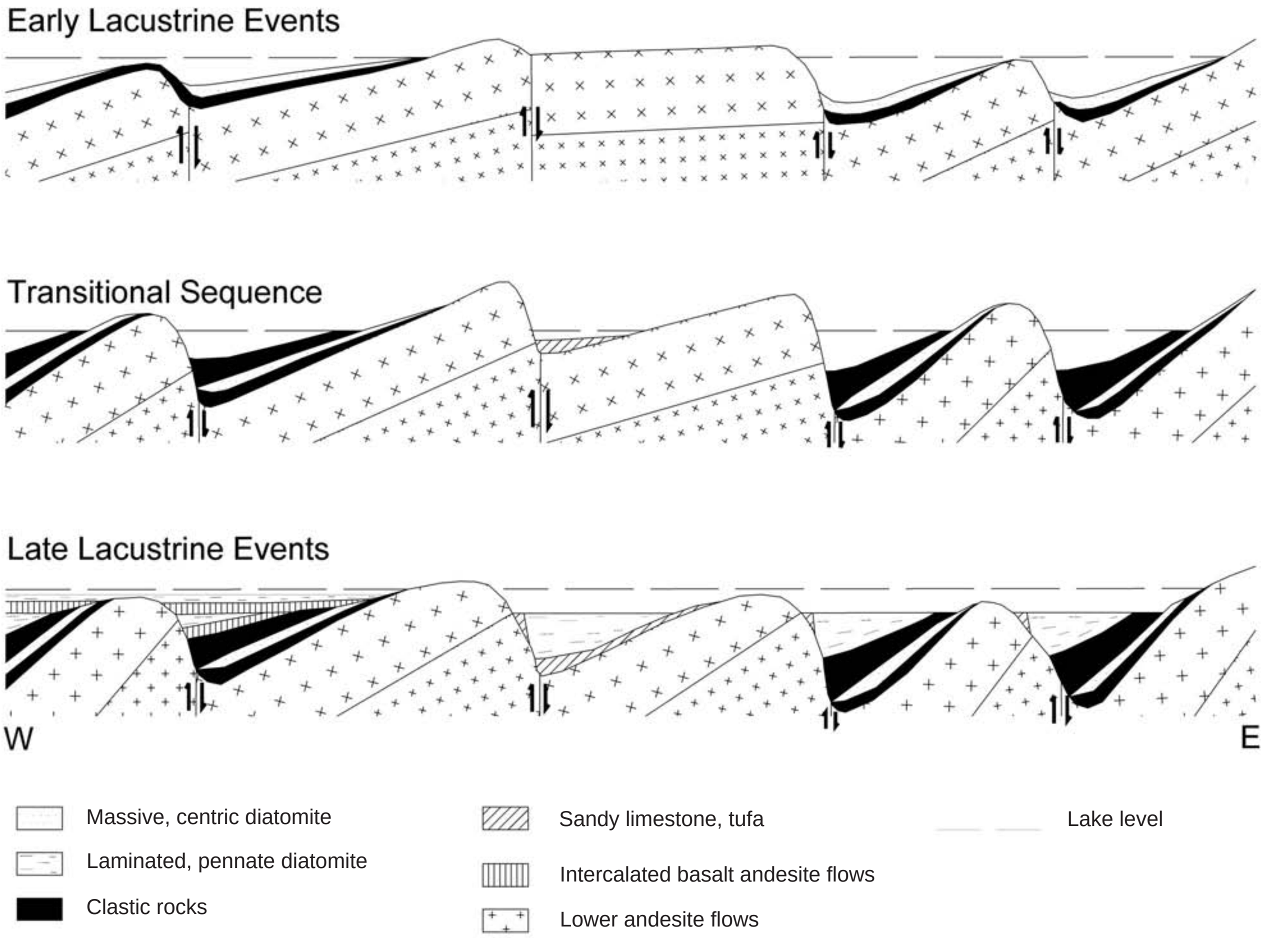

Figure 5. Cross sections through the middle of the Fernley district showing the progression of faulting, tilting, and sedimentation over time. Sections are looking north. Not to scale.

diatom accumulation rates outpaced and diluted clastic input. Alternatively, if clastic sediment input remained stable over this period, diatom accumulation could be linked to periods of very rapid growth due to ideal water conditions.

Transitional Sequence

Lake levels may have fluctuated significantly during this period. Diatom morphology varied from bed to bed but became increasingly dominated by pennate forms. The sequence also includes several tufa interbeds that may be diagnostic of periodic shallow water and/or shoreline conditions. Increased tectonism also corresponded to renewed volcanism outside of the Fernley district. Transitional rocks in the western part of the district document the beginning of basalt-andesite volcanism that continued intermittently into the overlying sediments. Transitional rocks are found over a wide area of the Fernley district and locally sit directly on the lower andesite. This greater distribution may correspond to earlier infilling of many of the sub-basins. By the end of the transitional sequence, as much as 225 feet of sediment had accumulated in some sub-basins, and topographic relief within the area became more subdued.

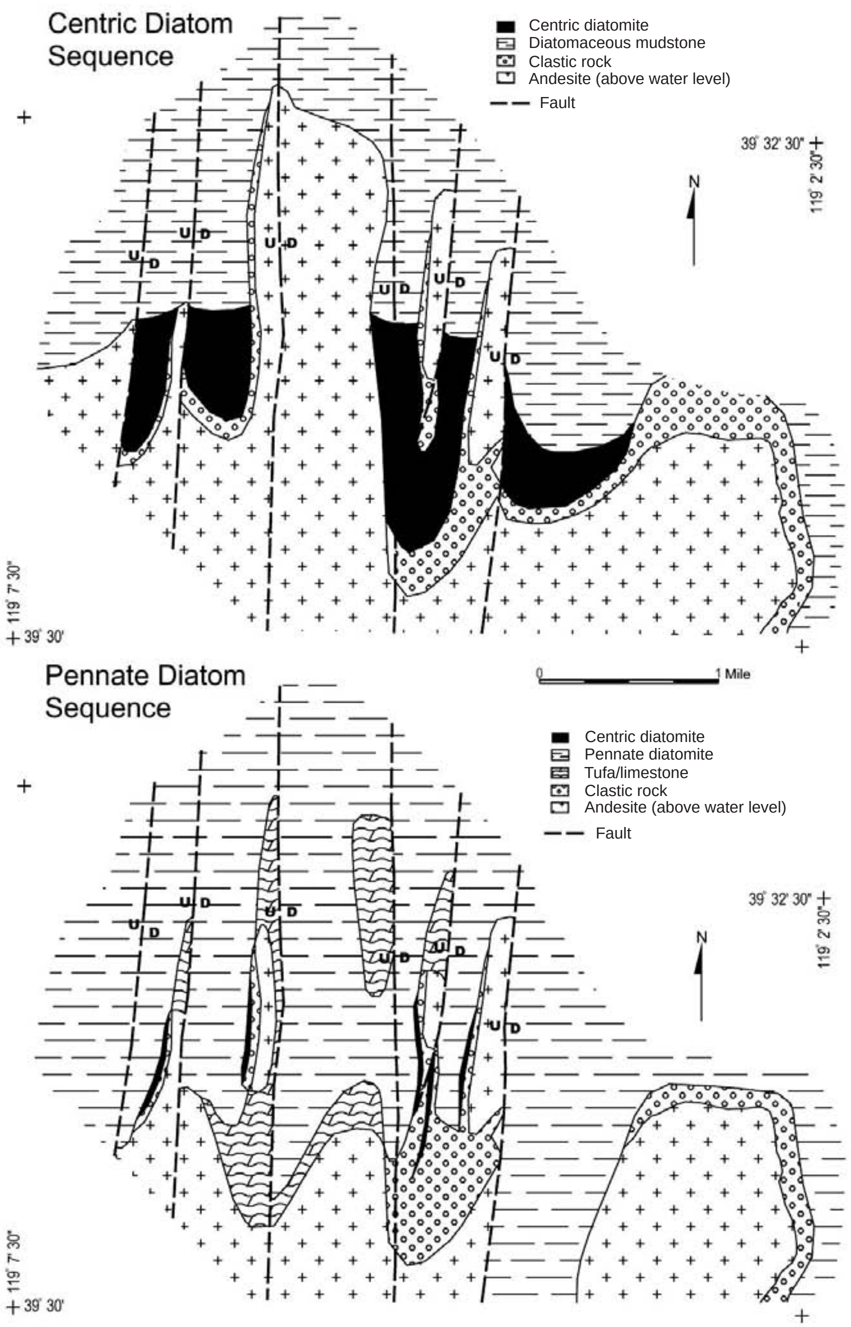

Figure 6. Depositional environment of centric and pennate diatom beds with respect to the late Miocene lake margin.

Late Stage Lacustrine Sedimentation

Following the deposition of the transitional sequence, the Fernley area entered a final stage characterized by decreasing tectonism. The final sequence consists almost entirely of laminated pennate diatomite that blanketed most of the Fernley district. The extensiveness of these rocks suggests progressively less basin relief over time. These sediments still contain some, albeit sparse, clastic interbeds but these decrease in abundance rapidly up-section. Over time, late-stage sedimentation completely filled in most of the sub-basins and diatomite deposition began to expand with the lake and covered adjacent andesite high-ground. Tufa deposits formed along new shorelines, particularly where underlain by andesite. As faulting subsided, many faults were buried. The upper half of the late-stage sequence is relatively untilted, and bedding attitudes mimic the local basin geometry. Finally, several basalt and andesite flows were erupted west of the Fernley district, flowed eastward, and now interfinger with laminated diatomaceous sediment.

The dominance of pennate diatoms during this final stage indicates shallow water conditions. *Fragilaria*, *Synedra*, *Cymbella*, and *Pinnularia* are all regarded as benthic genera in freshwater, lacustrine environments (Patrick and Reimer, 1966) and require shallow water to receive adequate sunlight. These genera often imply marshy conditions (Bradbury, 1997), but with sufficient water throughput to avoid the alkali or saline waters seen in many closed lake basins of the present Basin and Range Province. The prevalence of pennate diatoms is often seen as an indicator of increased lake eutrophy (Patrick and Reimer, 1966), and this may be particularly so for araphate pennate diatoms such as *Fragilaria* (Hall and Smol, 1999). Many pennate genera do have higher nutrient demands, but, as discussed earlier, some centric diatoms, including *Aulacoseira* do as well. At Fernley, eutrophism was maintained during the earlier stages through increased sediment loads and runoff into the lake. Over time, as the sediment input dropped off and the lake shallowed, eutrophism might have been maintained because of reduced water volumes and higher dissolved mineral content.

Conclusions

Diatomite deposition at Fernley took place in shallow water along the northern flank of a broad, elevated, andesitic high ground. The ultimate size and geometry of this late-Miocene lake is unknown but it clearly extended well beyond the limits of the Fernley district. Despite this uncertainty, the geology of the Fernley area is sufficiently understood to reconstruct the lake history and make some estimates on the timing of basin formation and regional tectonism.

Formation of the late Miocene lake basin at Fernley was dependent upon regional tectonism to provide the proper topographic framework. Extensional faulting modified the lower andesites shortly after their emplacement and created a series of narrow, half-graben embayments that probably opened northwards into open water. The age of the lower andesite is unclear. An andesite date of 9.6 Ma (Stewart and others, 1994) overlaps the age of early basin sedimentation (9.8–9.5 Ma) and indicates that further age dating of the underlying andesites is needed. Tephras in the Fernley district, interbedded with early-stage centric diatomite beds, have been dated by Brown (1986), at 9.75–9.79 Ma. Early-stage rocks indicate a dynamic lake environment characterized by high relief, high water input, and abundant clastic sedimentation. Diatomite formation during this stage produced an almost exclusive sequence of centric *Aulacoseira* diatoms that accumulated in a near-shore environment proximal to the zone of maximum clastic deposition.

This early sequence of events was followed by a brief period of accelerated tectonism. This tectonism resulted in significant tilting, or fault block rotation, and produced a thick sequence of coarse clastic interbeds that includes reworked clasts from the lower *Aulacoseira* beds. Based on tephra dates and tephra chemical correlation, the timing of this accelerated faulting and sedimentation was between 9.75 Ma and 9.4 Ma.

Over time, clastic rocks and diatomite filled in most of the lake embayments at Fernley, and the lake entered a mature stage characterized by low sedimentation rates. These lake embayments, now clogged with sediment, pushed lake levels onto the surrounding andesite and created an extensive shallow-water diatomite sequence dominated by benthic pennate diatoms. The upper age limit on these events is unknown but tephra correlations from the lower one third of the pennate sequence indicates a date of 9.4 Ma (Brown, 1986, Perkins and others, 1998, and Perkins and Nash, 2002). By this time, tectonism had all but subsided-most laminated pennate diatomite beds younger than this remains untilted. The end of the lake cycle at Fernley may correspond to eventual filling of the basin. Alternatively, the onset of volcanism, seen today on the west side of the Fernley district, may have ended the lake cycle prematurely. The emplacement of several basalt flows would have profoundly affected a broad, shallow lake.

This sequence of events may be common in other Neogene basin as well, providing a working model. Early tectonism is required to form a basin setting that supplied ample open, unstratified water, water throughput, and stable nutrient levels that favor early centric diatom formation. Many long-lived Neogene basins worldwide have been found to be dominated by early centric diatom accumulation (M. Houseman, unpub. data). Over time, as these basins matured, sediment influx led to increasingly shallow water conditions that favored pennate diatom growth. Departure from this centric/pennate model may indicate basins whose lake cycle was disrupted due to outside influence such as volcanism or renewed tectonism.

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Carbonate Rock Production in Israel

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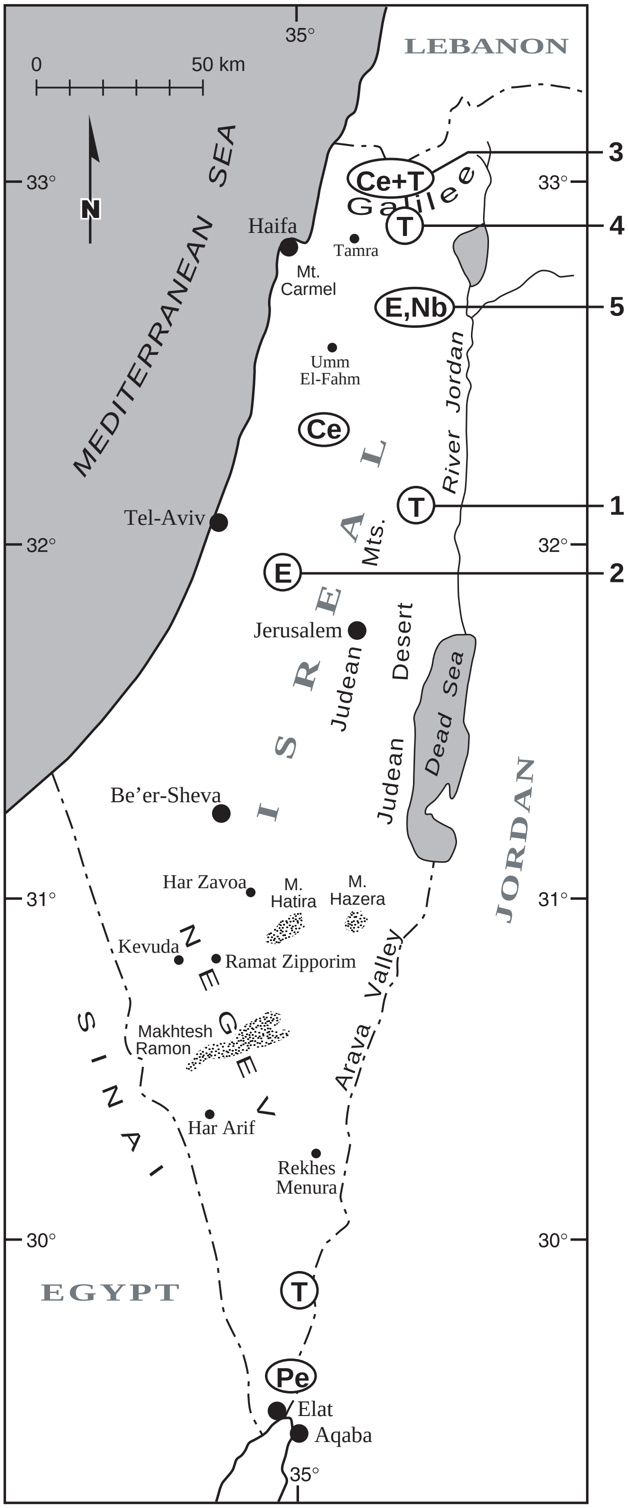

Figure 1. Map of Israel showing sources of carbonate rock and other sites noted in the text; Ce = Cenomanian dolomite, T = Turonian limestone, E = Eocene chalk, Nb = Neogene basalt, Pe = Precambrian rocks.

Abstract

Dolomite, limestone, and chalk are the most abundant rock types that crop out in Israel, hence they have been used for thousands of years as raw materials for various purposes: dimension stones and lime in ancient times; aggregates, cement, fillers, and chemical powders in modern times. The utilization of these carbonate rocks has many limitations including geological problems such as the presence of cavities and alteration, and political concerns such as planning requirements and environmental issues. There are also specialty uses for high quality carbonates, such as attractive variegated limestone used for dimension stone, and thermally metamorphosed chalk used for high quality aggregate. The extensive exploitation of carbonate rocks in Israel will require comprehensive planning and identification of new potential sites in the future.

Geology

The three main sources of carbonate rock in Israel are from Cretaceous to Eocene sequences. The Cretaceous rocks include Cenomanian dolomite, overlain by Turonian limestone, both of which comprise central anticlinal crests running along the country from north to south. The synclinal basins between these anticlinal ridges consist of Upper Cretaceous Senonian rocks (not all of which are carbonates), which are overlain by chalks of the last regional carbonate depositional phase of the Eocene. The most notable mining areas are shown in figure 1. The dominance of carbonate rocks in Israel's geology is reflected in the production of building materials. In 2002, of approximately 48 million tons of raw materials produced for building and construction, more than 40 million were extracted from limestone and dolomite sources (fig. 2).

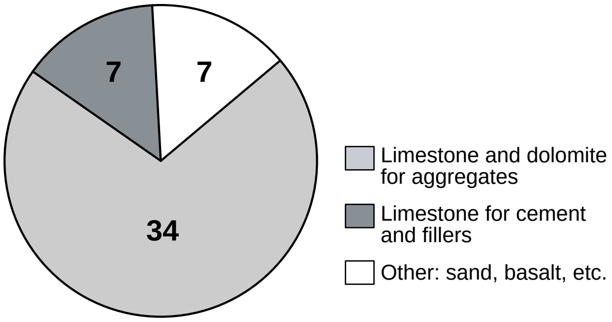

Figure 2. Production of rock products in Israel in millions of metric tons.

Uses of Carbonate Rocks in Ancient Times

During the last 2000 years and more, the consumption of carbonate rocks in Israel has changed significantly. In ancient times, dolomite was not used at all because of its relative hardness; the main rock used was the Turonian limestone, which is softer and more easily mined. Chalk was also used as a construction material in ancient times but is rarely used today.

Prominent historical monuments constructed with Turonian limestone blocks are abundant and include the Wailing Wall in Jerusalem (fig. 1, point 1; fig. 3). King Herod tried to have the Jewish Temple rebuilt using this stone, which is part of the stratigraphy that underlies the city of Jerusalem. A huge abandoned jointed column (fig. 4) is evidence of this activity. Southwest of Jerusalem, along the historical route to the coastal plain, the geology is very different; the anticlinal ridge in the Jerusalem area turns into an adjacent syncline in which the Eocene chalks are dominant (fig. 1, point 2). Because bulk transportation in ancient times was difficult, the population had to use locally available material, in this case soft chalk rather than limestone. However, some features in the chalk do enable it to be used as higher quality construction material. The upper parts of the chalk, which were exposed to rainfall and penetration of groundwater, have been converted into a hard shell, up to 10 m thick, which is sufficiently durable for use as building stone. The boundary between the hard and the soft chalk is sharp (fig. 5), enabling the lower, soft material to be mined easily for the construction of underground dwellings and for lime production. Thousands of ancient lime furnaces have been discovered throughout the area. One famous example of the use of the upper, hard part of the chalk was the great wall surrounding the old city of Lakhish (fig. 6), which was destroyed during the invasion of Nebuchadnezzar in 588 BC.

Modern Uses of Carbonate Rocks

With the development of more efficient long-distance transportation in the 18th, 19th, and 20th centuries, the use of chalk was almost abandoned (but not forever!), and higher quality types of stone were transported throughout the region. Today, major uses of Israel's carbonate rocks are in the production of aggregates and cement, along with some

Figure 3a. The Wailing Wall, Jerusalem.

Figure 3b. Detail of the original wall.

Figure 4. King Herod's column, about 3 m long.

lime, dimension stone, chemical powders, and fillers (fig. 7). Limestone and dolomite are the fundamental raw materials for the building industry. They are mined from more than 100 quarries throughout the country, which have a yearly production exceeding 50 million tons. Limestone and dolomite are the dominant sources of aggregate in Israel, whereas other materials, such as basalt and gravel, account for less than 10% of the total production (fig. 8).

Problems and Special Features

The exploitation of carbonate rocks in Israel is limited by some geological problems, such as the abundance of karstic cavities, which are locally so well developed that some former mining sites are not quarries any more but have been abandoned and converted into tourist attractions (fig. 9). In places, the rocks are filled with clay and soil (fig. 10). In addition, areas of extensive fault and joint systems limit the potential of some otherwise suitable dimension stone sources. However, despite such problems, some special kinds of carbonate rock may be mined in such areas. In one area of extensive faulting (fig. 1, points 3 and 4), there are exposures of solid, variegated Turonian limestone (fig. 11), which are exploited as sources of high quality "marble" dimension stone. Another special carbonate rock is Eocene chalk that was converted into hard, dark limestone in one area (fig. 1, point 5) along its contact with rocks of subvolcanic origin (fig. 12). This thermally metamorphosed chalk is used for high quality aggregates.

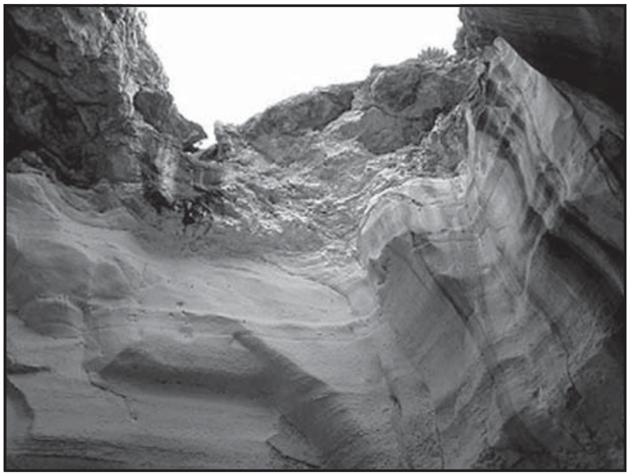

Figure 5. Hard (upper), and soft (lower) facies of Eocene chalk. The contact between hard and soft chalk is about 5 m below the top of the section.

Figure 6. The walls of Lachish City.

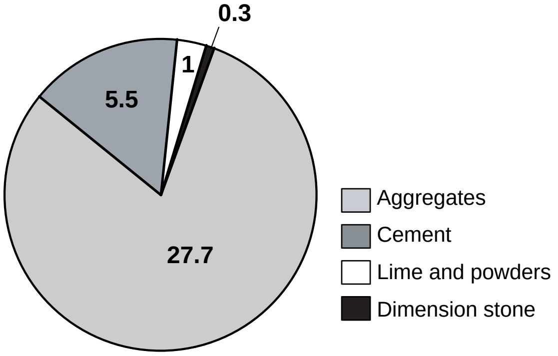

Figure 7. Limestone and dolomite exploitation in Israel in millions of metric tons, according to products.

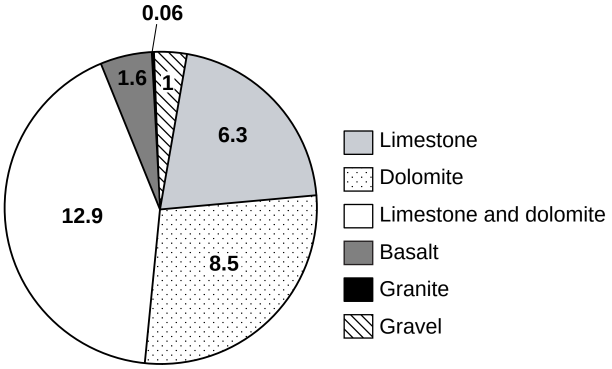

Figure 8. Aggregate production in Israel in millions of metric tons, according to lithologic type.

Figure 9. Karstic cavity within a dolomite quarry.

Summary

In spite of the abundance and variety of carbonate raw materials for building and road construction in Israel, four issues limit their exploitation: planning conflicts, environmental concerns, functional or quality requirements, and economic considerations. These difficulties may create a shortage of construction materials that will affect the building industry in about 10 to 15 years. Measures are now being taken to speed up the planning procedures required for the approval of potential new sites that will help in meeting future construction material requirements.

Acknowledgments

We would like to express our gratitude to Mr. C. Dallal, which contributed to this paper by his fieldwork and by designing the illustrations and editing the manuscript. Also we are grateful to Mrs. N. Homsky and Mr. A. Varshavsky for their help in editing the manuscript.

Figure 10. Joints in dolomite filled with soil and clay.

Figure 11. Turonian limestone quarried for marble.

Figure 12. Thermally metamorphosed chalk (left) adjacent to intrusive basalt (right).

An Overview of the Geology, Mining, Processing, and Uses of Industrial Sand and Gravel

Jeffrey P. Jahn, U.S. Silica Company

Introduction

Silica, which has the chemical formula SiO_2, occurs naturally and is manufactured synthetically with a wide range of purity and in a number of crystalline and non-crystalline (amorphous) forms. Unlike other mineral resources, such as limestone and coal, which are defined on the basis of chemical composition, sand and gravel are defined by end use and particle size distribution. For the purposes of this overview, "industrial sand and gravel" corresponds generally to the business described in the publications of the U.S. Geological Survey as distinct from the "construction sand and gravel" business. Industrial sand and gravel are generally purer than their construction counterparts, requiring a minimum of 95% SiO_2, having more stringent specifications, and bringing a higher price. Despite the differences, there are some grades of sand and gravel being supplied from industrial deposits to construction markets and to a lesser extent vice versa.

The U.S. Geological Survey reported consumption of industrial sand and gravel in the United States for 2001 at 30.75 million short tons (27.9 metric tons) (Dolley, 2001) compared to 1.25 billion short tons (1.13 metric tons) (Bolen, 2001) for construction sand and gravel, which is more common geologically and more widespread, geographically.

Geology of Industrial Sand and Gravel

Quartz is an essential constituent in most igneous and metamorphic rocks. It is chemically and physically resistant and commonly concentrated during sedimentary processes to form diverse deposits that range from hard, tightly cemented sandstone rock to loose unconsolidated grains, commonly associated with dune and coastal sands.

An economically viable industrial sand and gravel deposit must be a concentration of grains that are essentially pure quartz. There are several distinct regions in the United States where this has occurred via sedimentary processes. In each of these regions, the essential principles of forming the orebodies are the same, even though each deposit has its own distinct characteristics due to variations in process. Typically, the formation of a viable deposit is achieved only through many erosional and depositional cycles. Each erosion and deposition cycle enhances the purity of the quartz deposit and decreases the degree of angularity and increases the roundness of the individual quartz grains.

Industrial sand and gravel deposits are valued by quartz purity, grain shape and customer logistics. Frequently, only multiple mine locations within the same formation, situated over a large geographical area, are able to provide customers with the desired proximal and economically viable sources of quartz products. Most of these deposits serve local or regional markets. Only a few, because of quality or value-added processing, serve national and international markets, and most of these are generally associated with the eastern and mid-continent marine quartz arenites that contain less than 10% matrix material and 10% rock particles or feldspar.

As shown in figure 1, silica sand deposits in the United States can be grouped into five geological provinces (Heinrich, 1981). Each province has a distinctive geological history that has influenced the sand's grain shape and composition, grain size and distribution, surface area and accessory mineral content.

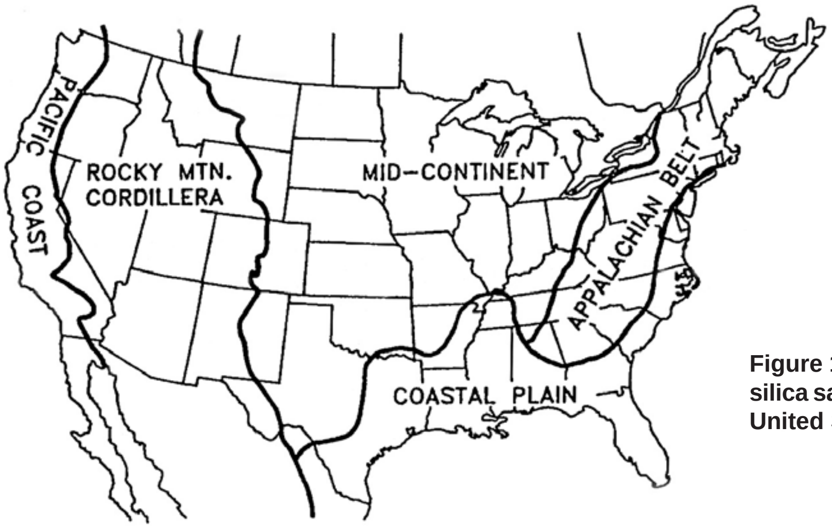

Figure 1. General geologic provinces for silica sand and sandstone resources in the United States.

Coastal Plain

Along the Atlantic Coastal Plain, unconsolidated, nearly flat-lying sediments of Late Cretaceous to Holocene age are mined for various industrial uses (Linkous and Zdunczyk, 1994). Many of the deposits occur along the fall line or the break between the resistant more crystalline rocks of the Appalachian Belt and the Coastal Plain sediments. Grains generally range from angular to sub-rounded. The choice of mining method is dependent on the unconsolidated nature of the materials and can include dredging, in-pit tramming and conveying, and dragline and scraper utilization.

Two examples are the Cohansey Formation in south New Jersey and the Pinehurst Formation of the Sandhills District of the Carolinas. The Cohansey Formation is a mid-shelf marine deposit of Miocene age. The sand is well sorted, sub-angular and fine- to medium-grained. The Pinehurst Formation is an eolian deposit of late Miocene to early Pliocene age. The sand varies from white to yellow-orange and is generally poorly sorted and medium- to coarse-grained.

Appalachian Belt

High quality quartz sandstones of Silurian and Early Devonian age were produced by the deposition and continued reworking of non-marine clastics. Conventional hard rock mining practices are utilized in the major industrial sand deposits of this province.

The Oriskany, or more accurately, its upper part, the Ridgeley Sandstone, is a thin sheet of sandstone extending from New York State south and west into Virginia and Ohio. In the folded belt of the central Appalachian Mountains, it has long been quarried for glassmaking purposes. Oriskany Sandstone is a hard quartzite rock, but several active mining sites are found where exceptional jointing and fracturing has allowed downward-percolating waters to leach the cementing material and reduce the hard rock to friable sandstone or loose sand. The Oriskany consists of medium to fine, well-sorted, sub-angular, quartz grains. The washed rock contains 99% or more pure silica.

Mid-Continent

Some of the highest quality industrial sands in the world are produced from the Mid-Continent of North America. These early Paleozoic deposits are flat lying and moderately consolidated (Linkous and Zdunczyk, 1994). Hydraulic mining is a suitable mining method for many of these deposits. Quality has been enhanced by repeated cycles of erosion, winnowing and redeposition, and the sand is characterized by the high degree of roundness of the grains. Forty-one percent of U.S. production comes from this province. The State of Illinois, producing 16% of the U.S. supply, produces more industrial sand and gravel than any other state.

One formation, the St. Peter Sandstone, is mined in several locations. It is widespread and records the advance of seas across what is now the east-central United States, which in the early Paleozoic was a featureless lowland. Younger sediments buried the sandstone, but it crops out along the southern margin of the Wisconsin Dome, notably in northern Illinois, and on the flanks of the Ozark Uplift, west and south of St. Louis, Missouri. This geologic unit is believed to have undergone a significant number of erosion and deposition cycles (some have estimated as many as 100). The best-known center of commercial production is the Ottawa District, Illinois, some 75 miles southwest of Chicago. In this area, the St. Peter Sandstone is light gray to white, and quarried rock contains more than 97% silica. Most of the non-quartz fraction is clay, which provides a weak bond and is readily removed in washing. The sand is well sorted, more than 80% falling in the medium to coarse range, and the grains are well rounded. Washed sand has silica content of over 99%.

Another deposit, the Ordovician Oil Creek Formation in central Oklahoma, is unique due to the lack of coarse sand and overall fineness of the deposit with an average AFS (American Foundryman's Society Standard) of 90.

Rocky Mountain Cordillera

Deposits of Ordovician orthoquartzites extend from British Columbia to southern California. These deposits are strongly indurated and dip at varying attitudes. They have not been extensively developed commercially because of their distance from large industrial markets and lack of favorable rail access (Linkous and Zdunczyk, 1994).

One example is the Addy Quartzite of Stevens County, Washington. It varies from unconsolidated sand to true quartzite. It is buff to white, and individual grains range from angular to sub-angular. Most of the sand is sold to container glass manufacturers in western Washington.

Pacific Coast

Feldspathic, clayey sands of Paleocene to Pliocene and Pleistocene age are mined in California for the glass industry. These coastal deposits require extensive processing to remove shale chips, feldspar, and heavy minerals, and they are often blended with higher purity sands from other sources to improve overall quality.

The Eocene Domengine Formation is one example of a feldspathic sand being mined for container glass and construction uses. It is widely distributed around the margins of the Diablo Range and considered to be of shallow marine origin.

Processing

Just as the extraction method varies with the type of ore deposit, so do the processing methods employed. Tightly cemented sandstone must be crushed, using jaw, cone, and third stage rod or ball mills to liberate the grains of sand. Moderately indurated or unconsolidated deposits do not require any crushing to liberate the grains.

Once individual sand grains have been liberated, fine clays are separated from the sand using rake or screw classifiers, cyclones and hydrosizers. Entrained water is removed with vacuum filters or drain piles. Drying with rotary or fluid-bed dryers remove any remaining moisture before the material is mechanically screened to final size and required particle distribution.

Additional beneficiation of the sand is dependent upon the purity of the orebody. Younger, less pure deposits typically require scrubbing, gravity, or magnetic separation of magnetic particles and/or chemical flotation to remove heavy minerals and other impurities. This is critical for plants that supply the glassmaking industry.

Some locations, like the Spruce Pine and Kings Mountain area of North Carolina, produce high quality silica products as a flotation concentrate after separation of feldspar or mica. Still other locations include silica-grinding facilities. Pebble mills operate in closed circuit with air classifiers to produce ground silica of various size distributions including some with a maximum particle size of a few microns.

Industrial sand processing plants vary in size from less than 25,000 tons per year operations to large multiple grade plants capable of shipping millions of tons annually. The majority of shipments are bulk rail car (35%) or truck (62%) (Dolley, 2001). Some processing plants bag various grades of sand in 50-pound to 1-ton bulk bags.

Markets and Applications

Industrial sand and gravel is used in a wide spectrum of products from high technology applications in the electronics and optical fields to bunker golf course sands. Market consumption, based on USGS statistics for 2001, are listed below (Dolley, 2001).

Glass Sand (37% of market)

Most glass manufacturers have specifications for each source of silica sand used. These specifications define the limits for chemical and physical properties of the sand and are used by the manufacture in calculating the desired batch mix. Although the majority of glass produced in this country is of the soda-lime-silica variety, different glassmakers will vary the composition depending upon their ultimate end products (containers, flat glass, glass fiber, etc.), their particular formula, and the purity of the sources of raw materials. A glass company is, therefore, usually more focused on the consistency of the raw materials on a day-to-day basis.

Heavy minerals such as ilmenite, leucoxene, kyanite, and zircon are impurities on which strict limits are placed. Coloring oxides and certain metal oxides, like aluminum, nickel and copper, are also strictly controlled. Because of their refractory nature, they either do not melt or only partially melt, causing stones or other imperfections in the finished glass.

Silica is the largest single ingredient in a glass batch (50 to 70%) causing some to say that silica is the “backbone” of glassmaking. If this is true, then it follows that the glass market, which accounts for over a third of the total industrial silica market, is also the backbone of the industrial sand and gravel industry. The United States is the largest producer of glass, accounting for 77% of the total North American glass production, with rapidly growing Mexican production accounting for 18%. Each of the following end uses of glass represents a significant market segment.

Glass containers (18% of market)—The glass container market in the United States and Canada has become primarily for beer and food containers. The move to plastic for soft drinks has severely impacted the container industry, followed by plastic alternatives within the food industry. Glass manufacturers countered with marketing programs for premium products such as wine coolers, new age drinks, iced teas, premium microbrews, and longneck beer. Even though the decline was countered, silica sales to this market have continued to decline because of lighter-weight alternative containers and increased use of post-consumer recycled glass.

Flat glass (13% of market)—New architectural and automotive uses continue to increase flat glass demand. Strong building in both United States and Mexico has added to this demand.

Fiberglass (3% of market)—Fiberglass as insulation is also dependent upon housing construction and remodeling. Growth is being driven by the roofing market and by increased use of materials for the leisure and automotive markets where lightweight materials are desired. Fiberglass yarn is used in electronics, filtration, and specialty applications. Continuous glass fiber specifications are very demanding. Batch grain-size control is critical, and strict limits on grain size of ground silica are required.

Specialty glass (3% of market)—Specialty glass consists of several end-use markets such as tableware, lighting, television monitors and flat panel display glass, optical glass, and glass-ceramics. Glass for light bulbs and fluorescent tubes is the largest segment.

Foundry Sand (21% of market)

Foundry sand consists primarily of clean, round, uniformly sized, high-quality silica or lake sand that is bonded to form molds and cores for ferrous (iron and steel) and nonferrous (copper, aluminum, brass) metal castings. The molds are used to form metal into a variety of shapes. Core sand fills the spaces where metal is not needed or wanted. The requirements are very demanding. The sand must withstand the high temperatures and associated pressures of pouring the molten metal, it must allow gasses to escape through the sand, and the sand must have the proper texture and composition to make a smooth casting. Virtually all sand cast molds for ferrous castings are of the green sand type. Green sand consists of high-quality silica sand and about 10% bentonite clay (as the binder). In addition, chemically bonded systems are most often used for “cores” (used to produce cavities that are not practical to produce by normal molding operations) and for molds for nonferrous castings. The type of metal being cast determines which additives and what gradation of sand is used.

Building Products (9% of market)

This market segment has a diverse customer base. Whole grain and ground silica is used in the production of face bricks, asphalt sealant, asphalt shingle backing, fiber cement panels, mortars and grouts, stuccos, and self-leveling underlayment.

Recreational and Agricultural (6% of market)

The United States Golf Association has developed specifications not only for golf-trap sand, but also top dressing and other root zone mixtures used to build greens and tees. Some large-scale farm operations use silica sand in their feedlots and holding pens to help control mastitis in dairy cows.

Frac Sand (6% of market)

Hydraulic fracturing sand is pumped at very high pressures into subsurface rock strata to prop open fractures created by the high pressures. This process is used to increase the permeability of the rock, thus increasing the rate of oil and gas flow. “Frac” sand is normally free of impurities, well sorted, and composed of very well-rounded grains. Frac sand demand varies with the level of activity into the oil and gas well industry.

Abrasives (6% of market)

Silica sand is an effective abrasive for cleaning metal, concrete, brick, and other surfaces. Applications include air-blast and coating to scouring powders and liquids. Grains are angular, hard, durable, and free of impurities. Coarse sand is used on large steel or iron structures while finer sand is used in cleaning brass, aluminum, and even wood.

Metallurgical and Refractories (6% of market)

Silica is used as a flux in smelting base-metal ores where iron and basic oxides are slagged as silicates. Silica refractories have excellent load resistance at high temperatures and are used in ceramic kilns and glass tank crowns, and as checkers in glass tanks and blast furnaces.

Chemicals (3% of market)

Sodium and potassium silicates are produced by reacting silica sand and soda ash or potassium carbonate in a furnace. One application for sodium silicate is in the production of synthetic zeolite. Potassium silicate is used primarily in welding rods. Exciting high tech production of specialty silica is also accomplished by chemical and thermal processing of natural silica. These include: silianes; colloidal silica; fumed, fused, or precipitated silica; and ultra-high-purity silica. These silica-based products find application in adhesives, beverages, coatings, electronics, food, health care, optics, paper, plastics and rubber, to name a few products and markets.

Filtration (3% of market)

Well-sorted coarse grades of silica sand are used in municipal water filtration and for residential pool-water filtering. Two important measures of sand for this application are effective size and uniformity coefficient.

Fillers (2% of market)

Ground silica is used as functional filler in paints, plastics, and silicon rubber. A number of additional specifications (reflectance, brightness, yellowness, oil absorption, and fineness of grind) can apply to the use of ground silica in various filler applications. Acceptable values vary depending on the source of silica and the specific product being produced.

Ceramics (1% of market)

Silica, in both whole grain and ground form, is used in ceramics. Whole grain silica makes up 20 to 30% of the ceramic body of sanitary ware (sinks, toilets, urinals, etc). Ground silica is used to control viscosity and expansion coefficient in ceramic glazes and other applications. A growing market in advanced ceramics is the production of silicon carbide and silicon nitride. Silicon carbide is used in seal rings and composite bearings. Silicon nitrides are finding use in dental drills and aerospace components as hybrid bearings.

Outlook and Trends

The raw material industry in general and the silica industry in particular are still in the process of consolidation. The silica market for glass making is mature with little or no overall growth. In the foundry industry, the recycling of used foundry sand is thought to be increasing. Development and use of substitute materials for glass and cast metals could further reduce the demand for silica in these markets. Many advances in high-tech materials using specialty silica will increase the consumption of value-added silica sands. Although overall demand is decreasing, the total value of production could increase because of the increased unit value of the more specialized sands.

Except for a few end uses that require a high degree of processing, the location of a deposit in relation to the market is an important factor that a sand producer must take into account. A number of relatively small operations supply local markets with a limited number of products.

The health risks associated with respirable crystalline silica dust pose a continuing challenge to the industry. Permissible exposure limits will continue to be scrutinized and the exposure guidelines will likely be reduced in the future.

The industrial silica industry is changing. Soft demand, increased regulatory pressures, and cost containment demands by customers will require the development of more efficient mining and processing plants and the development of lower quality silica sand deposits that are not currently mined.

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Lacustrine Calcareous Diatomite and Its Mining History in East-Central Nebraska, USA

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Abstract

Calcareous diatomites crop out within a thin (2–3 m) stratigraphic horizon along the North Loup River between Scotia and Cotesfield in east-central Nebraska. Within certain thin intervals, the CaO content of these deposits exceeds 50%, and the SiO_2 content falls below 10%. Calcareous diatomite was mined on the surface and underground at the Happy Jack Mine near Scotia during the period 1877–1945 for use as a building stone, a source of lime, a paint additive, and an abrasive. There may have been additional, minor uses. The mined horizon contains diverse planktonic and benthic diatoms and has continuous, 2- to 14-mm-thick laminae; persistent light-dark laminae couplets may reflect changes in productivity and the rate and mode of deposition. Calcareous diatomite in the mine is overlain by a thin, diatomaceous limestone with irregular, wavy to lenticular bedding. These deposits are enclosed within very fine- to medium-grained fluvial sandstones, which show evidence for weak soil development at multiple levels.

The Happy Jack Mine has a highly irregular room-and-pillar layout. Wasting of pillars under load, leading to a decrease in pillar-base widths of one-half to two-thirds, is prominent in the deeper parts of the mine. Cumulative roof failure since the abandonment of the mine about 1945 also has had a strong effect. Today, after rehabilitation and safety improvements, the Happy Jack Mine is a regionally important tourist attraction. The limited volume, chemistry, and diatom morphotype composition of deposits in the Scotia-Cotesfield area makes them economically nonviable under present conditions, but they have potential in interpreting the depositional and climatic history of the Great Plains during the Neogene.

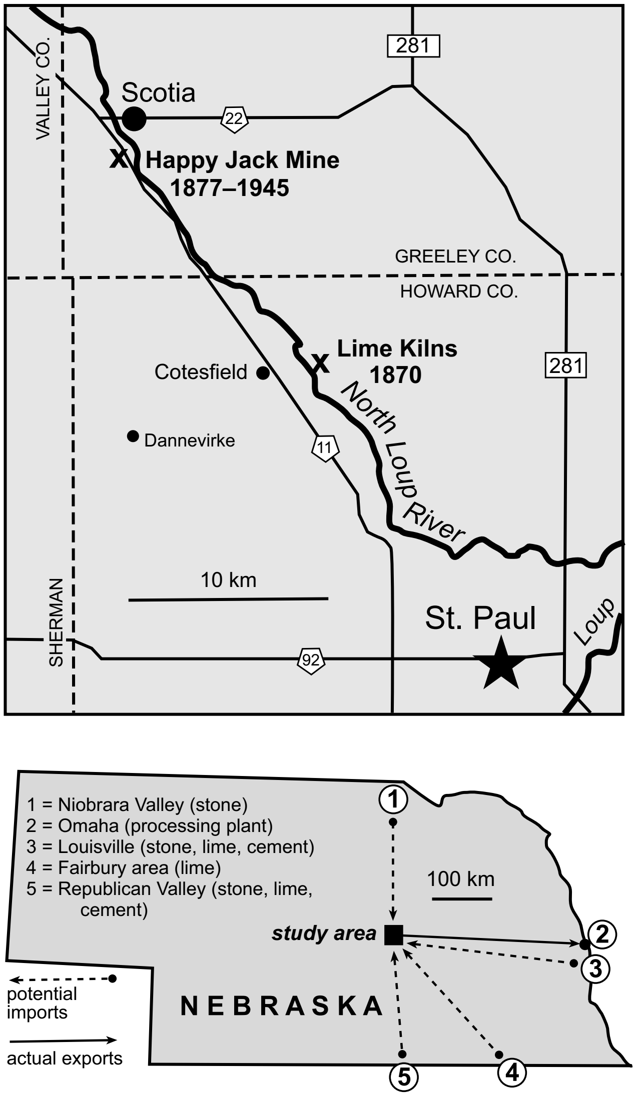


Figure 1. Map of study area with locations of Happy Jack Mine and 1870s lime kilns, both of which extracted upper Ogallala Group calcareous diatomite and associated facies; index map below shows distance from study area to nearest major sources of other industrial mineral commodities (potential imports). Use of local materials in the Scotia-Cotesfield area substituted for these and other potential imports into east-central Nebraska before 1900. Opaline-cemented sandstone (so-called "green quartzite") of the upper Ogallala Group crops out in the Niobrara and Republican valleys (1, 5) and was used in those areas as building and foundation stone, and later as riprap. Limestone from Niobrara Formation (Upper Cretaceous) is also available in Republican Valley (5), and was used to produce cement at Superior, Nebraska well into 20th century. Lime was produced from the Greenhorn Limestone (Upper Cretaceous) near Fairbury (4) from 1840s into the 20th century. The Louisville area (3) has been a historical center of limestone, lime, and cement production for 140 years, and today (2003) contains the only cement-manufacturing plant in Nebraska. A paint factory in Omaha (2) actually used raw materials exported from Happy Jack Mine during 1930s and 1940s. In early settlement times in Greeley and Howard counties (1870s–1880s), difficulties and cost of shipping bulk mineral commodities favored use of local materials; ironically, in first half of 20th century, demand "reversed" and calcareous diatomite was shipped far offsite to Omaha.

Introduction

Euramerican settlers in Nebraska faced major restrictions on the availability of mineral resources, even for basic building purposes, as they spread westward from the Missouri River after the Civil War. East-central Nebraska, at the margin of the Great Plains, was one area into which settlement spread rapidly. This region is thickly mantled by loess and dune sand, so bedrock outcrops, which might otherwise yield building stone or other commodities, are rare. Furthermore, timber resources were limited. In the North Loup Valley (fig. 1) there were sand and gravel deposits along streams, but these were only mined on a significant scale after 1900. A few small-scale brick works utilized loess as a raw material during the late 1800s and early 1900s (McDermott, 1939). Other industrial mineral resources—particularly those suitable for export—were conspicuously lacking, with a single and very noteworthy exception. Lacustrine calcareous diatomites (LCD) in the upper Ogallala Group (late Miocene), cropping out in the walls of the North Loup Valley in Greeley and Howard counties, Nebraska (fig. 1), proved to be a regionally important, multi-use mineral resource over a period of nearly eight decades.

The utility of LCD as a source of building stone and lime was realized almost immediately when permanent settlements were established in the North Loup Valley during the 1870s. Anecdotal accounts suggest that associated Ogallala Group facies, particularly freshwater limestones, carbonate-cemented sandstones, and calcretes also had some early value as sources of calcium carbonate, calcium oxide, and even building material. LCD in the Scotia-Cotesfield, Nebraska area (fig. 1) ceased to be of economic importance at the end of World War II, but an abandoned underground LCD mine, the Happy Jack Mine near Scotia (figs. 2, 3), continues to generate income as a tourist attraction rather than an active producer of mineral products. Ogallala LCD deposits in the study area have always been referred to as "chalk" in the local vernacular because of their consistency, whiteness, and high lime content (as much as 50% CaO). To this day, the Happy Jack Mine is still referred to as the "Chalk Mine."

The unusual setting and circumstances of LCD deposits and related facies, their geologic origin, their petrographic

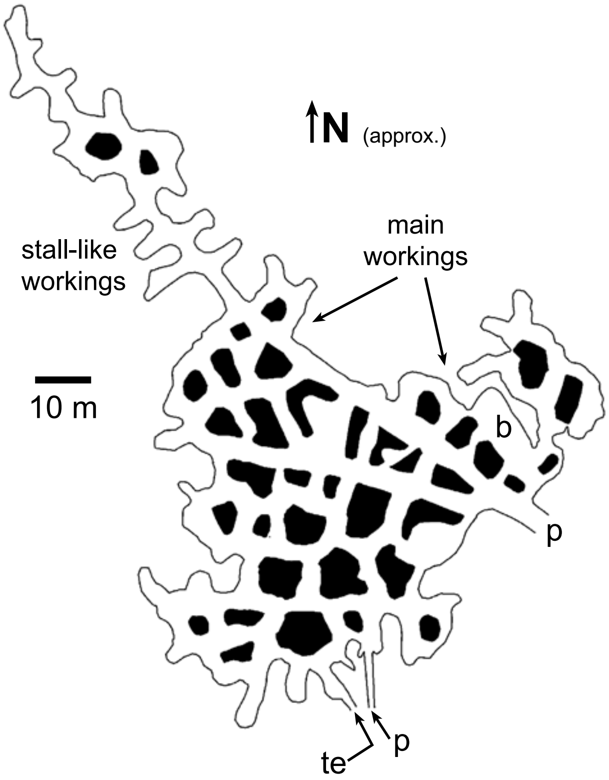


Figure 2. Map of Happy Jack Mine; pillars are shown in black. Two of the original portals (p) to the mine and a tour entrance (te) remain open; "Ballroom" (b) is site of extensive roof fall postdating the closure of the mine.

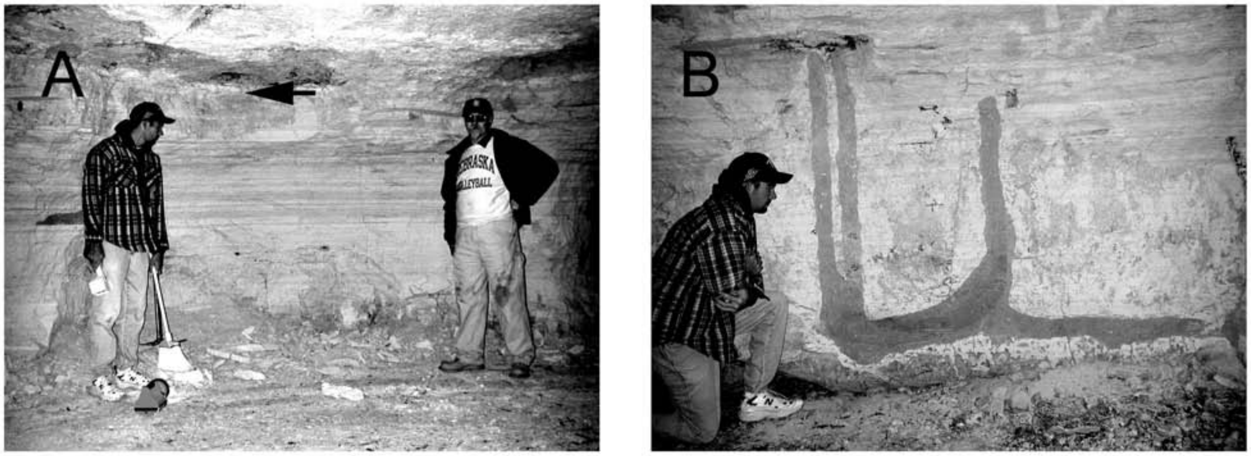


Figure 3. A, Thinly laminated diatomite (note upward transition from lighter to darker strata) in Happy Jack Mine. White marker layer (arrow) is nearly pure diatomite that marks change from calcareous diatomite to diatomaceous limestone. B, Large rodent burrow in diatomite (see Joeckel and Tucker, 2002).

and geochemical characteristics, their place in local lore, and the history of their utilization have barely been investigated (e.g., Pabian and Swinehart, 1977). The purposes of this paper are to correct these gaps in knowledge, to provide a "post-mortem" account of an important, early mineral industry and its impacts on vernacular architecture and local economies at a critical point in history, and to support future investigations into the industrial mineral resources of east-central Nebraska. Furthermore, in this paper we provide the first surveyed map of the Happy Jack Mine, which yields new information about its design, the mining practices employed within it, its current safety status, and its potential longevity in the light of failure hazards under relatively unique geologic and engineering conditions.

Materials and Methods

Extensive observations and measurements were made within the Happy Jack Mine and at several nearby Ash Hollow Formation outcrops. One exploratory core, University of Nebraska-Lincoln Conservation and Survey Division (UN-L CSD) test hole 49-A-02, was drilled at the site with a combination drilling rig using a split-tube sample barrel inside a hollow-stem auger. This technique was chosen over rotary coring because of the softness of most Ogallala Group sediments in the study area and their tendency to slake in water or drilling fluid. Samples from the mine, outcrops, and the core were subjected to several standard analyses. X-ray diffraction (XRD) was carried out using CuKα radiation, with a scan range of 2° to 60° or 70° 2θ, scanning at 2°/minute. The JADE 6.0© mineral identification program and Joint Committee for Powder Diffraction Standards (JCPDS) files were used to identify mineral phases. X-ray fluorescence (XRF) was carried out on ground samples from core 49-A-02; boric-acid-and-copolymer-binder-backed pressed pellets were employed. Three XRF standards, fly ash type "C", fly ash-cement blend, and National Institute of Standards and American Society for Testing and Materials (ASTM) argillaceous limestone (Standard Reference Material 1c), were applied in the XRF analysis, but the most precision was achieved with the argillaceous limestone standard. Scanning electron microscopy was performed on Pt-Pd-coated samples mounted on Al stubs.

Selected ground samples of diatomite from the Happy Jack Mine were heated to 1100° C in a muffle furnace in order to assess chemical or mineralogical changes generally relevant to industrial processes. These samples, as well as unheated control samples, were ground to pass a 1 mm sieve and then pelleted (~25 mm in diameter and ~7 mm thick) with a hydraulic press at 207 Kpa (30 psi). The heating of experimental pellets to 1100°C for approximately 16 hours was preceded and followed by approximately 4 hours transition from/to room temperature.

The colors of LCD samples from core 49-A-02, ground to pass a 250 µm sieve, were measured with a colorimeter. The powders were back-loaded and smoothly packed against a low-reflection glass plate in a sample-holding attachment. A standard calibration plate was used to calibrate whiteness and color values. Color measurements were made in the Commission Internationale de l'Eclairage (CIE; e.g., CIE, 1986) XYZ, CIE Yxy, CIE L*a*b, CIE L*C*Ho, and Hunter Lab L*a*b color systems. The Happy Jack Mine was electronically surveyed over a period of months and the data were successively transferred to a Geographic Information Systems (GIS) program in order to construct a digital map.

Regional Stratigraphy

Deposits of LCD in the vicinity of the Happy Jack Mine are in the upper Ogallala Group, near its contact with Pliocene or Pleistocene sediments (figs. 4, 5). In Nebraska, the Ogallala Group was deposited almost entirely by Miocene streams draining the Rocky Mountain Front and High Plains, although localized lacustrine deposits can be found in multiple stratigraphic horizons and at far-flug locales. In this paper, the Scotia-Cotesfield LCD are considered to be part of the Ash Hollow Formation because of their high stratigraphic position within the Ogallala Group (see discussions in Swinehart and others, 1985 and Souders, 2000).

UN-L CSD rotary test holes drilled in Greeley and Howard counties, Nebraska show that 80% or more of the Ogallala Group consists of very fine to medium sands, weakly cemented sandstones, and silt or weakly cemented siltstones (see Burchett and Smith, 1992; Dreeszen, 1999; Souders, 2000). Souders (2000) emphasized the occurrence of fining-upward sequences in the Ogallala Group throughout east-central Nebraska. Electric logs and corresponding lithologic logs from boreholes in Greeley and Howard Counties (see Burchett and Smith, 1992; Dreeszen, 1999), however, show multiple stratigraphic patterns. These patterns include: (1) fining-upward packages approximately 1.5–5 m thick, which are very rarely capped by diatomites or putative lacustrine limestones; (2) coarsening-upward packages of similar thickness; (3) interbedded thin siltstones and sandstones; and (4) thick (> 3 m), relatively uniform, sandstones. Pabian and Swinehart (1977) interpreted the LCD at Happy Jack Mine as having been deposited atop sandy channel-belt sediments in an abandoned river channel segment, possibly within an oxbow lake on the floodplain of a higher-sinuosity stream.

It is currently impossible to determine the total area and volume of Scotia-Cotesfield LCD deposit. To our knowledge, the operators of the Happy Jack Mine never engaged in an exploratory drilling program, and the steep, broken terrain along the walls of the North Loup Valley strongly discourages drilling in most places. Exposures near the Happy Jack Mine, southward down the North Loup River, and east of Cotesfield (fig. 1) are all at nearly the same stratigraphic altitude, suggesting that the original lacustrine deposit could have been as much as 12 km in length and a few kilometers in width. The river has eroded through much of the area that might have been underlain by LCD, however, and it is possible that multiple, smaller lake deposits existed within the same stratigraphic horizon.

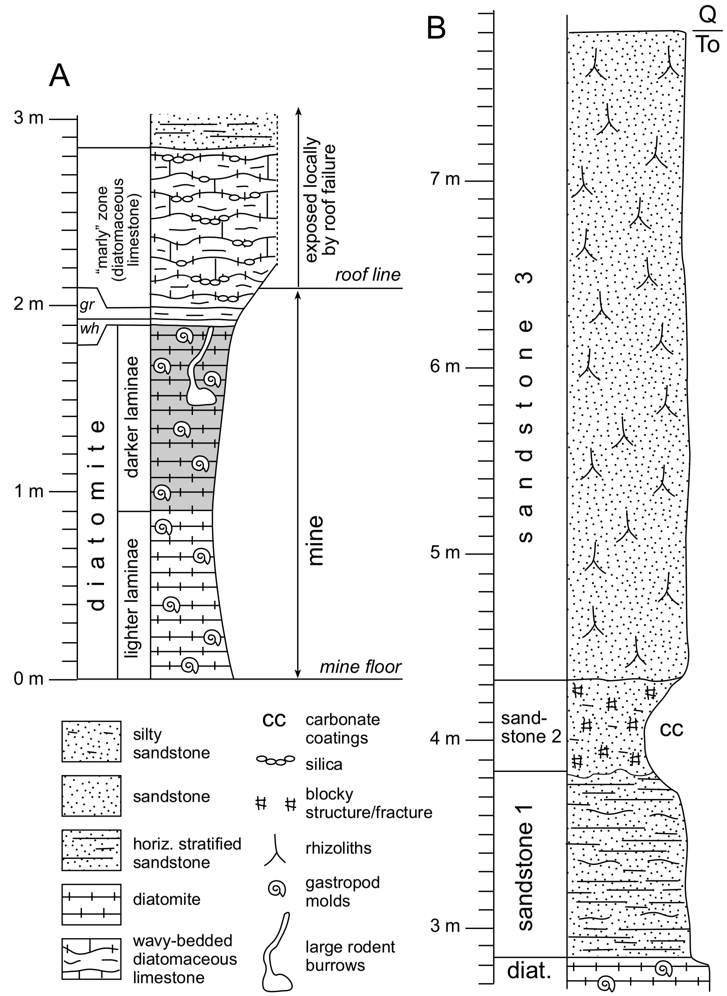


Figure 4. A, Stratigraphic section in Happy Jack Mine. White marker layer (wh) and green marker layer (gr) persist throughout mine; green layer records influx of clastic sediment. Large rodent burrows in the calcareous diatomite are an important paleontological find (Joeckel and Tucker, 2002). B, Section at adjacent road cut, showing overlying sediments, including sandstone 2, which has blocky structure (peds) and carbonate coatings that record weak soil development before burial by sandstone 3.

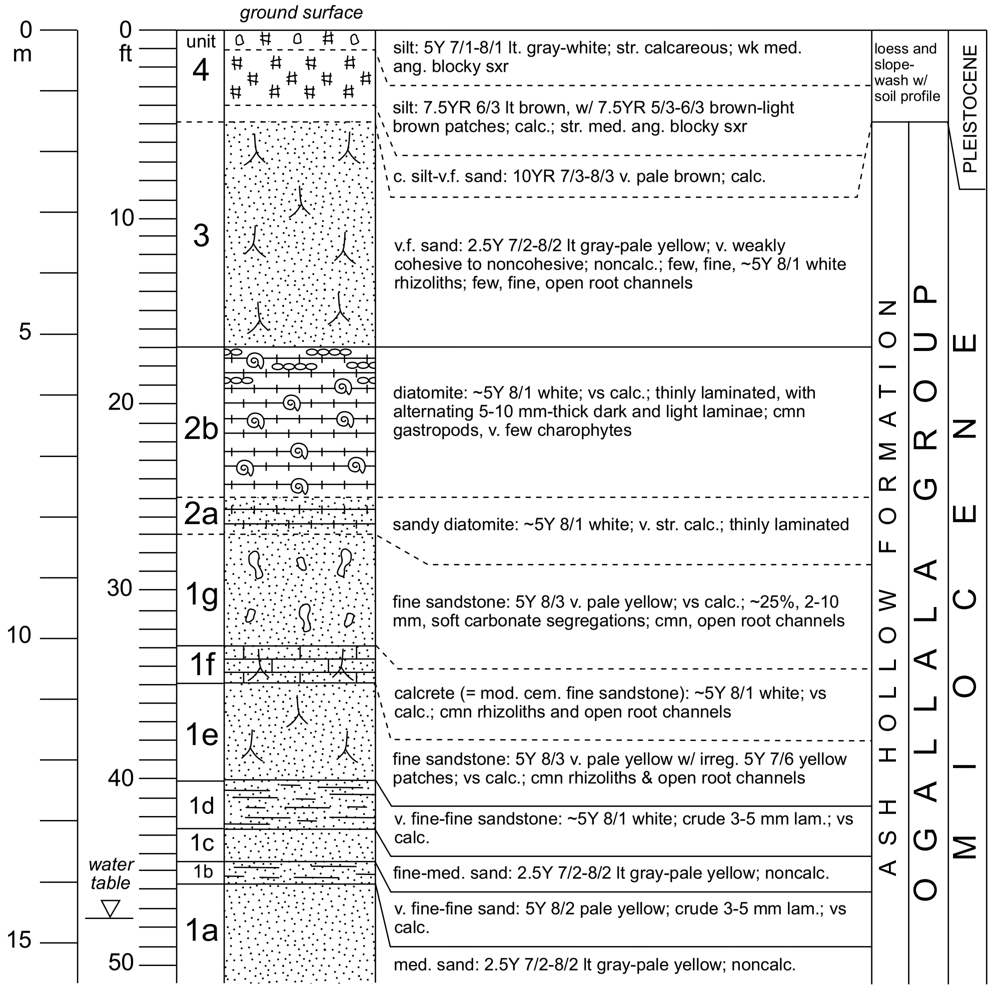


Figure 5. Log of University of Nebraska-Lincoln Conservation and Survey Division core 49-A-02. Rhizoliths, calcrete, and carbonate nodules (units 1e, 1f, 1g, and 3) are evidence for pervasive and persistent weak soil development in sediments enclosing calcareous diatomite (2a, 2b).

Physical Characteristics, Petrography, and Stratigraphy of Calcareous Diatomite in the Study Area

The application of petrographic terminology to all of the upper Miocene lacustrine deposits in the study area is slightly problematic because of their high calcium carbonate content and simultaneous abundance of diatoms. In this study, the term “calcareous diatomite” has been applied to the mined horizon at the Happy Jack Mine (and equivalent strata in the surrounding area) in order to underscore both essential aspects of rock composition. Hicks (1888), in the first substantive scientific account of the deposits, described the deposits around Scotia with surprising accuracy as “diatomaceous earth” in which “the diatoms form but a small proportion of the whole mass of rock.” Pabian and Swinehart (1977, p. 10) referred to these same deposits as having been derived from “diatomaceous marl,” and Souders (2000) refers to the surface mining of “lacustrine limestone” for building purposes at the Happy Jack Mine site, although close examination demonstrates that this material is actually calcareous diatomite (fig. 6). Charophytes, which are visible to the naked eye, form less than 1% of rock volume, but they are frequently concentrated in thin horizons within the deposit.

Fresh LCD is cohesive, but soft, and has a relatively low bulk density. Air-dried lengths of cored LCD can easily be broken with a single blow from a rock hammer, and “plates” of diatomite less than 5 mm thick can be broken by applying moderate pressure between the hands. The bulk density of LCD from core 49-A-02 (fig. 5) ranges between 1.09 and 1.22 g/cm^3, less than half the density of typical limestones used for industrial purposes. LCD is extremely porous because of the inherent porosity of diatomaceous sediments, the lack of deep burial compaction, and because it consists of 5–15% by volume external molds of small gastropods, whose aragonitic shells were dissolved preferentially over the enclosing calcitic sediment.

LCD in the Scotia-Cotesfield area is overlain by, and may grade laterally into, diatomaceous limestones (figs. 4, 6B). Very fine (< 5 µm) in intermediate diameter, flake-like to subhedral calcite grains are ubiquitous throughout lacustrine deposits in the study area, either as interstitial

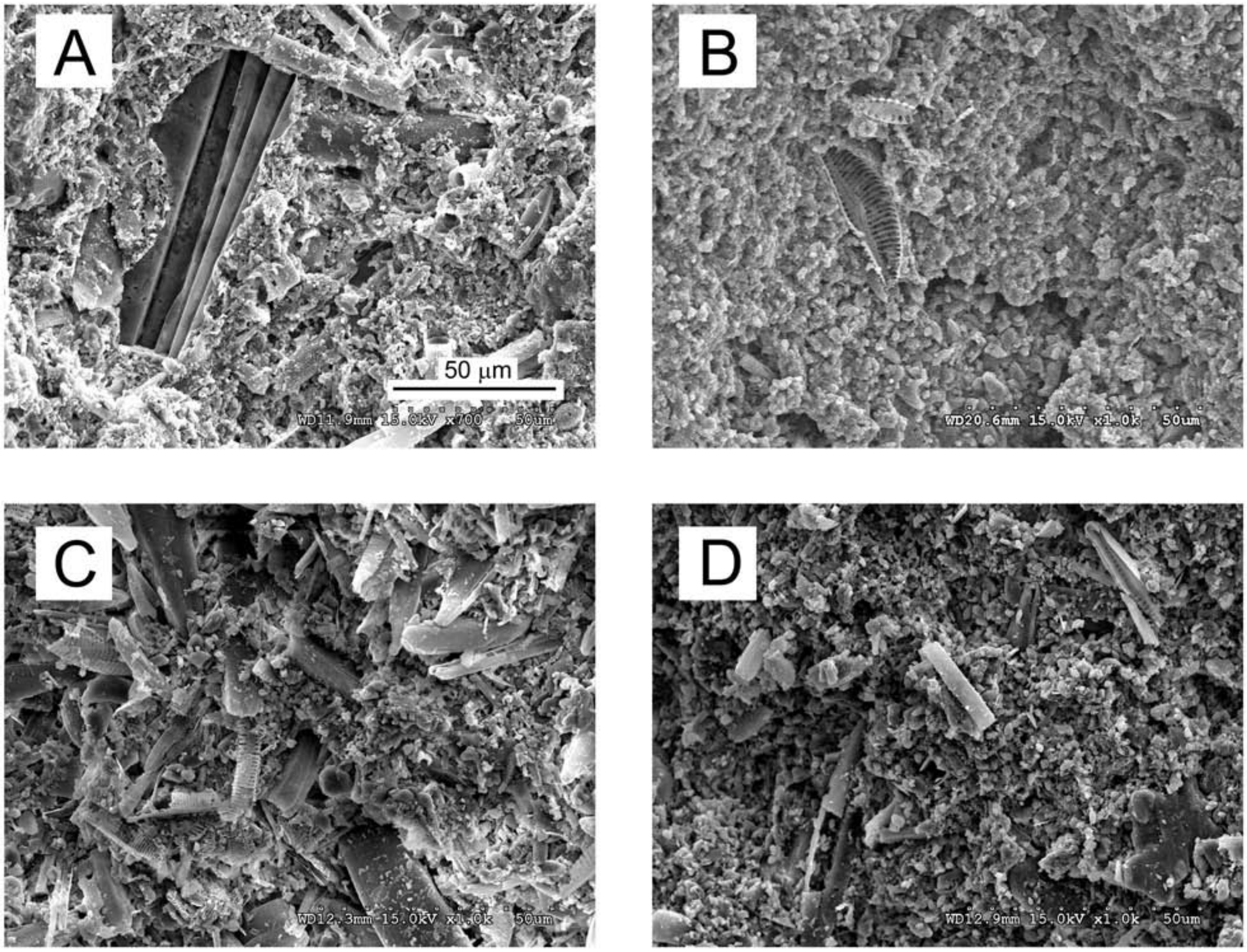


Figure 6. A, SEM photograph of calcareous diatomite from 6.57 m (25 ft) below surface in core 49-A-02 (see fig. 5); scale is same A-D. B, Diatomaceous limestone (“marly” zone) 20–25 cm above white marker layer (see fig. 4) inside Happy Jack Mine; fine-grained carbonate is pervasive, continuous phase, but slightly coarser than in A. C, Correlative calcareous diatomite from site of 1870s lime kilns approximately 12 km SSE of Happy Jack Mine. D, Case-hardened calcareous diatomite from same site; excess carbonate in this case appears to be limited to exposed surfaces of long-lived outcrops, and therefore is a weathering/late diagenetic phenomenon.

material between diatoms in calcareous diatomite or as the continuous micritic groundmass of the diatomaceous limestone (fig. 6A–D). This micritic carbonate is typically loose and does not show evidence for extensive overgrowth of crystallites, such as might arise from wholesale precipitation of calcite out of sediment pore waters during diagenesis. Indeed, the micritic carbonate in LCD is morphologically dissimilar to the fine, euhedral calcite cements that occur in pores within friable sandstones above and below the LCD. Therefore, most fine-grained carbonate in calcareous diatomite appears to be primary sediment deposited simultaneously with the diatoms. Nonetheless, there are localized occurrences of surficially exposed case-hardened calcareous diatomite, in which additional fine-grained calcite has been precipitated in pores as part of surficial weathering processes (fig. 6D).

Under the SEM, a high content of diatoms appears to be the salient feature of the LCD at the Happy Jack Mine. The actual SiO_2 content of the LCD, however, can be as low as 10%. Because diatom tests are thin-walled and hollow, they form a hollow framework that can accommodate a large volume of fine-grained carbonate sediment. The diatom assemblage from the Happy Jack Mine deposit is a mixture of diverse pennate and centric forms, including the genera *Aulacosiera*, *Cymbella*, *Fragilaria*, and *Tabellaria*. Both benthic and planktonic types are represented, and some of the forms suggest low-alkalinity waters.

The mined LCD horizon within the Happy Jack Mine shows a differentiation between: (1) an upper, darker and more prominently laminated zone, and (2) a lower, lighter-colored zone of approximately the same thickness (fig. 4). Throughout both zones are remarkably continuous 2- to 14-mm-thick laminae, which have a persistent pattern of successive light-dark couplets (fig. 3).

Two very distinct and laterally continuous strata, which can be traced throughout the Happy Jack Mine, overlie the LCD. The white marker layer (figs. 4, 7A) is a 1.5- to 4.0-cm-thick, highly reflective diatomite with little or no interstitial clay, silt, or carbonate. Local sources claim that the white marker layer was used as a guide for establishing the roof line and the upper limit of desirable material in the mine. The green marker layer (5–7 cm thick) directly above the white layer (figs. 4, 7B) is diatomite with interstitial siliciclastic clay and silt, but it appears to be fissile shale in hand specimen. Lamination in the green layer is very irregular and much less distinct compared to that in the LCD in the mined horizon below it. This comparison underscores the strictly biogenic origin of the LCD and the possibly seasonal significance of stratification within that deposit.

Above the green layer is an 80- to 85-cm-thick “marly” zone of diatom-bearing sediment in which micritic to finely microsparitic carbonate overwhelmingly dominates the rock fabric (figs. 4, 6B). This unit is therefore more accurately identified as a diatomaceous limestone rather than a calcareous diatomite. Close inspection shows that the unit has irregular, 1- to 5-cm-thick wavy to lenticular bedding with interlaminated, 5- to 20-mm-thick zones of brownish and whitish, microglobular opaline silica. Unfortunately, this distinctive succession is difficult to trace with precision to the adjacent highway road cut just on the outside of the hill in which the mine is excavated, much less to the core hole (fig. 5), where equivalent strata may have even be removed by post-Miocene erosion. The uppermost part of the LCD in core 49-A-02 probably correlates with part of the diatomaceous limestone/”marly” zone because of the abundance of opaline silica laminae at that level. Correlation problems arise primarily because the exposures inside the mine are pristine, continuous, and cover a much larger area than do any outcrops at the surface.

Friable, calcite-cemented sandstones underlie and overlie the Scotia-Cotesfield lacustrine deposits (figs. 4, 5). Rhizoliths are very common within most of these sandstones, and thin, massive, impure carbonate horizons occur in a few places. These carbonate horizons contain rhizoliths and sand grains, but they lack diatoms and any other evidence for lacustrine deposition. Furthermore, reworked clasts of identical carbonate material can be found in a outcrop of channel sandstone below the Happy Jack Mine along a

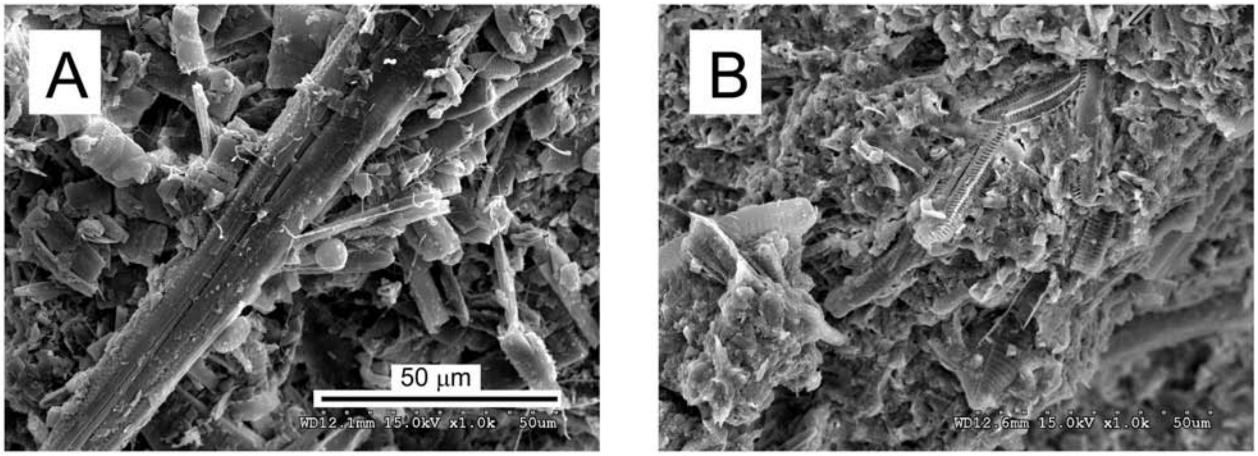


Figure 7. A, White marker layer (nearly pure diatomite) from Happy Jack Mine. B, Green marker layer (impure diatomite with clay) from Happy Jack Mine. Scale is same for both photographs.

railroad cut 100 m due east, indicating that the originally intact carbonate horizons formed while Ogallala sediments were still being deposited. These observations identify the thin carbonates as shallow subsurface calcretes.

Chemistry and Mineralogy of Calcareous Diatomite

The CaO content of LCD in 49-A-02 is notably high (15.2–52.5%) and in all but one sample it exceeds 29.0% (fig. 8A; table 1). SiO_2 is almost always lower (5.5–35.9%) and in all but one sample it is less than 23.0% (fig. 8B; table 1). Based on these data, the average $CaO:SiO_2$ molar ratio throughout the cored LCD interval is 3.6. Al_2O_3 (0.15–4.4%), Fe_2O_3 ($\leq$ 1.2%), and K_2O ($\leq$ 1.1%) are very low, and the contents of other elemental oxides (Na_2O, MgO, MnO_2, TiO_2, P_2O_5, SO_3) are less than 1.0% (fig. 8C-H; table 1). At the top and near the base of the calcareous diatomite in the core, an increase in several of these minor constituents, particularly Al_2O_3 and K_2O, corresponds with a greater content of sand and silt (particularly feldspar grains) and clay. Loss on ignition throughout the diatomite interval in the core is approximately 40%.

The LCD has variable color parameters (table 2), reflecting the variable content of clastic sediment impurities and corresponding changes in bulk chemistry, but much of it is relatively white compared to enclosing and surrounding sediments. No doubt the whiteness of the deposit attracted the attention of paint manufacturers (see discussion below). Lightness (Y, L, Hunter Lab L) is highest in the middle part of the LCD drilled in core 49-A-02 (fig. 9). LCD at the top and bottom of the cored interval are darker (i.e., less white) and contain more clastic sediment.

X-ray diffractograms of ground LCD are dominated by calcite peaks, and do not show any evidence of silica. A ground and pelleted sample underwent significant mineralogical and chemical change over a 24-hour heating to 1100° C in a muffle furnace. An unheated control pellet showed strong calcite peaks and no evidence for either an amorphous silica “hump” or crystalline silica peaks (figs. 10A, 11A). After heating the experimental pellet, however, calcite was decarbonated and CaO was produced, along with Ca_2SiO_4 through a solid-state reaction of calcite silica (figs. 10B, 11B) with the original calcite.

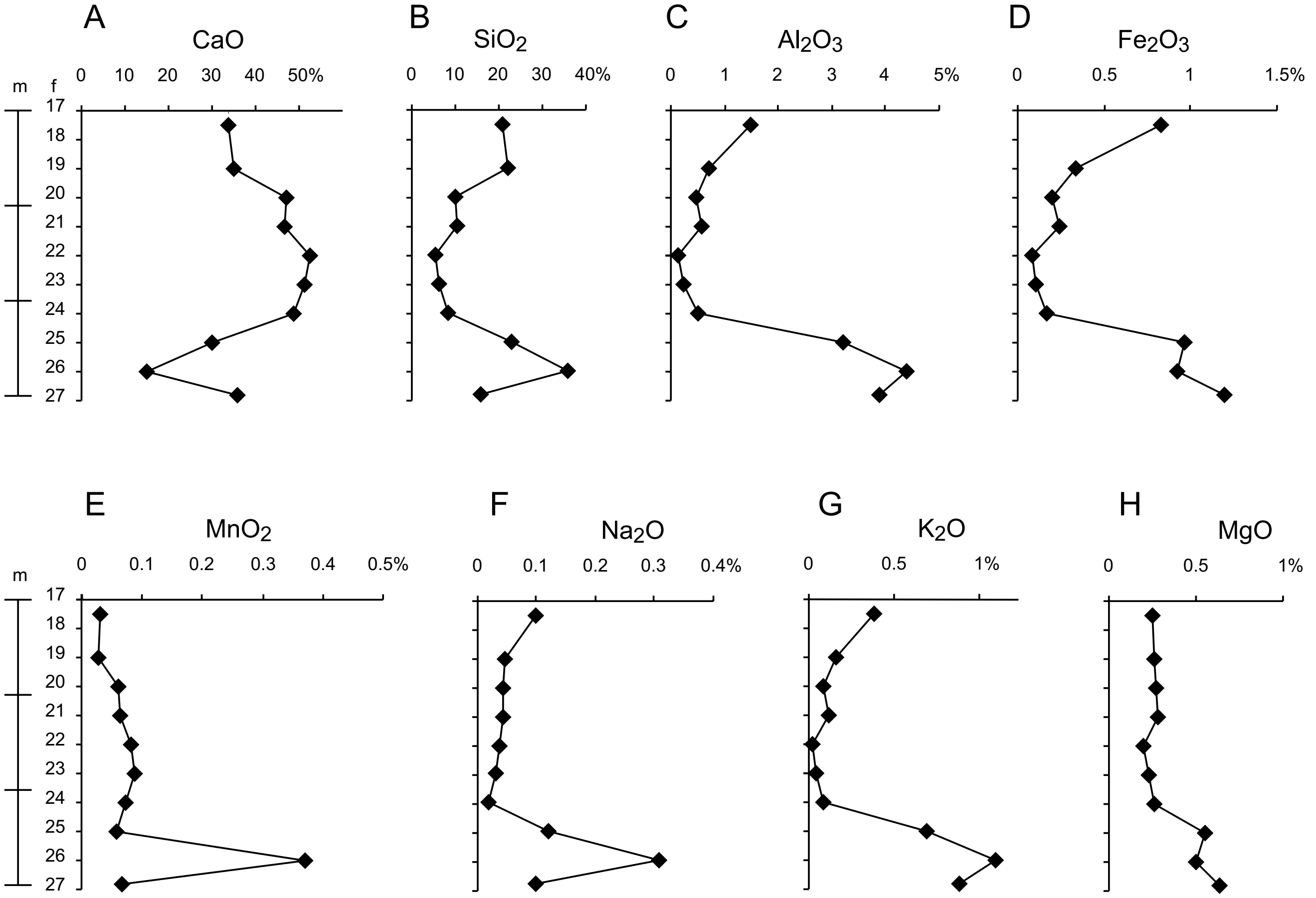


Figure 8. A–H, XRF analyses of calcareous diatomite samples from core 49-A-02 (see fig. 5). Note increase in CaO content toward middle of unit and general increase in other constituents near base of unit, wherein clastic sediment content is more common. See table 1 for data.

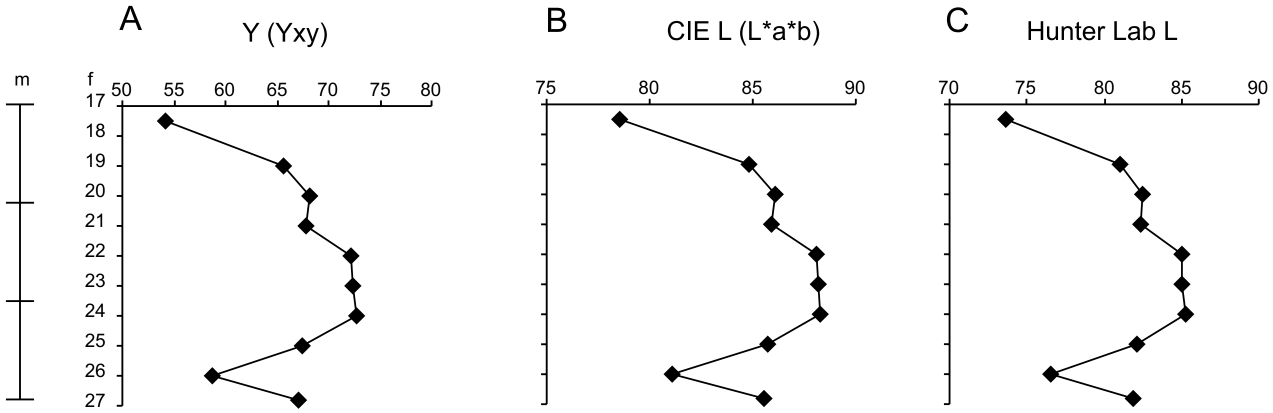


Figure 9. Lightness measurements of samples of calcareous diatomite from core 49-A-02 (fig. 5, units 2a, 2b). Lightness (~whiteness) is highest in the middle of the unit. See table 2 for other color parameter values.

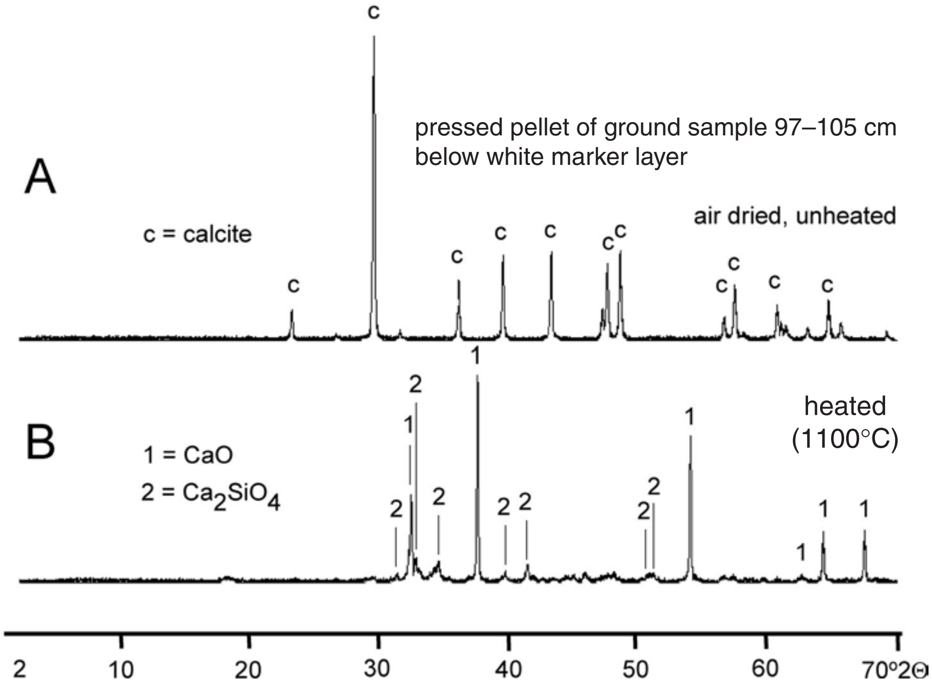


Figure 10. A, XRD of unheated control pellet pressed from calcareous diatomite, showing calcite (c) peaks. B, Pellet made from material split from same sample that yielded A; note production of CaO and dicalcium silicate following dehydration of amorphous silica and decarbonation of calcium carbonate.

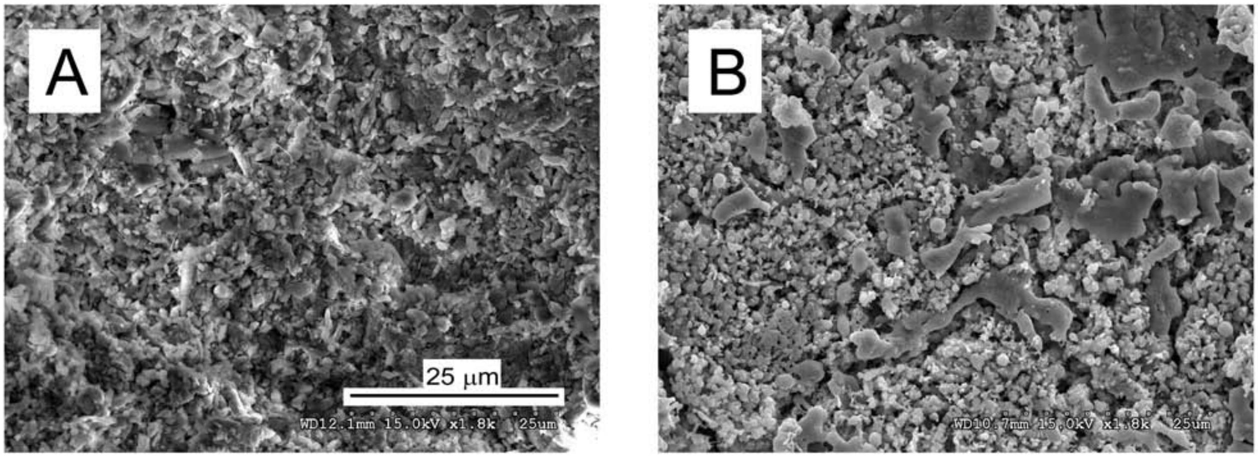


Figure 11. SEM photographs of pressed pellets (see fig. 9). A, surface of unheated pressed pellet; diatom fragments are still visible. B, Surface of heated pressed pellet; coarser grains have coalesced as chemical transition to CaO and Ca_2SiO_4 has taken place; traces of diatom structure are still visible.

Table 1. **X-ray fluorescence (XRF) data for diatomite samples from UN-L CSD core 49-A-02. Samples taken meters below land surface, elemental oxide values in percent.**

Depth m	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
5.33	0.098	0.250	1.500	21.000	0.670	0.120	0.380	33.800	0.065	0.030	0.830
5.79	0.045	0.260	0.710	21.900	0.140	0.100	0.160	35.000	0.018	0.027	0.340
6.10	0.044	0.270	0.470	10.100	0.130	0.086	0.089	47.200	0.011	0.059	0.200
6.40	0.044	0.280	0.560	10.400	0.110	0.089	0.120	46.700	0.017	0.063	0.240
6.71	0.036	0.200	0.150	5.500	0.039	0.072	0.022	52.500	0.000	0.082	0.086
7.01	0.032	0.230	0.230	6.400	0.420	0.071	0.045	51.400	0.000	0.087	0.110
7.32	0.017	0.260	0.510	8.500	0.051	0.076	0.086	48.900	0.015	0.073	0.170
7.62	0.120	0.550	3.200	22.900	0.320	0.069	0.690	29.800	0.100	0.057	0.960
7.92	0.310	0.500	4.400	35.900	0.100	0.083	1.100	15.200	0.120	0.370	0.920
8.17	0.100	0.640	3.900	15.900	0.049	0.085	0.880	35.700	0.110	0.067	1.200

Table 2. **Color parameters for LCD samples from core 49-A-02; five common color systems are used (e.g., CIE, 1986).**

CIE XYZ					CIE Yxy					CIE L*a*b					CIE L*C*H°					Hunter Lab L*a*b				
depth (m)	(ft)	X	Y	Z	depth (m)	(ft)	Y	x	y	depth (m)	(ft)	L	a	b	depth (m)	(ft)	L	C	H°	depth (m)	(ft)	Hunter Lab L	a	b
5.33	17.5	53.5	54.19	51.89	5.33	17.5	54.2	0.335	0.34	5.33	17.5	78.6	0.973	11.06	5.33	17.5	78.6	11.1	85	5.33	17.5	73.6	0.93	9.8
5.79	19	64.4	65.61	66.03	5.79	19	65.6	0.328	0.335	5.79	19	84.8	0.053	9.09	5.79	19	84.8	9.09	89.7	5.79	19	81	0.08	8.41
6.10	20	66.8	68.1	69.21	6.10	20	68.1	0.327	0.334	6.10	20	86.1	-0	8.66	6.10	20	84.9	8.66	90	6.10	20	82.5	-0.01	8.12
6.40	21	66.5	67.89	68.76	6.40	21	67.9	0.327	0.334	6.40	21	85.9	-0.2	8.83	6.40	21	85.9	8.836	91.2	6.40	21	82.4	-0.2	8.27
6.71	22	70.7	72.27	74.23	6.71	22	72.3	0.326	0.333	6.71	22	88.1	-0.33	8.21	6.71	22	88.1	8.21	92.3	6.71	22	85	-0.33	7.81
7.01	23	70.8	72.39	75.31	7.01	23	72.4	0.324	0.331	7.01	23	88.2	-0.46	7.5	7.01	23	88.2	7.51	93.5	7.01	23	85.1	-0.46	7.16
7.32	24	71.1	72.69	75.59	7.32	24	72.7	0.324	0.331	7.32	24	88.3	-0.49	7.53	7.32	24	88.3	7.54	93.7	7.32	24	85.3	-0.48	7.19
7.62	25	65.8	67.41	69.31	7.62	25	67.4	0.325	0.333	7.62	25	85.7	-0.8	7.97	7.62	25	85.7	8.01	95.7	7.62	25	8210	-0.79	7.5
7.92	26	57.4	58.69	59.73	7.92	26	58.7	0.326	0.334	7.92	26	81.1	-0.42	8.15	7.92	26	81.1	8.16	92.9	7.92	26	76.6	-0.4	7.46
8.17	26.8	65.4	67.11	68.5	8.17	26.8	67.1	0.325	0.334	8.17	26.8	85.6	-0.94	8.37	8.17	26.8	85.6	8.42	96.3	8.17	26.8	81.9	-0.92	7.85

History of Mining And Use

Early History

Surface mining of calcareous diatomite at the Happy Jack Mine site began at least as early as 1877 (Pabian and Swinehart, 1977). The primary early use for mined material was in small-scale construction. By 1887, Ed Wright, a Scotia merchant, had constructed a locally celebrated store building out of blocks of stone quarried from the north end of the mine site (fig. 12A), and a Scotia business was simultaneously advertising building stone, possible of local origin (McDermott, 1939). Early users of the resource were cognizant that the LCD is soft when first dug but does harden slightly with exposure to the atmosphere. In its fresh condition, the LCD is easily workable by the kinds of equipment that would have been readily available in late-19th century Nebraska.

The Wright store building in Scotia is still standing (2003), and another, no longer extant building was built out of stone blocks immediately next door, probably also in the 1880s or shortly thereafter. At least one other building in the Scotia area was constructed from the stone, and numerous period houses had foundations made of the same material (Charles Beebe, Scotia resident, personal commun.). Blocks in the existing Wright building range from about 3 x 14 x 14 cm to 13 x 21 x 57 cm, but in general, they are tabular and 12 to 16 cm thick (fig. 12A, B). Some places on the exterior of the building are heavily weathered: blocks have eroded to as deep as 7 cm below their original finished surfaces. Some blocks, especially on the front of the building, are relatively unweathered, although successive laminae weather may differentially within a single block (fig. 12B). Non-uniform weathering within individual blocks is probably the result of weathering along light-dark laminae couplets. All of the stone used in the building is soft (it scratches with a fingernail) compared to conventional building stones. Several blocks on the exterior of the rear wall of the building, long ago spared from extreme weathering by the protection of an add-on shed, show concentric grooves about 4 mm apart, revealing that the stone was sawed with a circular blade, rather than being pried and dressed by chiseling.

Underground mining at the site of the Happy Jack Mine probably began in the early 1890s, and a fatality occurred in 1907, and shortly after this incident an effort to produce bricks at the site failed (Morris, 1963).

Upper Ogallala Group sediments stratigraphically equivalent to the deposits at the Happy Jack Mine were surface-mined in the early 1870s along the east wall of the North Loup Valley near Cotesfield, Nebraska, approximately 12 km SSE from the Happy Jack Mine. J.B. “Doc” Beebe operated as many as three lime-producing kilns for raw material in the construction of Ft. Hartsuff, a U.S. Army infantry post near Elyria, Nebraska (35 km NW of Happy Jack Mine) that was active from 1874 to 1881. Most buildings at Fort Hartsuff were made from low-grade concrete, the formulation of which relied heavily on local materials. George Towar, an Army surgeon at the fort, described the formulation for the concrete as a 24:4:0.5 ratio of locally derived gravel, “common lime,” and cement produced by kilns in the vicinity of Louisville, Nebraska (~250 km ESE of the fort), where cement has been produced from local Pennsylvanian limestones for nearly 150 years. Towar’s “common lime” refers to the material produced near Cotesfield by J.B. Beebe (R. Lindsay, Nebraska Game and Parks Commission, personal commun.). Cement from Louisville, Nebraska would probably have been relatively expensive to ship by wagons from a railhead at Grand Island, necessitating the use of a greater volume of locally produced lime for economy’s sake. The former J.B. Beebe property near Cotesfield includes outcrops of calcareous diatomite within 100 m of the old lime kilns, and fragments of material found in the immediate vicinity of the abandoned kilns include carbonate-cemented sandstone, calcrete, impure lacustrine limestone, and dense,

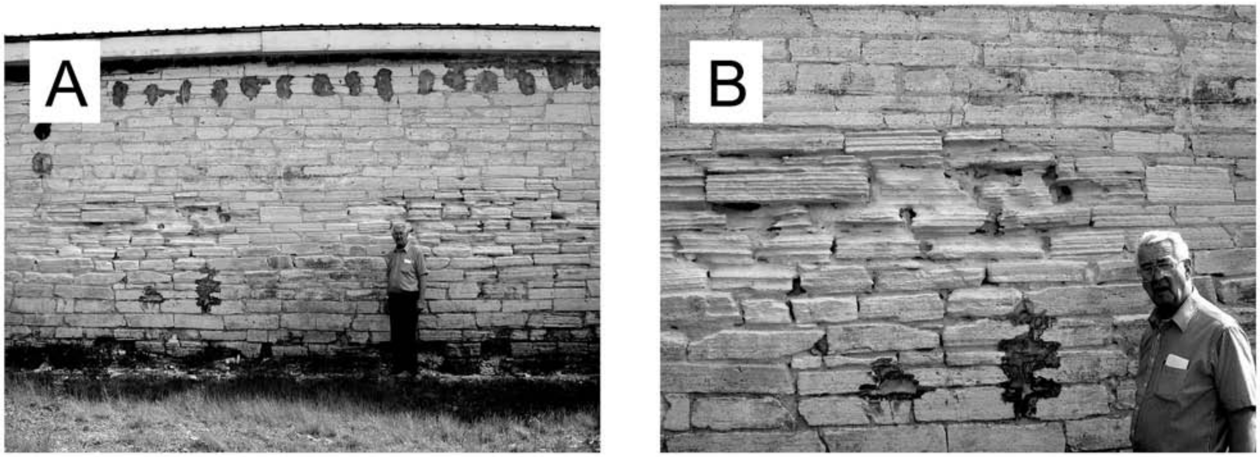


Figure 12. Charles Beebe at Wright store building, Scotia, Nebraska. A, North side of building; sawed diatomite blocks are generally tabular and of roughly uniform size, but much larger and smaller blocks appear in places. Individual blocks have weathered to different degrees. B, Weathering hollows, as much as 7 cm deep, on external surface of blocks. In an individual block, calcareous diatomite laminae also weather differentially.

calcite-rich, silicate-glass-bearing material interpreted as potential discarded kiln product (incompletely burned clinker?). The rock types are typical Ash Hollow Formation facies, and could have been used in lime production, given that they all contain calcium carbonate. The close proximity of easily mined, relatively uniform, high-$CaCO_3$ LCD exposures to the old kilns suggests that LCD might have been the most important kiln feed.

Developments in the 20th Century

Underground mining probably did not resume again until 1930, and then to supply raw material for the Nelson-Evans Paint Company of Omaha, which was formed in 1907. Nelson-Evans later became the G.H. Nelson Paint Company, which had a "splendid" plant in Ralston, Nebraska (then at the far outskirts of the Omaha metropolitan area), which was valued at $225,000 in 1921 (Anonymous, 1921). Another paint company, the Devoe-Reynolds Company, may have been negotiating to buy the Ralston plant at one point (Anonymous, 1921).

A February 1942 Greeley County, Nebraska deed granted the Happy Jack Mine property to United Mineral Products Company of Omaha, presumably in conjunction with the closure of the G.H. Nelson Paint Company. However, G.H. Nelson owned a major interest in United Mineral Products, a company that he and a business associate started in the 1930s (Anonymous, 1943). In this latest stage of mining, material continued to be used in paints and whitewash, but various anecdotal accounts claim that it was also used as poultry feed supplement and/or bedding, in polishes and/or cleaners, and possibly even as a material used to simulate blasts in "dummy" training bombs during World War II. In at least one instance, an unsuccessful attempt was made at using the LCD as crushed rock for a residential driveway. The mine was abandoned in about 1945.

Mining Procedures in the 1940s

Mining procedures at the Happy Jack Mine were unique because of the improvisation forced upon the operation by stringent economic conditions and the absence of local technical skills in mining engineering. Charles Beebe, a relative of J.B. "Doc" Beebe, provided the following description of mining operations during the early 1940s. Mr. Beebe's father worked at the mine when its original "manager," Charles "Chink" Rother, a locally celebrated amateur wrestler, left the area for service in the armed forces. Neither man is known to have had any previous training in mine design and operation.

Two men, usually working at least nine hours per day six days a week, carried out the mining, hauling, and loading (fig. 13). No training in mining methods or mine safety was provided, and no specialized mining equipment was used, except for the miner's caps and carbide lamps figured in a 1943 Omaha World-Herald article (Bailey, 1943). Instead, mining equipment was manufactured locally or improvised. According to Beebe, the light for mining operations was provided by coal-oil lanterns.

The chief mining tool was an improvised cutting bar: a flat, steel blade, 21 cm wide and 10 cm long, attached to a heavy steel rod (probably a Ford Model T driveshaft), 1.3 m in length (fig. 13: 1). Two examples of this tool were produced by a local blacksmith. The weight of the surviving example, now on display in the mine, is sufficient to fracture medium-sized blocks of diatomite merely when it is dropped from a height of about 30 cm. These bars were used to undercut a working face of diatomite by 30-45 cm prior to blasting (fig. 13: 1). Later, the same tools were used to break up any large blocks of diatomite remaining after a blast (fig. 13: 4). After undercutting, charge holes were drilled with a carpenter's brace, to which an extra-long (85 cm) bit with four turns had been welded (fig. 13: 2). Charges were prepared by wrapping newspaper and retail-catalog pages around a broom handle to make a tube, filling that tube with black powder, twisting both ends, and adding a slow-burning fuse. The charges were slid into the holes, which were then backfilled with loose diatomite fragments and tamped with the broom handle, supposedly to help direct the relatively weak blast energy forward into the working face (fig. 13: 3). About 3.8 to 5 cm of fuse were left exposed beyond the backfilled hole. Three sets of charges were used for each blast. Mining proceeded up to the white marker layer, which is consistent throughout the mine (figs 4, 7A).

Blasted rock was loaded into a modified Ford Model A using a cob fork: a tool certainly common to any Nebraska farm at that time and today (fig. 13: 5a). The roof, doors, and sides of the Model A were removed and the vehicle was turned into a makeshift dump truck by attaching a hinged box to the rear of the chassis. The force produced by abruptly backing the vehicle into a stockpile released a modified automobile-suspension leaf spring hooked to the box, and the box rotated upward to dump its load. Apparently, this procedure was made possible, or more likely unavoidable, by the Model A's nearly complete lack of braking ability. Under strict wartime gasoline rationing, the extra coupons made available for a utility vehicle like the Model A were an important operational consideration.

After it was loaded, the modified Model A was driven about 1.6 km south of the mine site to a railroad siding where cattle were loaded. In the mine's later years of operation, a large, wooden, corn-crib-like building was used as a drying and stockpiling shed as an intermediate step between mining and shipping (fig. 13: 6).

If mining the diatomite was strenuous, then loading it was even more taxing. One boxcar at a time was loaded on demand at the railroad siding for shipment to Omaha. Because loading was done by hand, it required a period of days to complete (fig 13: 7). Two rubber-tired wheelbarrows were used to move the diatomite from a stockpile into the boxcar. The wheelbarrows were wheeled to opposite ends and their loads were dumped, both operators gradually working backward toward each other at the center of the boxcar. After the first course of diatomite was laid down in this manner, "car doors" (large, wooden doors from railroad grain cars) were laid down atop the diatomite to provide a hard surface over which to move the next course of diatomite. The doors were picked up one by one to allow diatomite in the second course to be laid over the first. This procedure was laboriously repeated until the boxcar was full. Each boxcar was hauled to Grand Island, Nebraska (~80 km SSE) and then switched onto a line leading to Omaha (~200 km ENE from Grand Island). On at least one occasion, an overloaded boxcar required the miners to drive (in their modified Model A) to Grand Island in order to remove some of the excess load.

In the event that the drying crib was full and no boxcars were available for loading, mining proceeded and temporary stockpiles of blasted rock were accumulated within the passageways of the mine.

Mine Design and Failure Modes

To our knowledge, no accurate map of the Happy Jack Mine existed prior to this study, and neither had a formal assessment of design and potential failure hazards. The Happy Jack Mine has a highly irregular room-and-pillar layout, reflecting the lack of formal training in mining methods among those who carried out the excavation (fig. 2). According to Charles Beebe, in at least the later stages of mining, the driving of workings was relatively haphazard. The floor, at least, is virtually flat because of the horizontality of the mined strata. Originally, there was no artificial support or stabilization of the immediate roof, but since the mid-1990s, short runs of cedar timbering and a few cedar posts with bearing blocks have been installed selectively to help stabilize the entries and secure potentially unstable roof slabs.

Pillars vary greatly in shape (nearly square to rectangular to irregularly polygonal), horizontal cross section (8.6 to 63.2 m^2), and distribution. Passages range from about 2.5 to 4.0 m wide (fig. 14A) and the original working height from the floor to the back of the mine was about 1.8 m. There is one long (125 m), relatively straight passage extending throughout the mine, and along its northernmost penetration, stall-like workings proceed laterally from this passage (fig. 2). On the basis of the map (fig. 2) produced during this study, the total area mined is calculated to be approximately 3,300 m^2 at 77% extraction. Considering the

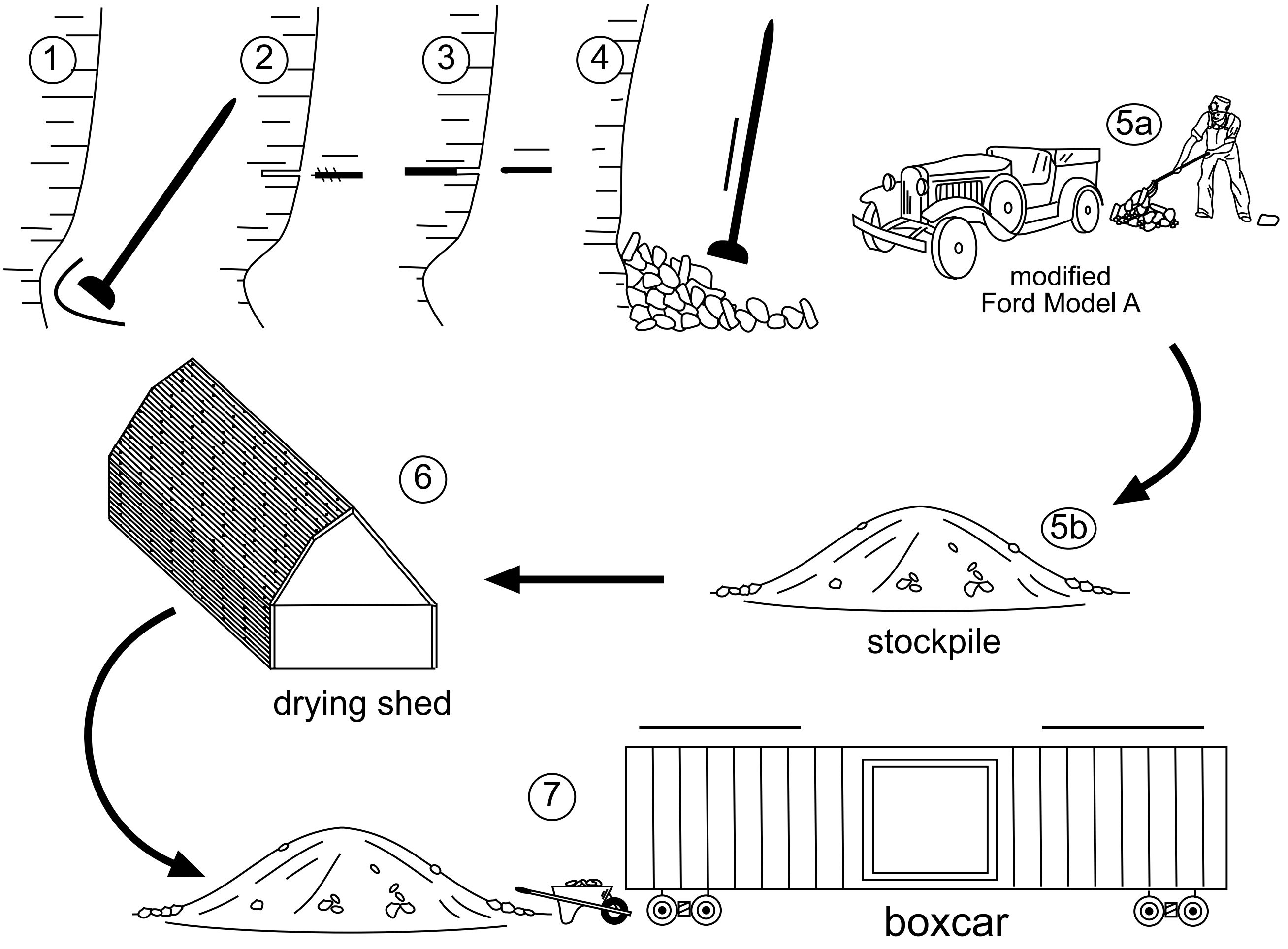
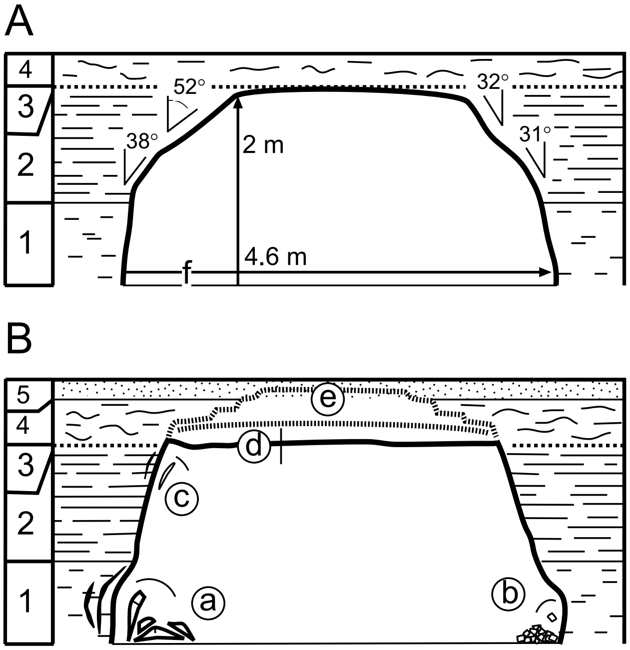


Figure 13. Mining and loading procedures at Happy Jack Mine, circa 1943. Undercutting and blasting were carried out with locally made tools and black powder purchased from local hardware store (1-4). Mined material was loaded and stockpiled (5a, 5b) using a modified Ford Model A as dump truck; stockpiles were used in mine and at loading site. Eventually, material was dried in shed (6) before being loaded by hand into single boxcars (7) for shipment to Omaha.



1 = lighter thinly lam. calc. diatomite
2 = darker thinly lam. calc. diatomite
3 = white and green marker layers
4 = “marly” zone (diatomaceous limestone)
5 = fine sandstone

Figure 14. A, Typical passage in Happy Jack Mine, after reopening as tourist attraction; calcareous diatomite (1, 2) was target horizon for mining, which extended upward to white marker layer (3; see figs. 3A, 4, 7A) below diatomaceous limestone (4). B, Modes of failure observed within Happy Jack Mine: spalling of slabs and chips from pillar bases (a, b) and tops (c), and progressive failure of roof slabs (d, e) upward into overlying soft, fine sandstone.

mine area, the thickness of mined deposits, and the dry density of LCD material, we estimate that a minimum of 6,900 metric tons (dry weight) of LCD were removed from the mine during its entire lifetime.

Failure modes within the mine are a result of the “design” of the Happy Jack Mine and rock mechanics. Identifying and assessing modes of failure will be necessary in assessing the long-term tourism potential of the mine. Almost all pillars narrow floorward, possibly in part because of undercutting during the mining procedure itself (fig. 13: 1–4), but mostly because of the progressive loading of soft diatomite by overburden and the gradual failure by tension at the outside of pillars (fig. 14B). Many pillars deep in the mine are two-thirds to one-half as wide at their bases as at their tops, and some of these pillars have a particularly alarming appearance (fig. 15A). In these parts of the mine, which are strictly closed to the general public, all pillars have quantities of spalled diatomite chips a few centimeters wide, thin sheets, or slabs as much as 40 cm long accumulated at their bases, sometimes in debris aprons at least 70 cm deep (fig. 14A: a, b). Arcuate fractures can be found within in-place failing rock in the lower 100 cm of most pillars (fig. 14A: a). Similar spalling occurs near the tops of pillars at the roof line (fig. 14A: c). High year-round humidity within the mine accelerates the rock decomposition in the pillars and the roof.

Photographs taken inside the mine during the post-mining period indicate that roof falls had been common (figs. 14B: d, e; 15B) after abandonment. The raising of the mine floor level by the slow accumulated roof-fall debris is, according to Charles Beebe, the single greatest change in the mine since 1945. Complete failures of the roof have occurred at the perimeter of the mine, under the superjacent hillslope, where horizontal stresses (“lateral restraint”) are low (cf. Parker, 1987, p. 67). Large debris cones exist in these collapsed areas. Several places in the mine show gradual separation of flat, 20–40 cm-thick slabs of fine sandstone from the roof (figs. 14B, 15B). This arch-like

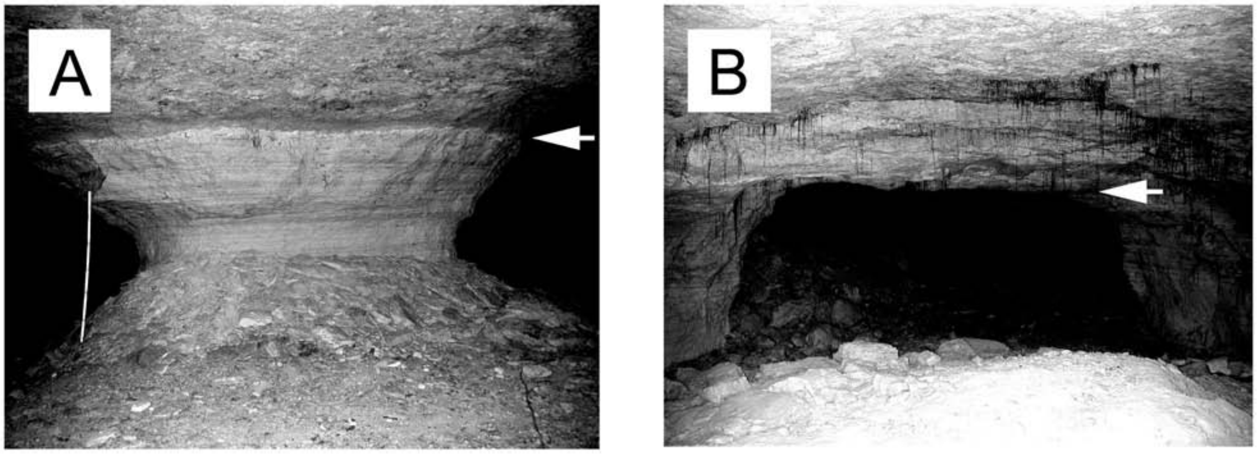


Figure 15. A, Wasting of pillar in closed part of Happy Jack Mine; note debris apron at base of pillar and white marker layer (arrow); 100 cm scale at left. B, Progressive roof failure (sandstone slabs above white marker layer at arrow) in “Ballroom” (fig. 2: b; fig. 14B: d, e); roof height varies between 1.8 m and 2.5 m in this area; debris cone in background resulted from complete roof failure.

mode of failure under tension (Scotese and others, 1981) is accelerated by the existence of moderately developed horizontal stratification in the sandstone (fig 4B: sandstone 1). Where the diatomaceous limestone or "marly" zone (fig. 4A) is exposed by roof failure, its pervasive, irregular, wavy to lenticular bedding at centimeter-scale intervals makes the roof rock weak enough that pieces of it can be successively pried loose by hand alone.

Roof falls of any size have never been witnessed by the authors, and, certainly, no evidence for large-scale roof falls anywhere in the mine was encountered during the 18+ months of intermittent study and mapping in 2002–2003, even though a Richter Mn 3–4 earthquake occurred in the study area during the same period! Most important, though, the tour area within the mine is supported by relatively intact pillars, has a relatively stable roof, and does not appear to present any exceptional danger to visitors in the immediate future.

Conclusions

LCD in the Scotia-Cotesfield area of Nebraska occurs as a thin, localized deposit very high in $CaCO_3$/CaO, and therefore atypical if compared to many diatomites that are mined today in the United States. In the Scotia-Cotesfield segment of the North Loup Valley, LCD represents a single ancient lake or a closely associated group of lakes. The deposit contains a diversity of diatoms, rather than being dominated by a single type that is particularly amenable to industrial use, such as the centric diatom Aulacosiera, which dominates some of the large diatomite deposits that are currently mined in Nevada. Most importantly, economically viable deposits today tend to be in the millions of tons, rather than the thousands of tons that were removed from the Happy Jack Mine over a period of decades. Thus, even if unfavorable chemical and bulk physical constraints were set aside, highly unfavorable competition with other diatomite sources (particularly Nevada) would alone render the mining of Nebraska diatomites eminently unprofitable. Nonetheless, it is just barely conceivable that if larger deposits of LCD were found, mined materials might eventually find local to regional markets as cement additives or as sources of other industrial materials, perhaps even calcium silicate (cf. Ibanéz and others, 1990, Ibanéz and Sandoval, 1998, Fragoulis and others, 2002).

The Scotia-Cotesfield LCD deposits are an exemplary case study of evolution in the use of local mineral materials, as dictated by changing needs, economies, and infrastructure. Large amounts of $CaCO_3$ in the Scotia-Cotesfield LCD, and the economics of transportation at the time, made it a viable source of lime and quicklime during the 1870s. Its early use as building stone is also understandable given that more durable natural materials were unavailable within 150–250 km (fig. 1), and that industrial brick production in the region probably began after 1885. Furthermore, local railroad lines, which would have made the large-scale importation of lime and stone products possible, were not fully established until the 1880s at the earliest (McDermott, 1939). By the 1930s, it is likely that the very low cost of labor in rural agricultural Nebraska during lean economic times, minimal regulatory restrictions, and the ready availability of the material itself made it a suitable ingredient in paint manufacturing and also a convenient local source for other applications. Although direct causal evidence is lacking, we speculate that rising labor costs and expectations, increasingly wider supply networks, growing regulatory concerns, the limited volume of local reserves, and increasing competition with materials from other sources forced, or in the least influenced, the demise of local LCD mining at the end of World War II.

The lacustrine interpretation of the deposits (e.g., Swinehart and Pabian, 1977) is irrefutable considering that the enclosing Ogallala Group sediments are exclusively continental, but the origin of the depositing lake or lake system remains unknown. Furthermore, completely equivalent modern analogs remain to be identified. It appears that carbonate within the Scotia-Cotesfield LCD is primarily of depositional, rather than diagenetic, origin. Therefore, the ancient lake or lakes in the study area was/were depositing calcareous and siliceous sediments simultaneously. Couplets of light-dark diatomite laminae at Happy Jack Mine may reflect seasonal changes in productivity and the rate and mode of deposition. Abundant rhizoliths and thin calcretes in sands both above and below the LCD indicate that deposition was incremental and that weak soil development occurred several times before and after the lake existed. These interpretations are consistent with overbank deposition. With additional study in the future, the Scotia-Cotesfield LCD has the potential to provide additional important information relevant to interpretations of sequence stratigraphy, paleoecology, and paleoclimate at the eastern margin of the Great Plains during the late Neogene.

The evolution of the Happy Jack Mine site from two major industrial uses to a tourist attraction is unique in comparison to other mining sites in Nebraska and adjacent areas. In a sense, the mine has a "non-design" because there is no evidence for a deliberate, preconceived engineering plan, and yet parts of it remain safe enough to permit touring. Thus, despite the developments of over 130 years of history, income and interest continue to arise from diatomites in east-central Nebraska.

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Specimen Recovery at the Meikle and Murray Mines, Elko County, Nevada

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Introduction

Non-ore crystallized mineral specimens encountered while mining are usually treated as gangue or waste unless the operating company consciously designates value. Geoprime Minerals works with mineral extraction companies to recover significant non-ore assets in ways that do not impede production or safety. Sites include metal and industrial mineral mines. Much of this recovery is for educational and research materials that are disseminated to the teaching community. Examples include calcium carbonate in the form of calcite, limestone, or marble; gypsum; massive barite; kaolinite; diatomite; and bornite. Other specimens are recovered for dissemination to museums and the private collecting community. In this paper we address the recovery of significant crystallized mineral specimens at gold mines in northern Nevada. Barrick Goldstrike Mines and AngloGold Jerritt Canyon Joint Venture have encountered voids with crystallized barite and calcite (Meikle Mine), and stibnite and barite (Murray Mine) while mining underground for gold. Although not considered an asset in the same way as gold, the specimens have been designated as having value as items of natural history. The golden barite from Meikle and the stibnite from Murray are both among the world's best of their species.

The Properties

Significant amounts of crystallized mineral specimens are found at both the Meikle Mine and the Murray Mine, which are located in different parts of Elko County in northeastern Nevada. The Murray Mine is in the Independence Mountains mining district, while the Meikle Mine, on the border near Eureka County, is in the Lynn mining district. Golden barite crystals and calcite have been recovered at the Meikle Mine. Stibnite, barite, barite with quartz, and quartz casts after stibnite have been recovered at the Murray Mine. Goldstrike's Meikle and Jerritt Canyon's Murray deposits are geologically similar. Both are Carlin-type gold deposits that are structurally controlled with gold ore concentrated in favorable sedimentary host rock. Meikle is a deep mine accessed by shafts, and mined in sublevels using a combination of long-hole and drift and fill mining methods, whereas the Murray is an adit-accessed mine, developed through a series of tunnels and crosscuts using the drift and fill method. The underground working temperatures at the Meikle Mine are commonly high, up to 130°F with visible steam escaping from newly opened cavities. Murray Mine underground working temperatures have so far averaged a more comfortable 65°F year round.

The Meikle Mine

History and Geology

Barrick Goldstrike Mines is owned and operated by Barrick Gold Corporation. The Goldstrike property exploits four orebodies: the Betze-Post, Meikle, Griffin, and Rodeo deposits, and a fifth, the Storm deposit, is in development. All are located in the northern part of the Carlin trend about 25 miles north of Carlin, Nevada. The Meikle deposit, discovered in 1989 and formerly known as the Purple Vein, is located about 1.5 miles north-northwest of the Betze-Post open pit. The regional geology is characterized by the siliciclastic (clastic noncarbonate rocks) assemblage of the Ordovician Vinini Formation and the carbonate assemblage of the Devonian Popovich Formation and Silurian-Devonian Roberts Mountains Formation. The Post fault zone is one of a series of faults that cut the mine area. Jurassic monzonite and lamprophyre dikes and sills intruded along this fault zone and locally controlled mineralization (Volk and others, 1993). Complex hydrothermal, tectonic, and collapse breccias in the Roberts Mountains Formation and the Popovich Formation host submicron gold (mostly in microscopic pyrite) at Meikle (Volk and others, 1995). The monzonite porphyry in the hanging wall is low in gold, whereas the high-grade ore occurs in the dolomite breccia near the limestone footwall. Gangue minerals include barite, quartz, calcite, stibnite, and sphalerite, among others. The location of the gold appears to have little bearing on the presence or absence of crystallized specimens, although voids and caverns that bear the richest crystal pockets are typically in the footwall of the orebody. The upper zone of the main orebody, between a depth of 875 feet and 1,225 feet deep, has so far contained the best occurrences of barite. The lower, steeply dipping zone of the orebody, which extends to more than 1,900 feet below the surface, has so far produced only calcite specimens.

Barite

Barite specimens were collected at the Meikle Mine as early as 1995. In early July 1997, having just completed a recovery project of rare chalcocite crystals for Kennecott Minerals in Wisconsin, we responded to an invitation to tour the Meikle Mine to consider specimen recovery.

The first area we visited was the 975 level at stope 3525. A large pocket had been exposed in the lower corner of the stope. This pocket was completely lined with gemmy, transparent, yellow to yellow-gold-colored, square, tablet-shaped crystals up to 6 cm on friable limonite matrix, which made collecting difficult. The pocket continued downward at a steep angle, with crystals as far as the light would penetrate. We collected at the edges of the pocket, but it was impossible to enter due to the tight space, high temperature, and sulfur dioxide gas. This pocket was one of the most beautiful underground scenes we had personally witnessed. It was also our first experience with the intense heat. As we put our hands on the pocket wall, the limonite was still hot, and a short distance away steam was escaping from another open void.

Our next stop on our first brief collecting tour was on the 1075 level, away from the orebody near the batch plant where they mix concrete with the waste rock to backfill mined-out stopes. While constructing this batch plant during mine development, a large cavern was opened that Barrick has maintained intact. It is commonly referred to as “the Bush Cavern” after a visit by the first President George Bush. This cavern is lined with calcite and, in select areas, beautiful orange barite crystals to 20 cm in predominantly flat, spear-shaped crystals. On subsequent trips we used a diamond chain saw to recover some of these specimens.

The tablet-shaped gemmy crystals (fig. 1) and the spear-shaped crystals, the two main barite habits found at the Meikle Mine, occur primarily between the 975 and 1075 levels. Other barite occurred in small caverns on the 1125 and 1225 levels. In a small (about 16 feet deep by 18 feet wide and 5 feet high) cavern encountered on the 1125 level, barite crystals lined the back and ribs but were curiously absent on the floor. Clear sections of broken crystals from these areas have yielded large clean faceted stones.

Calcite

Until January 1999, the calcite encountered at the Meikle Mine was mainly potato-chip-shaped crystals and cloudy or smoky dogtooth crystals. One large spectacular cave just off of the Griffin drift (fig. 2) produced large pieces of lime-green, blocky and bladed calcite, some with black tips, but no smaller pieces. The Griffin drift connects the Meikle deposit and the Rodeo deposit, a new adjacent mine still in developmental stages. As mining continued, large calcite voids were encountered at lower depth, many directly in the path of ramp development, making recovery difficult. Gemmy calcite twins were found on the 1450 and 1650 levels in January 1999 in what was literally a crystal cathedral. Unfortunately, safety necessitated that the void be filled with concrete even as we scurried to collect from it. This did not permit much camera time as we could collect only as long as it took for the concrete to dry. Large voids, some filled with calcite, continue to be encountered at the current mining depth of 1,900 feet.

Figure 1. Tablet-shaped gemmy golden barite crystals, Meikle Mine. Specimen is 8 cm wide. Photo by J. Scovil.

Figure 2. Cave at the Griffin drift, Meikle Mine.

Murray Mine

History

The Murray Mine sits on a site that was originally scouted for antimony ore. Thirty to forty tons of stibnite as antimony ore was shipped from the Burns Basin Mine in the Independence Mountain Range between 1918 and 1945. (Lawrence 1963; LaPointe and others 1991). In the early 1970s there was a short burst in antimony exploration when the commodity reached a high of $40 per pound and a number of parties were scouting northern Nevada, a known stibnite-producing area (personal commun., Ralph Pray, 1999). Around 1971, FMC began exploring for antimony in the Burns Basin Mine area. Some of the rock FMC encountered was similar to the gold-hosting rock found at Newmont’s Carlin Mine, and technology had made recovery of the Carlin-type anomalous gold viable. In the early to mid 1970s, FMC discovered a disseminated gold deposit in the Jerritt Canyon area and entered a joint partnership with Freeport Exploration Company, who became managers of the project. Mining began in 1981 on what was called the Enfield Bell Mine, or the Jerritt Canyon Mine (LaPointe and others 1991). The joint partnership remained essentially the same, although Freeport Exploration Company changed its name to Freeport McMoRan Gold Company and was purchased by Minorco, which changed the name to Independence Mining Company; and FMC’s gold division began using the name Meridian.

In early 1999, AngloGold acquired Independence Mining Company via acquisition of Minorco. At present, Queenstake Resources USA Inc. is finalizing steps to purchase the Jerritt Canyon properties. It is interesting that this property now producing gold was originally mined for antimony, and that the stibnite (antimony sulfide) specimens we have seen from here are perhaps the best to be found in North America (fig. 3).

Figure 1. Quartz on barite with stibnite, Murray Mine. Specimen is 10 cm high. Photo by J. Scovil.

Geology

The Murray Mine is located in the structurally complex Independence Mountains about an hour's drive north of Elko in the Independence Mountains district. The Murray Mine lies northwest of the original Burns Basin Mine (Kantor and others, 1998). Mineralization at the Murray and nearby SSX Mines in the Jerritt Canyon mining district is typical of Carlin-style sedimentary rock-hosted deposits. It is structurally controlled and hosted by intersections of faults and folds in favorable strata of the host rock. Ore in the Murray Mine occurs in the Snow Canyon Formation (Ordovician), which covers the deposit, the Roberts Mountains Formation (Devonian to Silurian), and the Hanson Creek Formation (Silurian to Ordovician), which underlies the deposit. Ore accumulated in, adjacent to, the New Deep fault system, which was one of the conduits for ore-forming fluids. It is also in and near the Saval discontinuity, another major conduit that separates the Roberts Mountains Formation from the Hanson Creek Formation.

Collecting history

Stibnite crystals have apparently been collected from Jerritt Canyon mines for many years, but few were saved from the crusher. The first mines were open pit mines, and a stibnite of a foot to a foot and a half in length was reportedly collected in the West Generator pit and used as a door stop (Joe Kantor, personal commun., 1999). In 1998 we ran across some impressive specimens that compared respectably to Chinese and Japanese stibnites, and which appeared to be superior to any stibnites from North America we had seen, including those from the Manhattan Mine in Nye County (Jones and Jones, 1999). Thus, while in the area to work at the Meikle Mine, we took advantage of an opportunity to visit Independence Mining Company's Murray Mine.

In January 1999, Greg Struble, mine operations manager, escorted us underground to an area known as Z5-100 (zone 5 drift 100), located in the Roberts Mountains Formation. The heading had just been blasted on the previous shift and was now being mucked by a 5-cubic-yard loader. Between loader scoops we would move in and inspect the broken ore while wetting down the muck pile with a hose. After about an hour of this, a pocket of clear, pseudocubic barite became visible on the right-hand rib of the drift. Our excitement grew as Struble informed us that this was a rare occurrence; voids of this size were hardly ever encountered. We were invited to stay into the night shift to allow for ground support so we could then access this void under safe ground conditions. Waiting for the next shift, we toured the mine, and saw where the extraordinary stibnites with barite and drusy quartz we had seen earlier occurred. It seems likely that the stibnite was deposited first in the void, then the barite, sometimes forming over the stibnite, and then the quartz. Quartz casts after stibnite have been observed locally.

We have been pursuing the elusive stibnite over a period of five years at the Murray Mine. The most significant recovery was not stibnite, but rather a cavern of quartz-coated barite, or "sugar-cube" barite (fig. 4), which was encountered in March-April of 2000. This cavity was dubbed "The Sugarbowl Pocket" by the StoneTrackers, a group of Sacramento, California, students who are our virtual team

Figure 4. Quartz-coated barite, Murray Mine.

members underground and follow progress online. Small pockets (ranging from fist-sized to football-sized) of stibnite have been found, with most containing small needle like crystals up to 2 inches in length, and many also containing stibiconite (antimony oxide hydroxide). On one collecting trip in early March 1999, after a blast, some broken stibnite crystals and groups and a couple of undamaged, extraordinary specimens were recovered from the muck pile, leading us to conclude that we were on the right track as far as fine stibnites go. Thus far, no large in-situ void of stibnite has been encountered, but we still hope to intersect the continuation of the good stibnite zone on a lower level. Typical of the best we have seen is a single, terminated crystal 11.5 inches long with high luster and tiny barite crystals, now in the Smithsonian Institution collection, and the group of stibnite crystals with barite featured in Rocks and Minerals magazine (Cook, 1999).

Conclusion

When we first visited the Meikle Mine in July 1997, we had just watched the last blast at the Flambeau Mine in Wisconsin that allowed recovery of chalcocite specimens found there. Collecting specimens at the small, open-pit Flambeau Mine was less complicated than at the Meikle and Murray Mines, two larger underground properties. However, the means of achieving the goal of targeted non-ore asset recovery is the same. Key ingredients for success include communication between corporate and local management; clear statement of purpose and policy by local management to personnel and crews; and great flexibility on the part of the outside collecting party, such as Geoprime Minerals, that has been permitted to enter. Our guiding principle is to respect the property rights of our host and never impede production, operations, or safety of our host company.

Mining companies open up the ground to extract minerals society wants to use. They do it professionally and efficiently. If significant mineral specimens of natural history value are encountered while mining, there are good reasons to make reasonable efforts to preserve them. AngloGold Jerritt Canyon Joint Venture and Barrick Goldstrike Mines demonstrate a reasonable and real desire to accommodate mineral preservation by contracting specimen collection and acting to accomplish this goal in northern Nevada. With this action, they and others like them epitomize what is best about the role business plays in society-doing those things too complex for individuals and too technical for government, and using the entrepreneurial spirit that makes free enterprise successful. Individuals within these businesses have chosen to act with the best of noblesse oblige, acting with generosity for a good beyond that which only benefits them or their company. Many specimens in the Smithsonian Institution and major natural history museum collections have been preserved because someone at these companies made it so.

Acknowledgments

We cannot thank all by name, but want to acknowledge all those both above ground and underground who have helped specimen recovery, including miners, team and crew leaders, geologists, electricians, engineers, staff, managers and company officers at Meikle, Storm, Betze-Post, Murray, SSX, MCE, Barrick Goldstrike, IMC, and AngloGold Jerritt Canyon Joint Venture. In particular, we thank John Carrington, Greg Struble, Brent Chamberlain, Steve Lang, Louis Dionne, Don Prahl, John Ellis, Ben Guenther, Greg Fauquier, Richard Quesnel, Chantal LaVoie, Steve Orr, Nigel Bain, Steve Kulinski, Vic Christensen, Don Weaver, Lucien Labbe, and Luther Cowen.

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Characteristics of the Near-surface Brine Resources in the Newfoundland Basin, Tooele and Box Elder Counties, Utah

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Introduction

The Great Salt Lake Desert of western Utah, also known as the West Desert, is underlain by a shallow aquifer system that contains brine from which potentially economic quantities of sodium, potassium, and magnesium salts can be produced. This brine is probably a remnant of freshwater Lake Bonneville, which occupied the basin from about 32,000 to 14,000 years ago. A similar origin is suggested for the Great Salt Lake. Comparisons of Great Salt Lake brine and West Desert brine indicate that they differ chemically.

In the 1980s, in response to flooding caused by the rising Great Salt Lake, the State of Utah installed pumps to move Great Salt Lake brine into a portion of the West Desert where some of the water could evaporate. The concentrated brines were expected to flow back into the Great Salt Lake. This project was called the West Desert Pumping Project (WDPP) and it operated from April 10, 1987 through June 30, 1989. During this period, the U.S. Geological Survey (USGS) estimated that brine containing 695 million tons of salt was pumped into the West Desert (Wold and Waddell, 1993). When pumping ceased, USGS estimated that 123 million tons of salt had been discharged from the evaporation pond back towards the Great Salt Lake. Of the salt not returned to the lake, the USGS estimated that 315 million tons remained in a pond in the West Desert, 10 million tons were contained in a salt crust on the floor of the pond, 71 million tons infiltrated the subsurface of the inundated area, and 88 million tons were withdrawn by a mineral extraction operation. The USGS was unable to account for about 88 million tons of the 695 million tons that they estimated had been removed from the Great Salt Lake.

Studies indicate that the Great Salt Lake brine pumped into the West Desert mixed with the West Desert subsurface brine creating brine that is chemically different from both original brines (Kohler, 2002). The purpose of this report is to characterize the West Desert brine in the area flooded by Great Salt Lake brine before, during, and after the pumping project. TEQUIL, a geochemical model developed by the University of California at San Diego, was used to characterize the various brines by comparing the minerals expected to precipitate as the brine evaporates and the concentration of key ions that remain in solution.

Geologic Setting

The Great Salt Lake Desert is a broad valley in the Great Basin portion of the Basin and Range physiographic province west of the Great Salt Lake. The Great Salt Lake Desert is a closed basin with all drainage towards the center of the basin. This broad basin consists of a number of smaller sub-basins that are separated by very low topographic divides. The principal sub-basins within the Great Salt Lake Desert are the Bonneville Salt Flats and Pilot Valley. This report focuses on the basin immediately west of the Newfoundland Mountains that was filled with Great Salt Lake brine during the duration of the state's pumping project. This basin has not been formally named, but it will be referred to in this report as the Newfoundland basin. Recent maps of this area refer to an area called the Newfoundland Evaporation Basin that is a man-made feature that was part of the West Desert Pumping Project and is bounded on the south and west by an artificial dike. In this report, the more restrictive Newfoundland basin refers to the topographic depression west of the Newfoundland Mountains (fig. 1). The West Pond refers to the brine pond that was in the Newfoundland basin as a result of the pumping project.

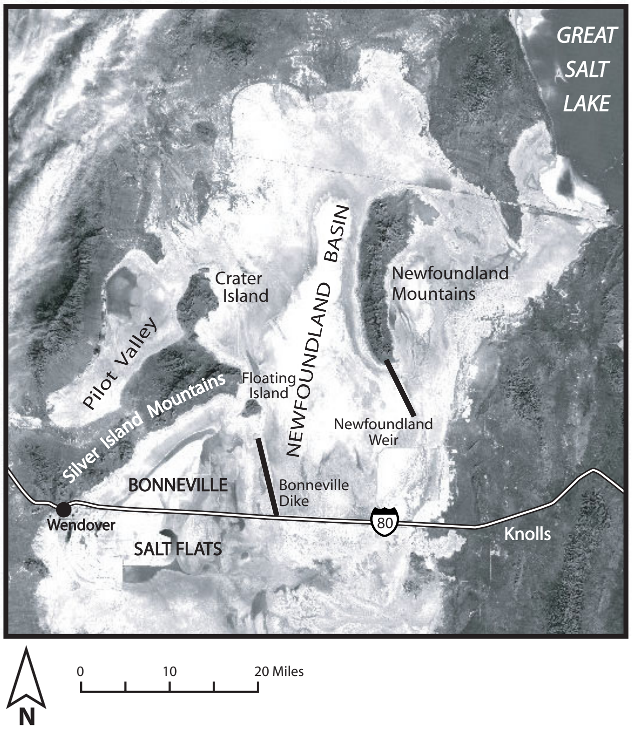


Figure 1. Great Salt Lake Desert showing sub-basins.

The sediments comprising the Great Salt Lake Desert mudflats consist primarily of carbonate muds, clay, gypsum, and salt. Minor occurrences of oolitic sand and thin carbonate layers of probable algal origin are also present in the surface sediments within the Great Salt Lake Desert. An ephemeral salt crust covers the playa surface in Pilot Valley, and the Bonneville Salt Flats has a permanent salt crust. Since cessation of the West Desert Pumping Project in 1989, a salt crust has also been deposited on the playa in the lower part of the Newfoundland basin. The area of the mud flats exhibits very low relief with elevations generally ranging from about 4,210 to 4,225 feet above sea level. Locally, small dunes of wind-blown gypsum sand provide a slight amount of relief to the otherwise flat surface. Extensive dunes of gypsum sand are present along the eastern edge of the playa.

The hydrologic system within the Great Salt Lake Desert generally consists of three types of aquifers: an alluvial fan aquifer adjacent to the mountain ranges around the perimeter of the playas, a shallow brine aquifer that occurs in the upper 20 feet of the playas, and a deep basin fill aquifer (Lines, 1979). Limited brine chemistry from the shallow brine aquifer suggest that it is the only part of the groundwater system that was affected by the West Desert Pumping Project.

Previous Work

The first assessment of the Great Salt Lake Desert brine resource was conducted by Thomas Nolan of the USGS in the 1920s (Nolan, 1927). Nolan completed 405 shallow test holes distributed over the entire Great Salt Lake Desert. Brine samples were collected and analyzed from these drill holes, but complete analyses were not included in Nolan's published report. However, the report does include a composite analysis of 126 samples taken during his field investigation. Nolan does not identify which of his 405 test holes were included in the composite sample. The results of Nolan's investigation were used by the USGS to classify much of the Great Salt Lake Desert as a known potassium resource area.

In the early 1960s, George J. Lindenburg, a graduate student at the University of Utah, conducted an investigation of the shallow brines in part of the Great Salt Lake Desert and compared them with brines of the Great Salt Lake (Lindenburg, 1974). As part of this investigation, brine samples were collected from the shallow brine aquifer at 65 different locations. Fourteen of these sites were within the area inundated by the pumping project, but none were within the Newfoundland basin. Lindenburg concluded that the shallow brines from the Great Salt Lake have a higher sulfate content than the shallow subsurface brines of the Great Salt Lake Desert. He attributed this difference to the addition of sulfate to the Great Salt Lake from the Jordan River and other tributaries that feed the lake. He concluded that higher sulfate values are not found in the shallow subsurface brines of the Great Salt Lake Desert because they represent a closed system that does not receive similar recharge.

In the mid-1960s, much of the area of the West Pond was explored for potassium by Reynolds Metals Company under a prospecting permit from the Federal government. During this exploration program, 92 shallow drill holes were completed within the area flooded by the pumping project, 72 of which were in the Newfoundland basin. Brine samples from these drill holes were analyzed for potassium, magnesium, chloride and sulfate, and the data are discussed below.

As part of the feasibility study for the West Desert Pumping Project, Dames and Moore (1983) completed a report that addressed the shallow brine aquifer within West Pond. As part of their field investigation, Dames and Moore drilled a number of wells along the alignment of the dike along the south and southwest boundary of the proposed West Pond. The Utah Geological Survey (UGS) analyzed water samples taken from these wells, and major ions were reported on a weight-percent basis. The sum of the weight-percent values for the individual ions was reported as percent total dissolved solids (TDS).

Data Compilation

The Reynolds data obtained from the Newfoundland basin are key to this study because they provide a good summary of the shallow brine composition before the area was inundated by Great Salt Lake brine. In order to model the Reynolds data, the missing sodium and calcium values had to be estimated. A strong linear relationship was found when the sodium content of other West Desert brine samples is plotted against the chloride content. By fitting a linear regression line to the plot of sodium against chloride, the following relationship is shown:

$$\text{Na (mmoles)} = (0.9349 \text{ x Cl (mmoles)}) - 42.19$$

Using this relationship, the missing sodium values were estimated. Calcium ions were estimated by determining the amount of Ca^{++} necessary to achieve charge balance for the solution. To convert the Dames and Moore data from weight-percent to grams per liter, it was necessary to calculate the density of the solution. This was accomplished by plotting density vs. TDS for West Desert samples with known values. The linear regression curve fit to these data provided the following relationship:

$$\text{Density} = 7.305\text{xTDS} - 1.009$$

These procedures are described in more detail in Kohler (2002).

The average pre-WDPP brine chemistry for the adjusted data from the various sources is listed in table 1. The Reynolds data are separated into two groups, Reynolds N from the Newfoundland basin, and Reynolds S from a small topographic depression southeast of the Newfoundland basin.

None of these studies developed quantitative information on the hydrologic characteristics of the shallow brine aquifer in the West Pond, but some qualitative

Table 1. Summary of pre-WDPP shallow brine samples from the West Pond (Newfoundland basin) area. Ion concentrations reported in moles per liter.

Data Source	Number of Samples	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	SO_4^{--}
Nolan	126	2.492	0.075	0.038	0.079	2.712	0.042
Lindenburg	13	1.875	0.072	0.045	0.060	2.057	0.071
Reynolds N	72	3.128	0.099	0.045	0.129	3.354	0.061
Reynolds S	20	2.537	0.148	0.048	0.107	2.728	0.060

observations were made. Nolan noted that the brine was found in thin horizontal zones in the sediments rather than being uniformly distributed throughout them. He also observed that in the areas away from the edge of the flat, the brine flow, if plentiful, was under a small hydrostatic pressure and would raise a few inches in the borehole (Nolan, 1927). Nolan also noted that brine flow was scanty in some areas but did not identify exactly where these areas were located. With regards to the characteristics of the shallow brine aquifer, Reynolds Metals Company (1966) offered the following: "A few holes filled very quickly, others very slowly. In many we could see liquid trickling down the walls from just below the collar, but we could not often distinguish successive lower points of influx that certainly contributed to the flow. In a few cases it seemed as if the liquid welled up from the bottom faster than it oozed in from the sides."

Great Salt Lake Brine Pumped into the West Pond

From April 10, 1987, to June 30, 1989, an estimated 2.7 million acre-feet of water was pumped into the West Pond (Wold and Waddell, 1993). The USGS periodically collected 13 samples at the outlet of the pump and analyzed them for the major ions (Kidd Waddell, USGS, personal commun., 1999). Of the 13 brine samples, only one sample had a mole balance of ±5% and was deemed reliable enough to be used in this study. However, the Utah Geological Survey (UGS) also collected samples from the Great Salt Lake during the period that the pumping project was operating. The UGS samples should be representative of the brine that was pumped into the West Pond. Analyses from these samples were obtained from the UGS (J.W. Gwynn, UGS, personal commun., 1999). In addition to sampling the brine at the pump, the USGS collected 24 samples from points scattered throughout the West Pond in June 1989 to estimate the amount of salt contained in solution in the pond at the end of pumping (Wold and Waddell, 1993). The average composition of the brine from these sources is summarized in table 2.

Great Salt Lake brine generally contains higher concentrations of magnesium and sulfate than brine in the shallow brine aquifer underlying the Newfoundland basin prior to pumping. This difference is emphasized when a comparison is made of the ratios of potassium to magnesium and calcium to sulfate for the two different brines. The pre-pumping project shallow groundwater brine represented by the Reynolds North data (table 1) has a K/Mg ratio of 0.77 and a Ca/SO$_4$ ratio of 0.74. In contrast, analyses of the Great Salt Lake brine using the average values from April 1987 to June 1989 (table 2) show a K/Mg ratio of 0.35 and a Ca/SO$_4$ ratio of 0.06.

When pumping stopped in June 1989, water remaining in the West Pond continued to evaporate, and the pond decreased in size and retreated to the lowest part of the basin and eventually dried up. Satellite imagery of the West Pond suggests that it disappeared by July 22, 1991, leaving behind an extensive salt crust in excess of 3 feet thick in the center of the basin. Since 1991, satellite imagery shows that a surface pond forms in the Newfoundland basin during periods of low evaporation in the winter and following heavy precipitation.

Present Shallow Brine Aquifer in the Newfoundland Basin

In order to make a preliminary assessment of the brine presently in the shallow brine aquifer in the West Pond, a field investigation was undertaken during the summer of 1999. As part of this investigation, brine samples were recovered from shallow boreholes (6 to 8 feet) drilled in various locations throughout the West Pond area. These boreholes were drilled with a standard 4-inch bucket soil auger and a log was kept of the sediments encountered as well as the brine depth. The brine was then bailed from the borehole with a portable centrifugal pump at a rate of 1 to 2 gallons per minute until approximately 50 gallons of brine had been removed. At this point, samples were collected for analysis. In a typical borehole, the pumping rate of 1 to 2 gallons per minute lowered the water level a few inches, but sustainable flow could be maintained. When pumping stopped, the water level in the borehole returned to the original level. In the boreholes away from the center of the basin, the brine was typically confined and the water level would raise a few inches above its original level. In the center

Table 2. Summary of brine samples representative of Great Salt Lake brine pumped into the West Pond. Ion concentrations reported in moles per liter.

Data Source	Number of Samples	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	SO_4^{--}
USGS West Desert Pump	1	2.175	0.066	0.005	0.160	2.454	0.115
UGS Great Salt Lake Average, April 1987 to June 1989	13	2.301	0.075	0.006	0.217	2.591	0.101
USGS West Pond, June 1989	24	4.789	0.153	0.010	0.342	5.308	0.188

of the basin, no confined conditions were observed. Three of the samples collected during this investigation, obtained in the center of the basin, on or near locations sampled by Reynolds Metals in the 1960s, are of particular interest because they provide a basis for identifying changes to the shallow brine aquifer chemistry in the area last occupied by the waters from the WDPP. The analyses from these three samples are summarized in table 3.

Table 3. Brine samples from the shallow brine aquifer collected in the center of the Newfoundland basin, 1999. Ion concentrations reported in moles per liter.

Well Designation	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	SO_4^{--}
NB-8	3.454	0.425	0.004	0.823	4.727	0.365
NB-9	3.341	0.527	0.008	0.848	5.012	0.373
NB-10	3.310	0.486	0.008	0.859	5.012	0.318
Average	3.368	0.479	0.007	0.843	4.917	0.352

Not surprisingly, the marked increases in concentrations of potassium and magnesium reflect brine that has been concentrated through evaporation.

Geochemical Modeling of West Pond Brines

The TEQUIL program was developed by the University of California at San Diego for the geothermal industry to predict the chemical behavior of the natural brines from which the energy is extracted. Although the program was developed for the geothermal industry, it has been found to have wide applications in other industries including solar pond engineering (Møller and others, 1997). The program is based on a model which uses semi-empirical equations of Pitzer (1973) that were used by Harvie and Weare (1980) to show that the free energy calculations on electrolyte solutions could be used to accurately predict complex solubility relationships in the Na-K-Ca-Mg-SO_4 system (Møller and others, 1997). Various versions of this program are available, but for the purposes of this investigation, the 25ºC model for the Na-K-Ca-Mg-H-Cl-OH-SO_4-HCO_3-CO_3-CO_2-H_2O system (Harvie and others, 1984) was used.

TEQUIL provides a user interface to input the composition (in moles) of the initial solution. The model then reduces water through an iterative process to simulate evaporation. For each iteration, the program calculates the solubility for the various minerals that could be expected to precipitate from the brine. When the solution becomes saturated with a given mineral, the mineral is allowed to precipitate. The precipitated salt remains in contact with and is allowed to react with the brine. The results of the evaporation simulation are saved by the program in a text file that lists the molar composition of the concentrated brine and any minerals that precipitate from the brine.

TEQUIL was used to better understand how the brines introduced to the Newfoundland basin from the Great Salt Lake may have interacted with the subsurface brines contained within the shallow brine aquifer. TEQUIL identified the minerals that would precipitate from the brine and the sequence of precipitation. The model shows that evaporation of samples of brine from the Great Salt Lake produced a very consistent sequence of minerals even though the brine chemistries appear to be different. The mineral sequence projected by the model for the Great Salt Lake is consistent with actual results reported from the evaporation of Great Salt Lake brine (Butts, 1993, Jones and others, 1997).

The model also shows that when brines from the shallow brine aquifer from the Great Salt Lake Desert (before the West Desert Pumping Project) are evaporated, an equally consistent sequence of minerals results which is significantly different than the minerals which precipitate from the Great Salt Lake. The mineral sequence projected by the model for brine from the shallow brine aquifer in the Great Salt Lake Desert is consistent with the sequence reported for Reilly-Wendover's potash extraction operation near the Bonneville Salt Flats (Bingham, 1980).

The model was applied to subsurface brine from the Newfoundland basin before the area was inundated by the pumping project, brine from Great Salt Lake, and subsurface brine presently found in the center of the basin. The program was run for sufficient iterations to simulate the removal of over 99% of the water through evaporation. The model results were then graphed to show the sequence of minerals that precipitated from the brines. To aid in understanding the graphs, the primary salt minerals that the model showed would precipitate from the brines used in this exercise are shown in table 4.

The results of using the TEQUIL 25ºC model to simulate evaporation of a Great Salt Lake brine reported from the North Arm in 1978 are shown in figure 2. The y-axis values on the left side of the graph show the mass of the halite precipitated from the brine. The y-axis values on the right side of the graph show the amount of the various salts precipitated in moles. For Great Salt Lake brine, the model indicates that the order of initial precipitation for the primary salts is as follows: anhydrite-halite-glauberite-polyhalite-leonite-kainite-carnallite-kieserite-bischofite.

Table 4. Evaporite minerals derived from West Desert brines (adapted from Braitsch, 1971).

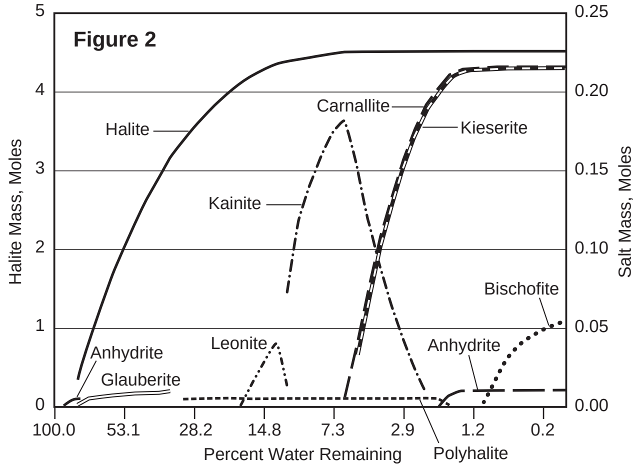
Mineral	Formula	Molecular Weight
Anhydrite	$CaSO_4$	136.15
Bischofite	$MgCl_2 \cdot 6H_2O$	203.33
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	334.51
Carnallite	$KMgCl_3 \cdot 6H_2O$	277.88
Epsomite	$MgSO_4 \cdot 7H_2O$	246.50
Gypsum	$CaSO_4 \cdot 2H_2O$	172.18
Glauberite	$Na_2Ca(SO_4)_2$	278.21
Halite (common salt)	NaCl	58.454
Hexahydrite	$MgSO_4 \cdot 6H_2O$	228.49
Kainite	$KMgClSO_4 \cdot 3H_2O$	244.48
Kieserite	$MgSO_4 \cdot H_2O$	138.41
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	366.71
Mirabilite	$Na_2SO_4 \cdot 10H_2O$	322.22
Polyhalite	$Ca_2K_2Mg(SO_4)_4 \cdot 2H_2O$	602.98
Sylvite	KCl	74.553
Syngenite	$K_2Ca(SO_4)_2 \cdot H_2O$	328.43

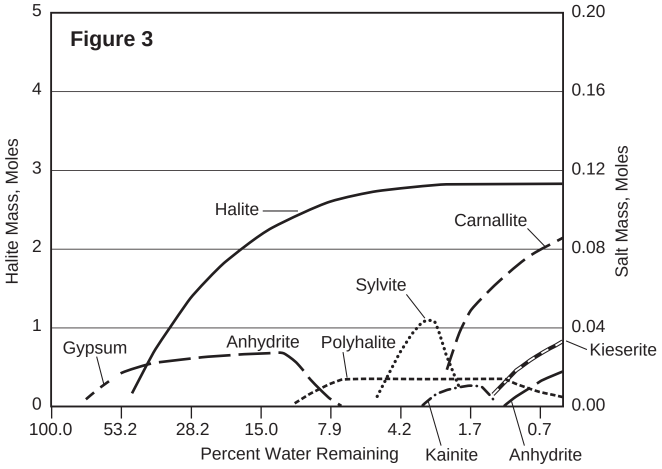
Similar results were obtained from modeling the average Great Salt Lake brine from 1987 to 1989.

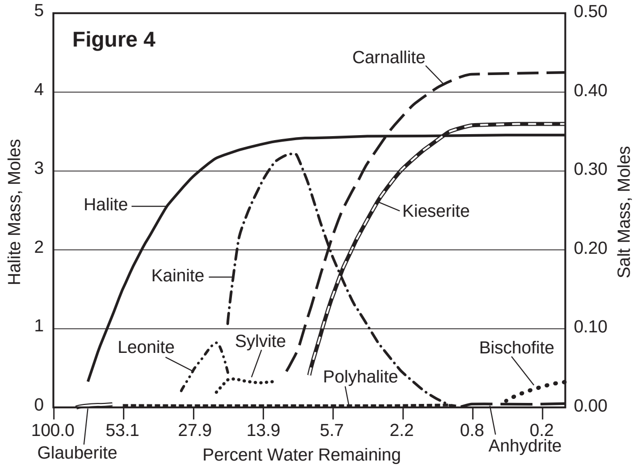
The model's prediction of minerals that would precipitate from brine sampled by Reynolds (Auger Hole #60238) before the basin was flooded by Great Salt Lake brine is shown on figure 3. The minerals precipitated from the subsurface West Desert brine, as predicted by the model, are quite different than minerals derived from Great Salt Lake brine. The model shows minerals precipitating as follows: gypsum-anhydrite-halite-polyhalite-sylvite-kainite-carnallite-kieserite.

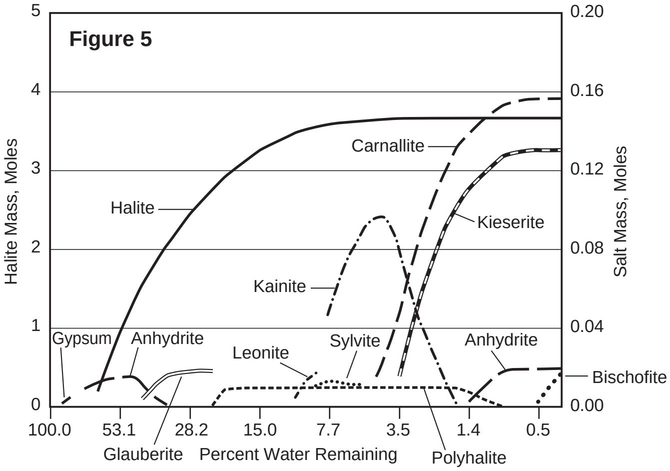
The TEQUIL model was then applied to the brine collected in the summer of 1999 from an auger hole (NB#8) located near Reynolds Auger Hole #60238. The results, as shown on figure 4, appear to be significantly different from either Great Salt Lake brine or the original Newfoundland basin brine. First of all, the brine has been significantly concentrated by evaporation. Because of this, the maximum value on the y-axis for the precipitated salts had to be increased to 0.5 moles from the 0.2 and 0.25 moles used on the other graphs to adequately show the distribution of the precipitated minerals. For the present groundwater brine in the center of the basin, the non-halite minerals precipitated out as follows: glauberite-halite-polyhalite-leonite-sylvite-kainite-carnallite-kieserite-bischofite.

The mineral suite projected by the model for the shallow groundwater brine in the center of the Newfoundland basin seems to contain components of both









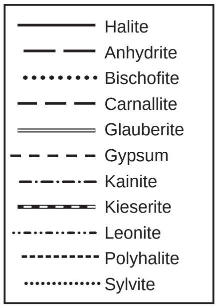


Figure 2. **Modeled mineral deposition during evaporation, Great Salt Lake-North Arm brine, 27 October 1978 (sample depth = 10 feet).**

Figure 3. **Modeled mineral deposition during evaporation, Deep Basin (NB): Reynolds auger hole #60238 brine (site of NB#8, 1999).**

Figure 4. **Modeled mineral deposition during evaporation, BLM auger hole NB#8, sample NBW-9 brine, Newfoundland basin, 27 August 1999.**

Figure 5. **Modeled mineral deposition during evaporation, Reynolds auger hole #60238 + 1978 North-Arm mix (50% + 50%).**

the Great Salt Lake and original groundwater. This suggests that the brine presently contained in the shallow brine aquifer in the center of the basin represents a mixture of the original groundwater brine with brine from the Great Salt Lake. To test this hypothesis, TEQUIL was used to project evaporation of an artificial brine representing a mixture of 50% Great Salt Lake and 50% of the pre-pumping Newfoundland basin brine (Reynolds auger hole #60238). The results are shown on figure 5. The resulting curves are very similar to those for the brine sample collected from auger hole NB#9 in 1999 (table 3).

The TEQUIL Model was also used to further characterize brine from various sources by plotting the ratio of potassium to magnesium as the brine is concentrated through evaporation. The graphed results are shown in figures 6 through 9. In each graph the molar ratio of potassium to magnesium remains constant until minerals containing potassium and magnesium begin to precipitate. Magnesium stays in solution longer than potassium so the K/Mg ratio decreases as evaporation proceeds. For the K/Mg ratio to increase, it would be necessary to either add additional potassium or reduce the magnesium content of the brine. One way to increase the K/Mg ratio for Great Salt Lake brine would be to mix it with a brine that has a higher K/Mg ratio. The K/Mg ratio for Great Salt Lake brine (fig. 6) is relatively low, starting out at about 0.24. On the other extreme, the pre-pumping brine in the Newfoundland basin (fig. 7) shows a K/Mg ratio of 0.77, showing a clear difference between the two brines. The K/Mg ratio of the brine in the basin from the pumping project from June 1989

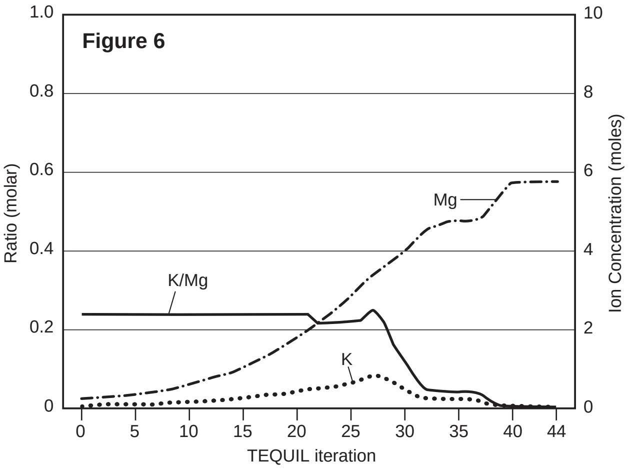


Figure 6. Modeled mineral deposition during evaporation, K/Mg ratio of Great Salt Lake brine (average of North and South arms).

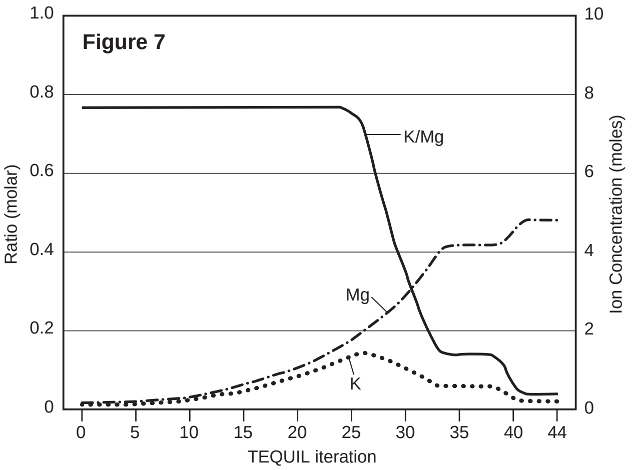


Figure 7. Modeled mineral deposition during evaporation, K/Mg ratio during evaporation of West Desert brine (Reynolds North data, 1966).

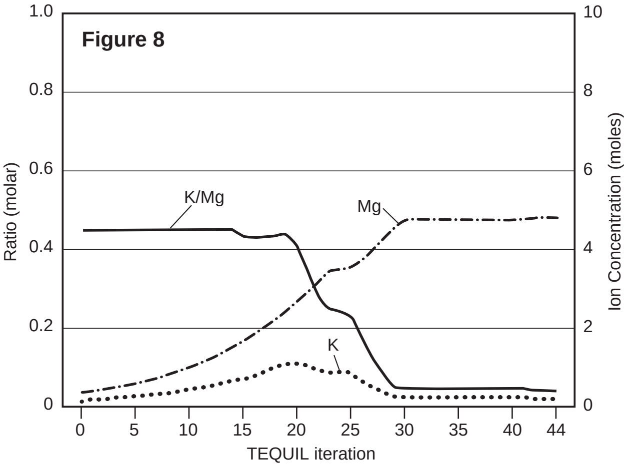


Figure 8. Modeled mineral deposition during evaporation, K/Mg ratio during evaporation of West Pond brine (final brine in pond, 1989).

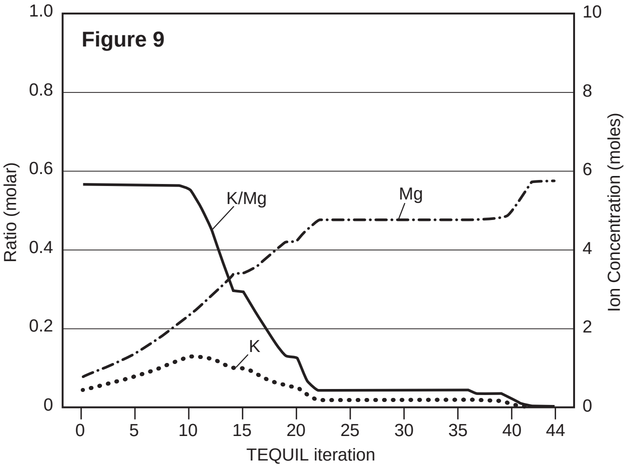


Figure 9. Modeled mineral deposition during evaporation, K/Mg ratio in Newfoundland basin shallow brine aquifer, 1999.

(fig. 8) starts at 0.45, suggesting the possibility of some mixing with Newfoundland basin groundwater while the pumping project was in operation. The K/Mg ratio of the brine sampled in the Newfoundland basin in 1999 (fig. 9) starts at 0.57, possibly indicating that the brine added to the Newfoundland basin from the Great Salt Lake continued to mix with the original subsurface brine.

Summary and Conclusion

Subtle differences in brine chemistry are not always readily apparent in brine from the Great Salt Lake and the Great Salt Lake Desert when these brines are compared using analyses of the major ions in the brine. This may be due to dilution of the brine by meteoric water or simply to the fact that the brines are dominated by sodium and chloride, which tend to mask differences in the other ions. By evaporating the brines and identifying the minerals that precipitate out of the solution, these subtle differences become more evident. The TEQUIL model at 25ºC seems to produce a reasonable prediction of the simple Na-K-Ca-Mg-Cl-SO_4-H_2O system to which these brines belong. Application of the model shows that the mineral suite precipitating from Great Salt Lake brine is very different than the minerals precipitating from groundwater brines in the Great Salt Lake Desert. The model also shows that the brine presently in the shallow brine aquifer in the portion of the Great Salt Lake Desert inundated by pumped Great Salt Lake brine contains components of both brines and may represent a mixture of Great Salt Lake and original West Desert brines. These conclusions are based on a limited field investigation, and more sampling should be undertaken to confirm and refine the interpretations.

Based on USGS estimates, as much as 386 million tons of salt from the Great Salt Lake was added to the brine resource in the area flooded by the pumping project. This is demonstrated by the elevated levels of potassium and magnesium in the Newfoundland basin. However, TEQUIL modeling indicates that brine from the Great Salt Lake mixed with the existing groundwater brine, resulting in a change in the chemical character of the brine. Instead of a simple halite-sylvite-carnallite system, the mixing of Great Salt Lake brine has resulted in a system with a more complex mineralogy.

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Developing Dimension Stone Deposits in Western North America

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Abstract

With the use of diamond tools and automated finishing equipment, new technology has allowed the cost of stone production to be reduced so that it is now cost competitive with manmade materials. This reduced cost has increased the usage of stone, generated a growing North American market, and created opportunities for new deposits to be developed. Determining the potential for success of developing a particular deposit becomes the domain of the geologist. The primary geological issue that needs to be addressed in a natural stone deposit is the size and quantity of blocks that are consistent in texture and color that can be produced.

Introduction

The success of the North American dimension stone industry at the beginning of the 20th century was due, in part, to the governmental and institutional building boom, which resulted in the expansion of cities in the United States. Now, at the beginning of the 21st century the current global economy has created a similar demand for dimension stone. Through globalization of the industry, stone that is used in North America comes from such diverse places as the deserts of Jordan and the mountain highlands of Brazil. Existing sources in North America have been expanded and idled quarry sources have been reactivated. Along with the expansion of previous sources, new sources have been identified, opened, and put into production; some successfully and others not so successfully. The single most important factor for success has been in maximizing recovery and minimizing waste. This is possible only with well-defined geology at the outset and experienced quarry supervision during development. The second factor for success has been the understanding of global market conditions and competition in the original business plan. If a new venture is to be successful, this information must be generated at the outset of the project and incorporated into a business plan that projects a realistic return on investment.

Successful Developments in North America

The Yule Colorado quarry development is an example of an expanding dimension stone market creating opportunities for a small producer with an acceptable, cost-competitive stone. The development of the Yule marble, which is a bright white stone, had numerous start-up issues to address; however, most of the issues have been successfully addressed and the stone is now taking its place in the world market. Additionally, blocks of white marble are being quarried in Vermont by an Italian company. These blocks are being shipped to Italy for sawing and returned to the North American market as a finished product. A South African granite company opened a quarry in Vermont to be an alternative source for Vermont granite, and a world-class black slate has been developed in Quebec. The Tennessee buff limestone quarries have been reactivated and are now owned and operated by the third generation family members of a long established dimension stone company. Texas limestone has been increasingly used on buildings and has become and accepted source of dimension stone in the Southwest. Various stone types being produced in Mexico and Canada are being brought into the western market place as well.

The Role of the Geologist in Quarry Development

The role of the geologist in the dimension stone industry is similar to the role of the profession in other industrial mineral commodities. You don't need geological training to recognize a massive outcrop, set up a wire saw, or ship blocks. You do need geological expertise, however, to evaluate the deposit's potential, predict the recoveries, and give direction to the development. With an understanding of some of the basic criteria and requirements for stone to be used on a building, a geologically trained person with experience in the stone industry can make fairly accurate judgments as to an outcrop's potential. It is the geologist who can determine the lateral and vertical dimensions of the deposit, the size of the blocks, and the quantities of waste rock that will have to be moved. The geologist is the person to develop the quarry plan that a seasoned production person would implement. Current dimension stone developments in New Mexico, Arizona, Texas, Idaho, Colorado, Wyoming, and Montana (fig. 1) have been brought on-stream by motivated individuals with "vision" and a clear understanding of their goals.

Figure 1. Montana travertine quarry (Geomapping Associates, Ltd. photo).

Exploration Methods

Because of the extensive quarry development related to the widespread use of stone in North America during the late 19th and early 20th centuries, most resources are well documented with state geological surveys. Exploration for quarries in North America, therefore, usually means revisiting previously quarried sites, identifying the reasons for closure, and evaluating their potential in the current market. If exploration efforts locate undeveloped properties, surface and subsurface mapping of the geological unit would be appropriate to initiate the geological investigation. With the advent of diamond-impregnated circular blades and wire saws, small test blocks can easily be extracted from outcrops during the initial stage of the investigation (fig. 2). Sampling the outcrop with these tools allows for adequate material to be excavated for mineral and physical property determinations. If the material is determined to be representative to what will be quarried at depth, then these test results as well as sample tiles can be prepared for market evaluations.

Figure 2. Sampling a Nevada outcrop (Geomapping Associates, Ltd. photo).

Strategies to Remain Competitive

Domestic stone producers face competition from offshore, low-cost producers. For example, Spanish marble was used in a commercial lobby in downtown Atlanta a few miles from Georgia Marble's processing plant. To offset the cost advantage of offshore producers, many domestic producers have expanded their market by introducing new products that utilize previously wasted material. Slate and granite counter tops help utilize all of the deposit and decrease the waste factor. Minimizing the in-pit and process waste factor is a major key to eventual profitability or subsequent failure of the project.

Value Added Products Drive Development

Architectural stone represents the high-end portion of the dimension stone industry. Quarry blocks sell in the range of $15 to $90 per cubic foot. A perfectly square, uniformly marked solid block with no fractures or flaws will gross 160 cubic feet, weigh 15 tons, and (depending on the stone type) range in value from $2,400 to $14,400. With further capital investment in a plant with sawing and polishing machinery, this block will yield salable slabs with a greater increased value. The typical retail price for a polished 3/4-inch-thick slab ranges from $10 to $20 per square foot, depending on how aesthetically acceptable it is to the customer. A typical 15/ton quarry block can yield up to 1,900 square feet of polished surface (no flaws, saw wastage or breakage) and an estimated retail value of $19,000 to $38,000. This high product end value means that transportation costs become a relatively small part of the price, explaining why prime architectural blocks can be shipped from quarries on one continent to fabricating plants on another, then to markets on even another continent. According to U.S. Geological Survey statistics, over 1.25 million metric tons of stone was used in the United States in 1999. There were 174,000 metric tons of slate, 398,000 metric tons of granite and 652,000 metric tons of marble imported during the same period. Currently, the U.S. is 88% reliant on imported dimension stone to satisfy the current market. The same statistics show that there are 142 domestic companies and 192 active quarries as suppliers in 33 states plus Puerto Rico. The states of Indiana, Vermont, Wisconsin, Georgia, and Texas led the nation in tons of stone produced in 1999.

The Importance of Technology

Strong demand for stone over the past 30 years generated much innovation and development of specific machinery for stone fabrication. Many Italian manufacturers export entire processing plants that are pre-engineered for specific stone types and final products. These fabrication facilities are for the most part very efficient and cost effective. Domestic North American shops have adapted to new technology but generally lack the integrated plant facilities that offshore producers have invested in. The stone producers of Jordan have added over 300,000 square meters of finishing capacity to their production facilities during 2002. This added capacity brings the total to over 1 million square meters of production capability. Along with Europe and the Mideast, the North American market has been targeted for much of this volume. With this large capacity, unit costs for finishing each square meter will be very low and it will be difficult for a small North American producer to compete.

Criteria for Successful Development

The first criterion for a successful stone operation is to develop a world class resource that can yield blocks, slabs, and finished products that would be cost competitive with sophisticated imported stone products. The second criterion is to have a vertically integrated finishing and fabricating facility that can produce a consistent product and develop consumer confidence. A third criterion is to create a well-connected sales/marketing group that understands the stone business. A fourth important criterion is to have an enthusiastic investment group funding the development.

Conclusions

To be successful, a newly opened dimension stone deposit must be capable of yielding stone that is competitive in the world market. This means that both quantity and quality are key factors as well as being cost competitive with low-cost, offshore producers. The geologist has a key role in the initial stages of project planning and with the implementation of a quarry plan that is based on the measured and observed realities of the deposit. To be cost competitive, the new venture has to incorporate the new technologies that have been introduced into the stone industry.

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Geology of Nevada

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Abstract

Geology plays a central role in Nevada's human history, economy, and future. Cordilleran tectonics have created the Basin and Range landscape and interior drainage of the Great Basin, provided a rain shadow to make Nevada the nation's driest state, and generated frequent earthquakes along normal and strike-slip faults. Geology is key to reducing risks from Nevada's natural and anthropogenic hazards (earthquakes, flash floods, drought, land subsidence, erosion after wildland fires, landslides, swelling and collapsing soils, radon, arsenic, and others).

Nevada's geologic fortunes make it the leading state in the production of gold, silver, barite, lithium, and mercury and a major producer of geothermal power and gypsum. The metals are primarily related to igneous activity, with major pulses of magma during the Jurassic, Cretaceous, and Tertiary. Barite is mined from Paleozoic sedimentary rocks, and gypsum occurs in sedimentary beds of Permian, Triassic, Jurassic, and Tertiary age. Lithium is extracted from brine beneath an unusual playa. Geothermal power production primarily occurs along Quaternary faults.

We are in the midst of the biggest gold-mining boom in American history. The Carlin trend is one of the world's premier gold-mining regions, and reserves along the trend and elsewhere in Nevada will sustain the boom for at least two more decades. Nevada's booming population will continue to increase demands for construction raw materials and for geological information to help manage growth while minimizing losses from geological hazards.

The geology of Nevada is the foundation of its natural resources and is closely linked to its human history. The complex geologic history of the state relates to such resources as minerals, water, and energy; to environmental issues; and to natural hazards. This article draws heavily from the references listed in the bibliography for general information on the geology of the state, particularly Stewart (1980), Stewart and Carlson (1978), Price and others (1999), and Price (2002).

In Nevada, mountain ranges, commonly about 10 miles wide and rarely longer than 80 miles, are separated by valleys. The geologic structure that controls this basin-and-range topography is dominated by faults. Nearly every mountain range is bounded on at least one side by a fault that has been active, with large earthquakes, during the last 1.6 million years. For the last several million years, these faults have raised and occasionally tilted the mountains and lowered the basins. Over the years, these basins have filled with sediments that are derived from erosion of the mountains and that are locally tens of thousands of feet thick.

Many of the range-bounding faults are still active (figs. 1 and 2). Nevada is the third most seismically active state in the nation (behind California and Alaska); over the last 150 years, a magnitude 7 or greater earthquake occurred

Figure 1. The Carson Range, with Lake Tahoe in the background, near Genoa and Walley's Hot Springs, Douglas County; photo by Terri Garside. A prominent fault scarp occurs at the base of the range.

somewhere in Nevada about once every 30 years. Most faults are normal, although some are strike-slip faults. The most apparent zone of strike-slip faults in Nevada is in a 50-mile wide swath along the northwest-trending border with California, the Walker Lane. These northwest-trending faults are accommodating part of the motion between the Pacific Plate, which is moving relatively northwest, and the North American Plate, which is moving relatively southeast. The San Andreas Fault takes up most of the motion between these two plates. The generally north-south trend of mountain ranges in most of Nevada transforms into northwest-trending ranges within the Walker Lane.

The climate of Nevada is closely tied to the geologic structure and resultant topography. Judging from fossil evidence of plants that grew in different parts of California and Nevada in the past, the Sierra Nevada (in California and far western Nevada) rose to current elevations only within the last six million years. Today the Sierra Nevada and other high mountains in California trap moisture coming off the Pacific Ocean and leave Nevada the driest state in the nation. Only a few rivers leave Nevada. These include the Bruneau, Jarbidge, and Owyhee Rivers in northeastern Nevada, which flow north into the Snake River in Idaho, and the White and Virgin Rivers in southeastern Nevada, which flow into the Colorado River (fig. 3). The Colorado, which is the largest river in Nevada, gets the bulk of its water from the Rocky Mountains to the east and provides much of the municipal and industrial water for Las Vegas and other communities in southern Nevada before flowing southward into the Gulf of California. Most of Nevada, however, is part of the Great Basin, a large area with no drainage to the ocean and centered on Nevada but including parts of California, Oregon, Idaho, and Utah. The Truckee, Carson, and Walker Rivers, which provide much of the drinking, industrial, and agricultural water for northwestern Nevada, flow generally eastward from the Sierra Nevada to terminal lakes and lowlands in the desert (Pyramid Lake, the Carson Sink, and Walker Lake, respectively). The Humboldt River, which supplies much of northeastern Nevada with drinking, agricultural, and industrial water, flows southwestward into Humboldt Lake, and, when the lake fills, into the Carson Sink.

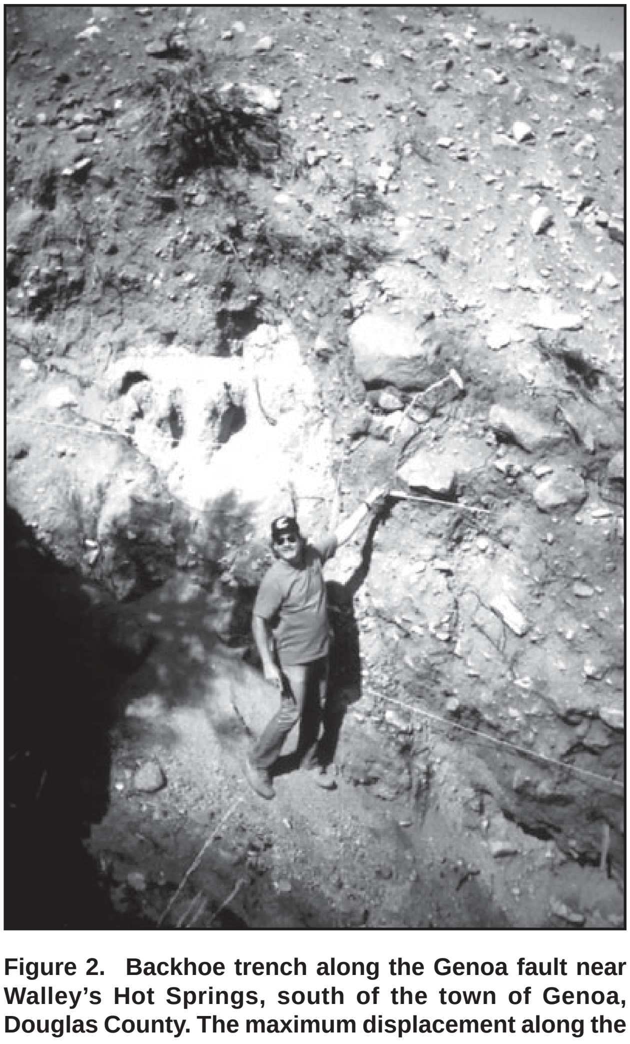

Figure 2. Backhoe trench along the Genoa fault near Walley's Hot Springs, south of the town of Genoa, Douglas County. The maximum displacement along the fault during its last event, about 550 to 650 years ago, was 5.5 meters (Ramelli and others, 1999). See http://www.nbmg.unr.edu/dox/sp27.pdf for Nevada Bureau of Mines and Geology Special Publication 27, a booklet on Living with Earthquakes in Nevada, for more information about earthquake hazards.

During glacial times (most recently about 10,000 years ago), large expanses in the Great Basin were covered by water. Great Salt Lake and the Bonneville Salt Flats in Utah and parts of far eastern Nevada were once part of ancient Lake Bonneville, and Pyramid Lake, the Carson Sink, and Walker Lake were once connected in ancient Lake Lahontan. Native Americans occupied the shores of these lakes as early as 10,000 to 12,000 years ago. Glaciers existed in the higher mountains, carving some of the spectacular U-shaped valleys in the Ruby Mountains (fig. 4) and sculpting high-mountain topography in the Sierra Nevada. Glaciers are still present high in the Ruby Mountains and Snake Range in eastern Nevada.

Groundwater, mostly from aquifers in alluvial basins, is used throughout the state. In some basins, groundwater has been pumped out more rapidly than it is naturally recharged from rain and snowmelt; this causes significant lowering of the groundwater table and can affect the land surface. In Las Vegas Valley, cracks have developed locally in the ground (near preexisting faults), and in a few places the land has subsided more than 6 feet in the last 60 years (fig. 5).

On a percentage basis, Nevada is the fastest growing state in the country. The U.S. Census Bureau reported a population of 1,201,833 in 1990 and 1,998,257 in 2000. Most of the increase has occurred in and around the urban areas of Las Vegas and Reno-Carson City. Urban expansion in the Las Vegas area has been at a rate of about two acres per hour and is expected to continue at a rapid rate. The Nevada State Demographer has projected the population to be 2.8 million in 2010 (fig. 6). This increasing population places demands on groundwater and other resources.

The ecological regions of Nevada are directly linked to the climate, elevations of the mountains, and rocks. A combination of precipitation and rock type (with the help

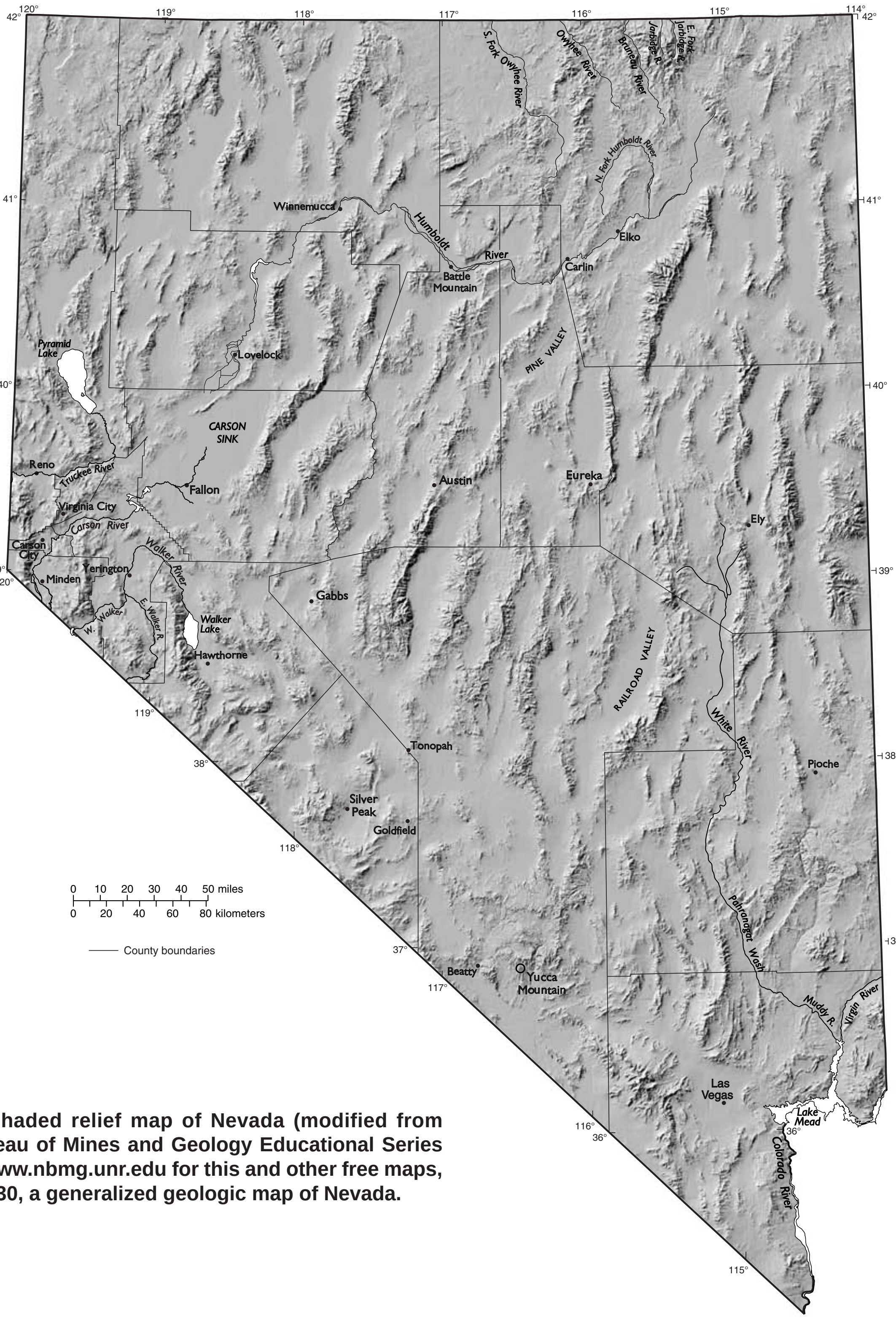

Figure 3. Shaded relief map of Nevada (modified from Nevada Bureau of Mines and Geology Educational Series E-31). See www.nbmg.unr.edu for this and other free maps, including E-30, a generalized geologic map of Nevada.

of ubiquitous microbes) dictates the types of soils that develop and the plants that grow, which, in turn, affect the types of animals that survive. Geologic evidence (primarily fossils) shows us that climate has changed substantially even within the last 10,000 years. For example, mammoths and camels once lived near springs and now mostly dry lakes in Nevada, as recently as 11,000 years ago.

Although Nevada is, on the average, quite dry (with about 10 inches of rainfall across the state, but locally less than 5 inches in some lowlands and over 40 inches in high mountains), major storms have caused significant floods and occasional landslides. Geologic evidence (and recorded history) abounds for large floods on the major rivers and "dry" washes throughout the state.

Figure 4. Hanging valley, carved by glaciers, that is a tributary of Lamoille Canyon, Elko County.

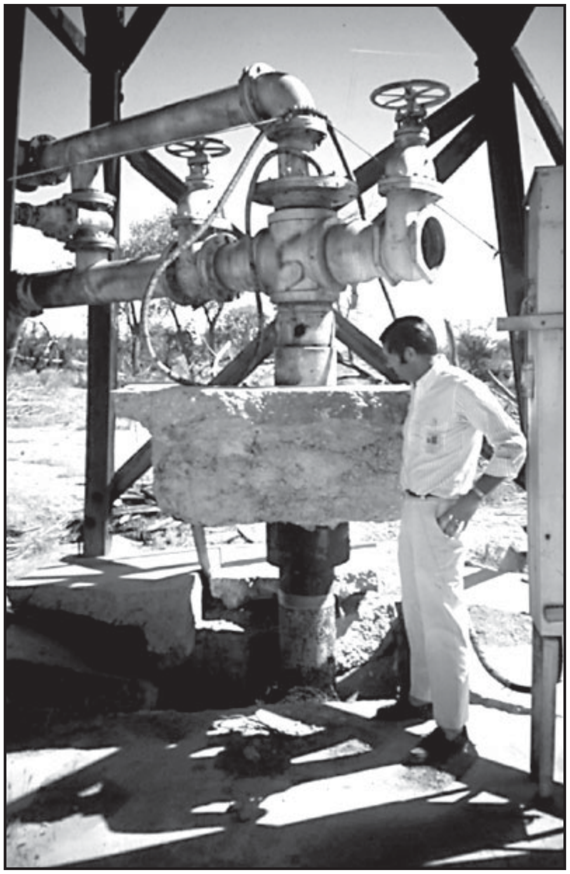

Figure 5. The land surface dropped about 5 feet since this well was drilled at the Las Vegas Valley Water District well field near the Meadows Mall, Clark County. Photo by John Bell, 1980.

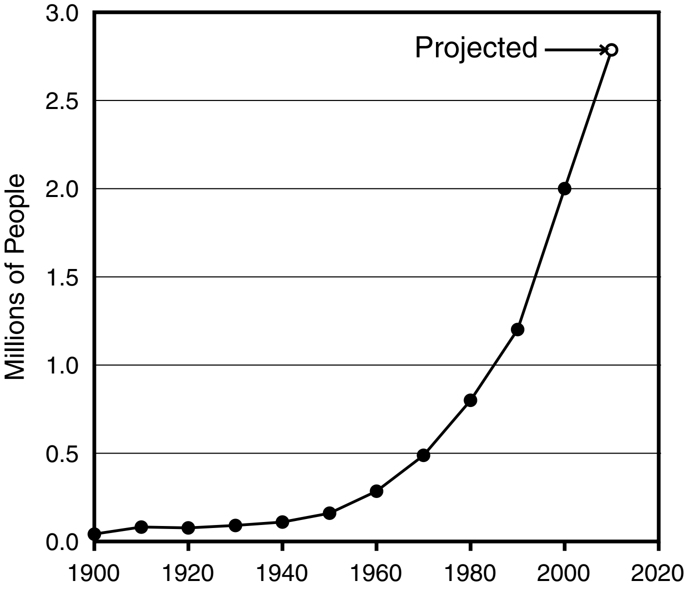

Figure 6. Nevada population. Data from the U.S. Census Bureau (www.census.gov) projected to 2010 by the Nevada State Demographer.

Table 1. Geologic time scale with major events in Nevada history.

Million years before present		
	CENOZOIC	
	Quaternary	Modern earthquakes, mountain building, volcanism, and geothermal activity are expressions of Basin and Range extension that began in the Tertiary Period. The crust is being pulled apart in Nevada, causing valleys to drop relative to mountains. Prior to 10,000 years ago, ice ages caused glaciers to form in the higher mountains and large lakes to develop, in places connecting today's valleys.
1.6		
	Tertiary	Basin and Range extension began about 30 to 40 million years ago. Igneous activity during the Tertiary Period was caused not only by extension but also by subduction (descent of oceanic crust into the Earth's mantle) of oceanic plates beneath the North American Plate and, in northern Nevada, by motion of the crust over the Yellowstone hot spot in the mantle. Numerous Nevada ore deposits, including most major gold and silver deposits and the copper ores near Battle Mountain, formed during this time. Gypsum deposits formed from evaporating lakes in southern Nevada.
65		
	MESOZOIC	
	Cretaceous	The Cretaceous Period and Mesozoic Era ended abruptly with the extinction of dinosaurs and many marine species; chemical, mineralogical, and other geological evidence suggests that these extinctions were caused by a large meteorite striking the Earth. Numerous granitic igneous intrusions, scattered throughout Nevada, originated from subduction along the west coast of North America. Much of the granite in the Sierra Nevada formed at this time. The igneous activity caused many metallic mineral deposits to form, including the copper-gold-silver-lead-zinc ores at Ruth, near Ely in White Pine County, copper-molybdenum ores north of Tonopah in Nye County, and tungsten ores in several mining districts. In southern and eastern Nevada, sheets of rocks were folded and thrust from the west to the east during the Sevier Orogeny (mountain building), which began in Middle Jurassic time and ended at or beyond the end of the Cretaceous Period.
144		
	Jurassic	A subduction zone to the west caused igneous intrusions, volcanism, and associated ore deposits, including copper deposits near Yerington. Sandstones, including those in the Valley of Fire, were deposited in southeastern Nevada, and sedimentary gypsum deposits formed in northwestern Nevada.
208		
	Triassic	The general geography of Nevada during the Triassic Period was similar to that during the Jurassic Period—igneous activity in the west and deposition of sedimentary rocks in continental to shallow marine environments to the east. Explosive volcanism produced thick ash-flow tuffs in west-central Nevada. Economically important limestone, gypsum, and silica-sand deposits formed in southern Nevada. The Sonoma Orogeny, which began during Late Permian time and ended in Early Triassic time, moved rocks from the west to the east along the Golconda Thrust in central Nevada. The large marine reptiles at Berlin-Ichthyosaur State Park lived during the Triassic Period.
251		
	PALEOZOIC	
	Permian	Volcanism to the west and deposition of thick limestones to the east were characteristics of much of the Paleozoic Era in the Great Basin. Some marine gypsum deposits formed in southern Nevada.
290		
	Pennsylvanian	The Antler highland, formed earlier, was eroded and shed sediments into the basins to the east. Carbonate rocks were deposited in eastern and southern Nevada.
320		
	Mississippian	During the Antler Orogeny, from Late Devonian to Early Mississippian time, rocks were folded and thrust from the west to the east. The Roberts Mountains Thrust, below which many of the gold deposits in north-central Nevada occur, formed at this time. Conglomerate, sandstone, siltstone, and shale were deposited in the thick basin of sediments derived from the Antler highland, and carbonate rocks were deposited further east.
360		
	Devonian	Limestone was deposited in eastern Nevada, and shale, chert, and economically important barite were deposited in northeastern and central parts of the state. No record of middle to lower Paleozoic rocks exists in the western part of the state. The quiet, shallow-marine tectonic setting that persisted earlier in the Paleozoic Era began to change, as small land masses from the Pacific Ocean collided with western North America.
418		
	Silurian	Carbonate rocks (dolomite and limestone) in the eastern part of the state and silica-rich rocks (shale, sandstone, and chert) in the central part of the state record similar deposition to that during the rest of the middle to early Paleozoic Era.
438		
	Ordovician	Marine deposition during the Ordovician Period was similar to that during the rest of the early Paleozoic Era, with the exception of basalts (metamorphosed to greenstones) locally interbedded with sedimentary rocks found today in the central part of the state. Some sedimentary barite deposits and copper-zinc-silver ores formed in sea-floor sediments during this time.
490		
	Cambrian	Middle and Upper Cambrian deposition resembled that during much of the Paleozoic Era, with carbonate rocks to the east and shale plus sandstone to the west. Lower Cambrian and uppermost Precambrian rocks are characterized by quartzite and metamorphosed siltstone throughout much of Nevada.
543		
	PRECAMBRIAN	
		The oldest rocks in Nevada (at least 2,500 million years old in the East Humboldt Range in northeastern Nevada and at least 1,700 million years old in southern Nevada) are metamorphic rocks (including gneiss, schist, marble, and metamorphosed granite, pyroxenite, hornblendite, and pegmatite). Precambrian rocks also include granites (about 1,450 million years old) and younger sedimentary rocks. Beginning approximately 750 million years ago, Antarctica and Australia may have rifted away from western North America, setting the stage for the development of a western continental margin that is similar to the Atlantic coast of today. A shallow marine, tectonically quiet setting persisted in eastern Nevada for the next 700 million years.

Major events in the geologic history of Nevada are highlighted in table 1. A western continental margin, similar to the Atlantic coast of today, persisted for hundreds of millions of years before the more active, Pacific coast margin of today began to take shape about 360 million years ago. Repeated and prolonged periods of interactions between the North American Plate and oceanic plates to the west, expressed in folds, thrust faults, strike-slip faults, normal faults, igneous intrusions, volcanism, metamorphism, and sedimentary basins, are recorded in the rocks.

Nevada rocks document volcanic and intrusive igneous activity intermittently and repeatedly from earliest geologic history to within the last few thousand years. Nevada's igneous rocks are connected to sea-floor spreading about 450 million years ago (much like the Mid-Atlantic Ridge or the East Pacific Rise today), collisions of ancient and modern plates, and hot spots in the Earth's mantle and perhaps outer core (some Nevada volcanic rocks can be correlated with the Yellowstone hot spot, which, as a result of plate tectonics, was once underneath and produced volcanoes in southern Idaho and northern Nevada). Some of the volcanic rocks in western Nevada represent the precursor of the Cascade Range, and significant intrusions about 40, 100, and 160 million years ago are probably linked to similar plate-tectonic settings, whereby oceanic plates were subducted beneath western North America.

Most, but not all, ore deposits in Nevada are associated with igneous activity. In some cases, metals came from the magmas themselves, and in other cases, the magmas provided heat for circulation of hot water that deposited metals in veins and fractured sedimentary rocks. Some spectacular mineral specimens occur in ore deposits that formed when magmas intruded and metamorphosed sedimentary rocks. Even today, driven locally by deep circulation along faults and perhaps locally by igneous activity, hot water shows up in numerous geothermal areas. Nevada produces approximately $100 million worth of geothermally generated electric power annually, and geothermal resources also are used for agriculture, industrial applications, and space heating.

Nevada produces approximately $3 billion worth of mineral commodities each year (figs. 7 and 8). Nevada is the nation's leading gold producer, accounting for approximately 75% of U.S. production and 10% of world production. Much of the gold comes from a northwest-trending belt of gold deposits in northeast Nevada known as the Carlin trend. One of the interesting features of the Carlin trend is that nearly all of the gold is contained in microscopic particles within Paleozoic sedimentary rocks. Although the sedimentary hosts for the gold are more than 250 million years old, the actual mineralization may have

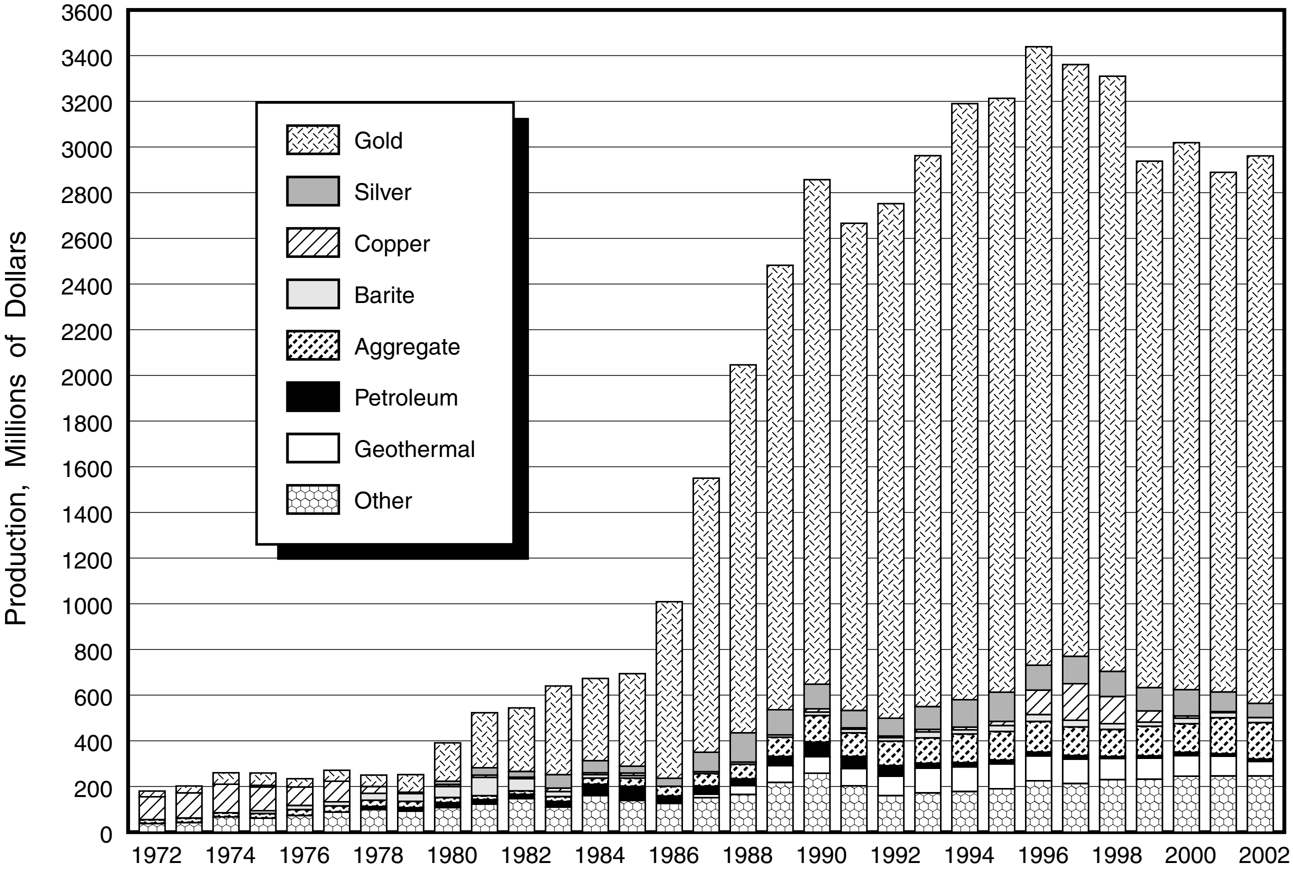

Figure 7. Nevada mineral, geothermal, and petroleum production, 1975–2002. Details on Nevada mineral production are available in Nevada Bureau of Mines and Geology Special Publications MI-2001 (www.nbmg.unr.edu/dox/mi/01.pdf) and P-13 (www.nbmg.unr.edu/dox/mm01.pdf).

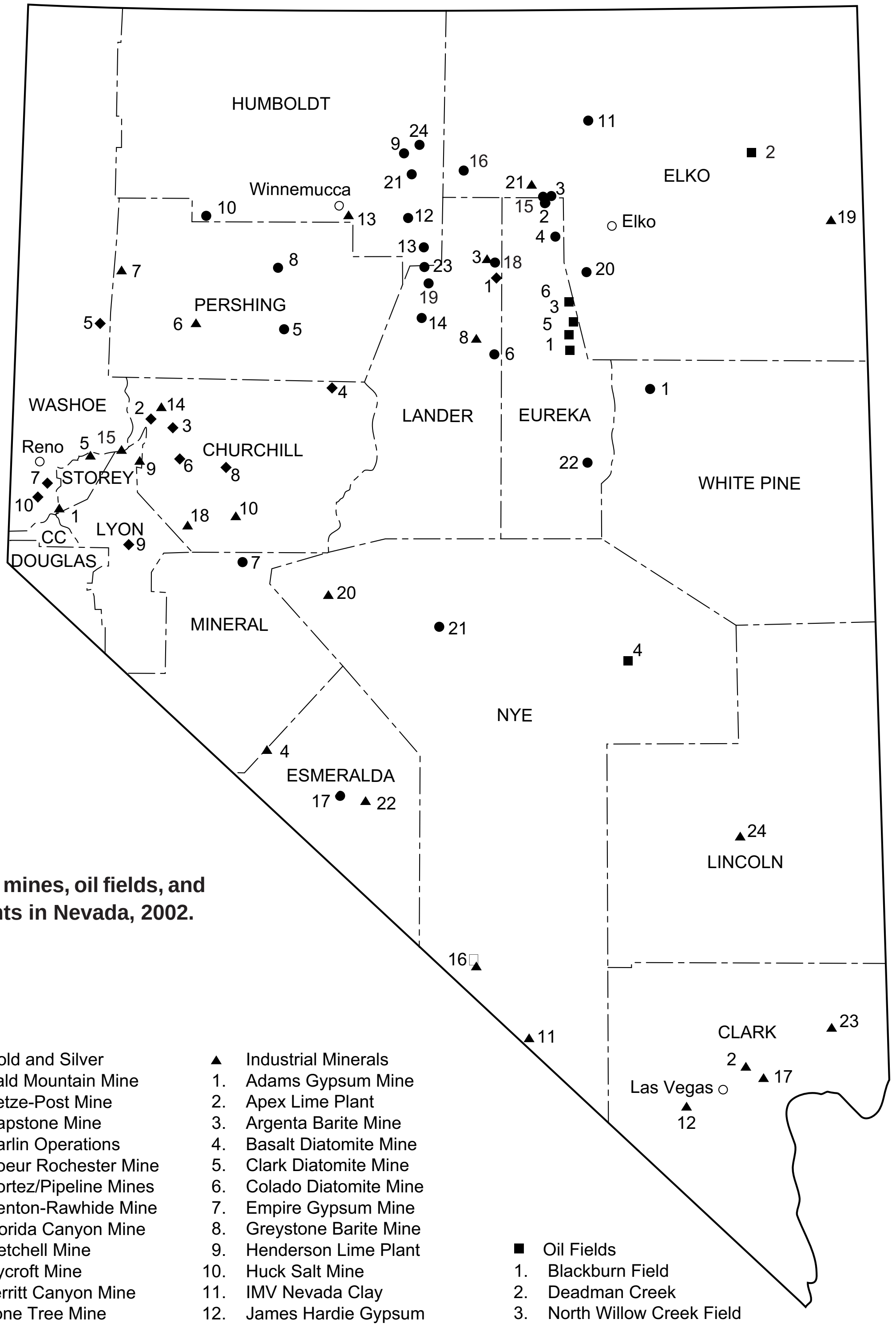

Figure 8. Major mines, oil fields, and geothermal plants in Nevada, 2002.

● Gold and Silver

1. Bald Mountain Mine
2. Betze-Post Mine
3. Capstone Mine
4. Carlin Operations
5. Coeur Rochester Mine
6. Cortez/Pipeline Mines
7. Denton-Rawhide Mine
8. Florida Canyon Mine
9. Getchell Mine
10. Hycroft Mine
11. Jerritt Canyon Mine
12. Lone Tree Mine
13. Marigold Mine
14. McCoy/Cove Mine
15. Meikle Mine
16. Midas Mine
17. Mineral Ridge Mine
18. Mule Canyon Mine
19. Phoenix Project
20. Rain Mine
21. Round Mountain Mine
22. Ruby Hill Mine
23. Trenton Canyon
24. Twin Creeks Mine

▲ Industrial Minerals

1. Adams Gypsum Mine
2. Apex Lime Plant
3. Argenta Barite Mine
4. Basalt Diatomite Mine
5. Clark Diatomite Mine
6. Colado Diatomite Mine
7. Empire Gypsum Mine
8. Greystone Barite Mine
9. Henderson Lime Plant
10. Huck Salt Mine
11. IMV Nevada Clay
12. James Hardie Gypsum
13. MIN-AD Dolomite Mine
14. Moltan Diatomite Mine
15. NCC Limestone Quarry
16. New Discovery Clay
17. PABCO Gypsum
18. Popcorn Perlite Mine
19. Pilot Peak Limestone Quarry
20. Premier Magnesite Mine
21. Rossi Barite Mine
22. Silver Peak Lithium Carbonate
23. Simplot Silica Products
24. Tenacity Perlite Mine

■ Oil Fields

1. Blackburn Field
2. Deadman Creek
3. North Willow Creek Field
4. Railroad Valley (Eagle Springs, Trap Spring, Currant, Sand Dune, Grant Canyon, Bacon Flat, Kate Spring, Duckwater Creek, Sans Spring, and Ghost Ranch Fields)
5. Three Bar Field
6. Tomera Ranch Field

◆ Geothermal Power Plants

1. Beowawe
2. Bradys Hot Springs
3. Desert Peak
4. Dixie Valley
5. Empire
6. Soda Lake No. 1 and No. 2
7. Steamboat I, IA, II, and III
8. Stillwater
9. Wabuska
10. Yankee Caithness

occurred much later (approximately 40 million years ago) in association with igneous activity.

We are currently in the midst of the biggest gold-mining boom in American history (fig. 9). The U.S. production so far in the current boom, the period from 1980 through 2002, has exceeded 170 million ounces of gold. This is significantly greater than the total production during the era of the California gold rush (1849 to 1859, with 29 million ounces), the Comstock (Nevada) era from 1860 to 1875 (with 34 million ounces), and the period from 1897 to 1920, when Goldfield (Nevada), the Black Hills (South Dakota), Cripple Creek (Colorado), and by-product production from copper mines in Arizona and Utah contributed to cumulative production of 95 million ounces. Reserves on the Carlin trend and elsewhere in Nevada are sufficient to sustain the boom for at least two more decades.

Nevada, the Silver State, is also the nation's leading producer of silver, barite, mercury, and lithium. Much of the silver is a co-product or by-product of gold production, and all the mercury currently produced is a by-product of precious metal recovery. Lithium is extracted from brine that occurs in Tertiary valley-filling sediments near Silver Peak (fig. 10). Other commodities that are currently mined in Nevada include gypsum, limestone (for cement and lime), clays, salt, magnesite, diatomite, silica sand, dimension stone, and crushed rock, sand, and gravel for construction aggregate. In the past, Nevada has been a significant producer of copper, lead, zinc, tungsten, molybdenum, and fluorite. Active exploration and recent discoveries of new ore deposits attest to the potential for finding additional ones.

Nevada became a State in 1864, during the Civil War (hence the motto "Battle Born"), in part as a result of mineral wealth. The 1859 discovery of silver-gold ores on the Comstock Lode enticed miners and prospectors, many of whom had come to California a decade earlier in search of gold. Over the decades that followed, they spread out from Virginia City, discovered other major mining camps, and established many nearby towns in Nevada (Austin, Battle Mountain, Beatty, Carlin, Elko, Ely, Eureka, Gabbs, Goldfield, Las Vegas, Lovelock, Pioche, Tonopah, Winnemucca, Yerington) and other parts of the western United States.

Nevada also produces some oil, although production is small relative to that in major oil states. An interesting aspect of Nevada petroleum production is that some of the oil is associated with hot water, although lower in temperature but otherwise much like the geothermal fluids that formed gold and silver deposits. Another curiosity is that some of the oil is trapped in fractured volcanic rocks, although the ultimate source of the petroleum was from organic matter in sedimentary rocks. Most of the oil has come from the eastern part of the state, primarily Railroad and Pine Valleys.

Some environmental hazards are associated with the abundant igneous rocks in Nevada. For example, many groundwaters in Nevada contain elevated concentrations of radon. Because radon is common in silica-rich igneous rocks, and because these rocks are widespread in the mountains

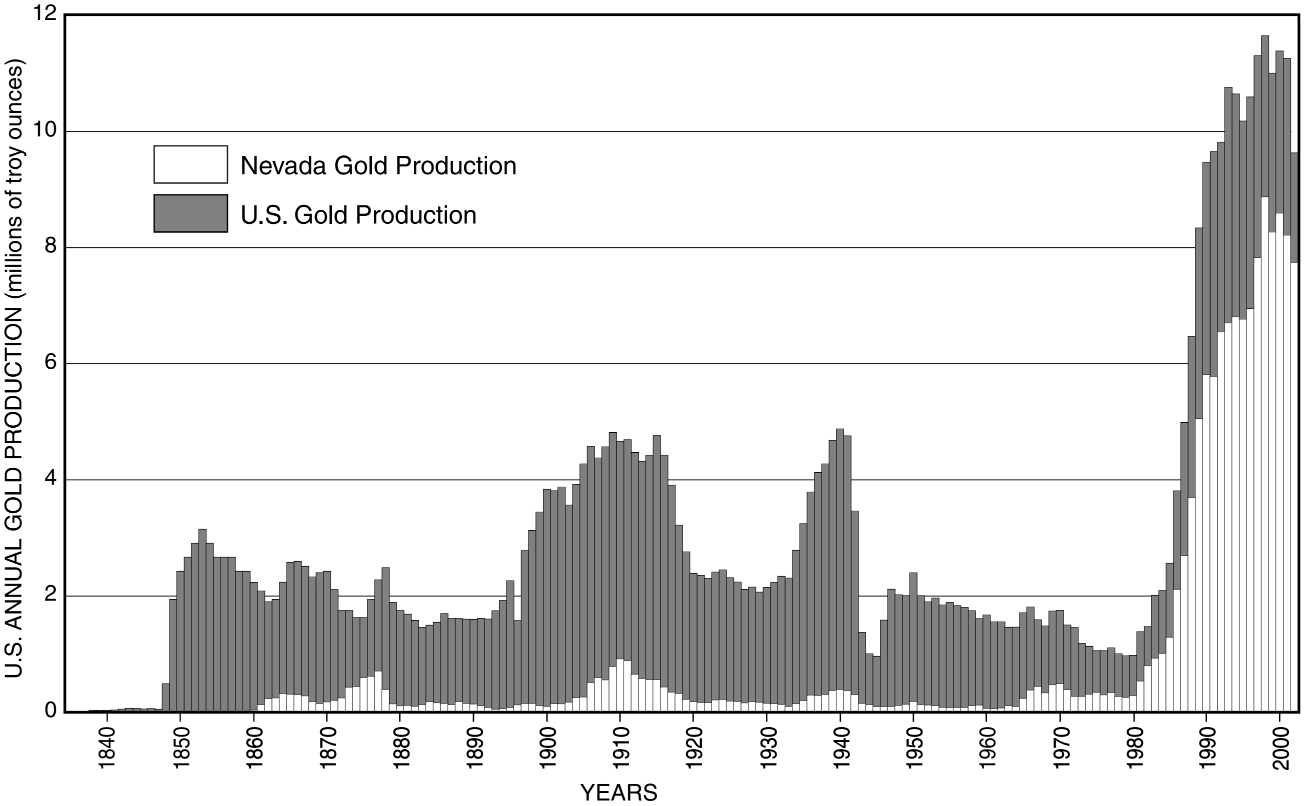

Figure 9. U.S. and Nevada gold production from 1835 through 2002. Data from Dobra (1998) and the U.S. Geological Survey.

and make up much of the sediment in the valleys, radon occurs in groundwater, soil, and air. Similarly, arsenic is relatively abundant in certain types of igneous rocks and is locally a problem as a dissolved natural constituent in Nevada groundwater and surface water. The proposed repository for high-level nuclear waste at Yucca Mountain is in Tertiary ash-flow tuffs, and Quaternary cinder cones occur nearby (fig. 11).

Given Nevada's mineral, energy, and water resources, its challenges in terms of environmental protection, and its exposure to natural hazards, geology will continue to play a central role in the state's economy, growth, health, safety, and history.

Acknowledgment

I thank Chris Henry, Steve Castor, Larry Garside, Jim Faulds, and Dick Meeuwig for help with earlier versions of this manuscript and Rich Schweickert and Jim Carr for constructive comments on this latest version.

Figure 10. A Quaternary cinder cone at the north end of Clayton Valley, Esmeralda County, is reflected by the brine pool that is part of the lithium-mining operation in the valley. Lithium-rich brines are pumped to the surface, where they are allowed to evaporate in the sun. The solution precipitates halite, NaCl, before being processed to remove lithium.

Figure 11. Black Cone, 1 million-year-old cinder cone, Yucca Mountain in distance, Nye County.

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Ruby Garnet Operation

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Abstract

The Ruby Garnet operation is approximately 60 miles southeast of Butte, Montana in the Alder Gulch Creek drainage. Garnets at the Ruby operation were derived from Precambrian metamorphic rocks to the east. The garnets are present as broken fragments of almandine crystals that were originally up to several inches across. Alder Gulch Creek has an extensive history of placer gold mining that yielded more than 2 million ounces. Approximately 100 million short tons of alluvium was mined using large bucket-ladder dredges from 1899 to 1922. The dredges separated gravel from the gold-bearing sand and placed the gravel back on top of previously discharged sand. This created a size-sorted manmade stratigraphy known as stacked tailings. Most of the garnet occurs in the lower "fines horizon." Cominco American acquired the deposit in 1989, initiated construction in 1994, and came onstream in 1996. The Oregon-Montana Investment Group acquired the operation in 2000. Mining is conducted with a dragline, which extracts approximately 40 feet of stacked tailings. After initial screening, the -3/16-inch material is fed to the jig and spiral plant. Further upgrading takes place in the wet plant resulting in a finished product composed of about 95% almandine garnet. Garnet product is shipped in bags and supersacks, predominantly by truck. Most sales are for waterjet cutting; some garnet has been sold for abrasive blasting and water filtration. In waterjet cutting, garnet grains are entrained in a stream of high-velocity water. Waterjet cutting is used to shape-cut materials such as marble, granite, concrete, aluminum, titanium, steel, glass, corrugated boxboard, plastics, and aerospace composites.

Introduction

This paper on the Ruby Garnet operation is updated from a Monarch Financial Corporation (1998) report and includes material from Austin (1994a, b), Gorrill (2003) and Olson (2003). The Ruby Garnet operation is in the Ruby River Valley, Madison County, Montana, about 60 miles southeast of Butte and about 0.5 miles east of the town of Alder (fig. 1). Elevations at the operation range from 5,100 to 5,200 feet.

The Alder Gulch Creek drainage (the site of the Ruby Garnet operation) has an extensive history of placer gold mining. Gold production for the entire 15-mile length of the creek exceeded 2 million ounces. Approximately 100 million tons of alluvium was mined using bucket-ladder dredges from 1899 to 1922 by the Conrey Placer Mining Company. Seven dredges worked the area. Six of the dredges separated gravel from the gold-bearing sand and placed the gravel back on top of previously discharged sand. This created a size-sorted manmade stratigraphy known as stacked tailings. Most of the garnet occurs in the lower "fines horizon" of the stacked tailings.

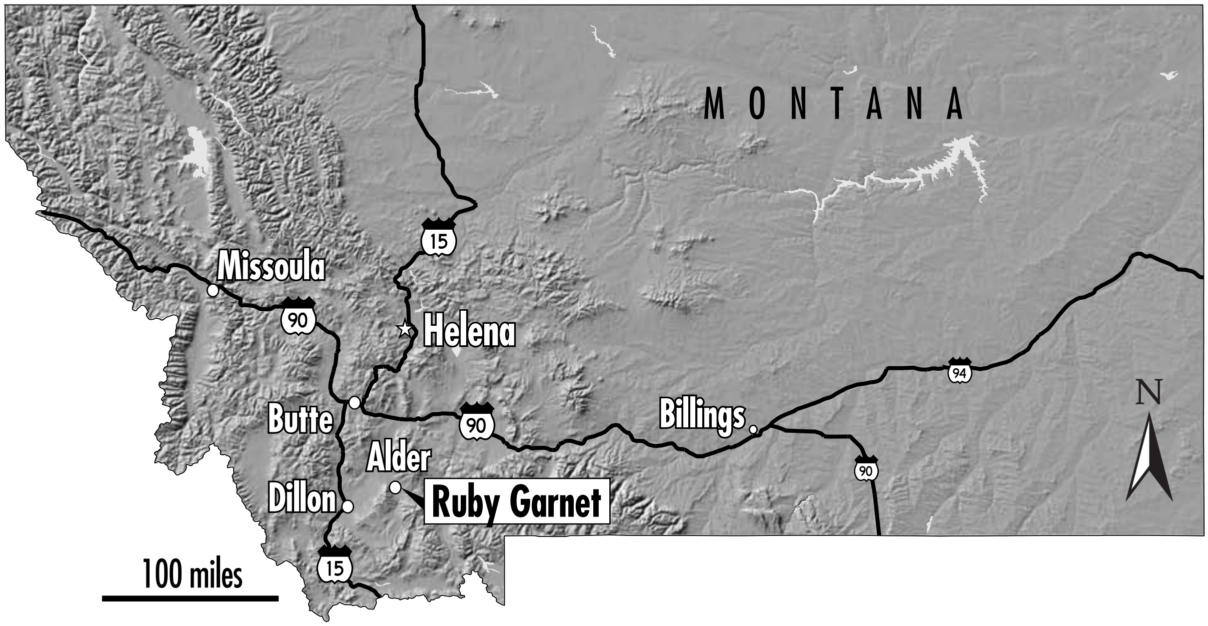

Figure 1. Ruby Garnet location.

The key developments that led to the start-up of the Ruby Garnet operation are:

- 1989 Cominco American acquired the Ruby Garnet deposit; exploration drilling (reverse circulation) completed; reserves estimated.
- 1992 Completed bulk sampling; bench-scale beneficiation test work; pilot plant testing; market studies; feasibility study.
- 1993 Engineering design of plant; permitting.
- 1994 Plant construction initiated.
- 1996 Plant start-up.

The Ruby Garnet operation was sold to Oregon-Montana Investment Group in 2000. As of mid-2003, Ruby Garnet is for sale and potential purchasers are completing their due diligence investigations.

Geology

The garnet group is one of the best examples of an isomorphous series. It is characterized by the ability to substitute ions without changing the garnet crystal structure. This yields two complete garnet solid-solution series (table 1). One exists between almandine, pyrope, and spessartine and another between grossular, andradite, and uvarovite. The preferred garnet for waterjet, abrasive blasting, and filtration applications is almandine but other types of garnet have been substituted.

Garnets at the Ruby operation are derived from Precambrian metamorphic rocks to the east, which crop out in the Tobacco Root and Greenhorn mountain ranges (figs. 2 and 3). Precambrian clasts that contain garnet are predominantly gneiss in the Alder Gulch Creek drainage. Garnets are present in Quaternary alluvium as broken fragments of almandine crystals that were originally up to several inches across. The alluvium overlies Tertiary lacustrine clay, known locally as “false bedrock,” whose top is the base of current garnet mining. Gold dredges avoided the clay because it stuck in their buckets and contained no gold.

Cominco American drilled 17 reverse-circulation holes into the stacker tailings. Approximately 7,000 st of tailings were processed in the pilot plant. Based upon this work, proven reserves are reported to be about 32.5 million st grading 4.5% garnet.

Mining

Mining is conducted from April to November by open-pit methods. The tailings are unconsolidated, and easy to mine. A dragline with a 7.25-cubic-yard bucket is used to extract approximately 40 feet of stacked tailings (fig. 4). A bucket-wheel dredge also was considered. The dragline moves north to south and mucks out the tailings and stockpiles them on the west side of the pit. The resulting pit is 35–45 feet deep and fills with water. This water is introduced into the process during mining because the plant uses wet gravity-separation methods to recover garnet.

Table 1. Garnet group.

Almandine	$Fe_3Al_2(SiO_4)_3$	Grossular	$Ca_3Al_2(SiO4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$	Andradite	$Ca_3Fe_2(SiO_4)_3$
Spessartine	$Mn_3Al_2(SiO_4)_3$	Uvarovite	$Ca_3Cr_2(SiO_4)_3$

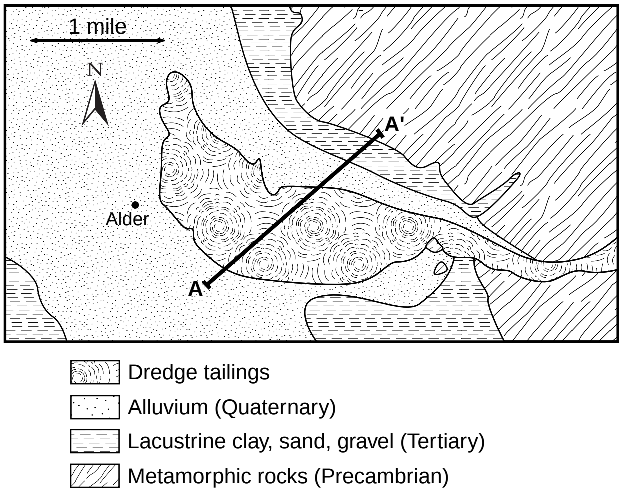

Figure 2. Surface geology.

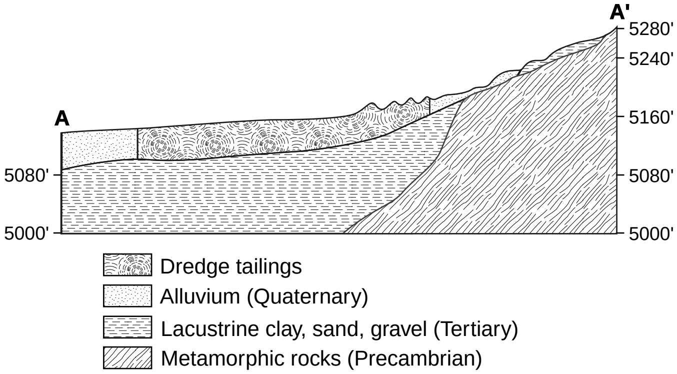

Figure 3. Cross section A– A´.

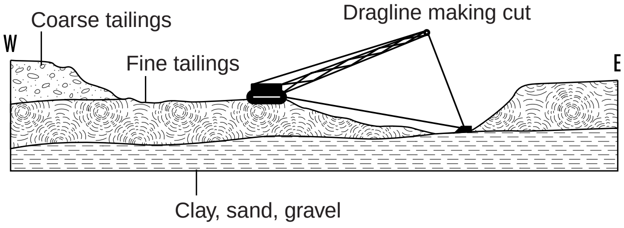

Figure 4. Mining schematic.

A typical production pit is 150–200 feet wide from the excavating side to the back-filling side, and is up to 400 feet in length. Tailings that have been mucked and stockpiled are reclaimed with a front-end loader. They are passed over a grizzly and conveyed to a 3/16-inch screen (fig. 5). Based upon a several-hundred-ton bulk sample extracted for pilot plant testing, the garnet occurs in the -3/16-inch fraction. Depending on the size fraction in the -3/16-inch cut, the garnet content ranges from 4.5% to 15.8%. Coarse reject from the 3/16-inch screen is utilized to backfill the pit by loader/truck combination. Mining and reclamation is concurrent, so as one side of the pit is mined, the opposite side is reclaimed.

Processing

The -3/16-inch material, containing approximately 8% garnet, is fed via a hopper to the jig and spiral plant for further upgrading (fig. 5). It is conveyed to the top of the plant and split on screens. The coarse split passes through rougher jigs, then cleaner jigs, and finally through a magnetic separator. The fine split passes through rougher spirals, cleaner spirals and a magnetic separator. Both splits are dewatered by a product sand screw. These beneficiation steps increase the garnet grade from approximately 8% to about 65% in the concentrate. Waste material from the jig and spiral plant is pumped via a slurry pipeline back to the pit.

The garnet concentrate is stockpiled adjacent to the jig and spiral plant. It is then hauled by truck to a stockpile adjacent to the wet processing plant. At several places in the process stream, material is moved by front-end loader and truck because of the lack of an adequate material-handling system such as conveyor belts. The concentrate (-3/16-inch) is then fed via a hopper to the wet plant for further upgrading. It is conveyed to the top of the plant and split on a double deck screen (8 and 16 mesh). The +8 mesh fraction (coarse) goes to rougher and cleaner jigs, while the -8 +16 mesh fraction (fines) are sent to a dewatering cyclone followed by hydroclassifers and tables. Both size fractions together go through a dewatering sand screw and onto a filter belt. Waste material from the wet plant is pumped via a slurry pipeline to settling ponds.

The garnet concentrate is next sent through a fluid-bed dryer and is conveyed to a bucket elevator that carries it to a product tower, which either feeds it to a high-intensity magnetic separator or to a surge tank. The concentrate contains about 95% garnet and 5% hornblende, staurolite, illmenite, and quartz after magnetic separation. It is then screened into size fractions before placement into individual storage tanks. The alluvial garnet product, when reclaimed from the tanks, is passed through a crusher (not shown in fig. 5) to provide increased angularity and sharp cutting faces. It is then conveyed to the quality control screen for final product sizing and blending into different products. The garnet product is placed in 50- and 100-pound bags and 4,000-pound supersacks for shipment predominately by truck. Nameplate capacity of the plant is 40,000 tons per year.

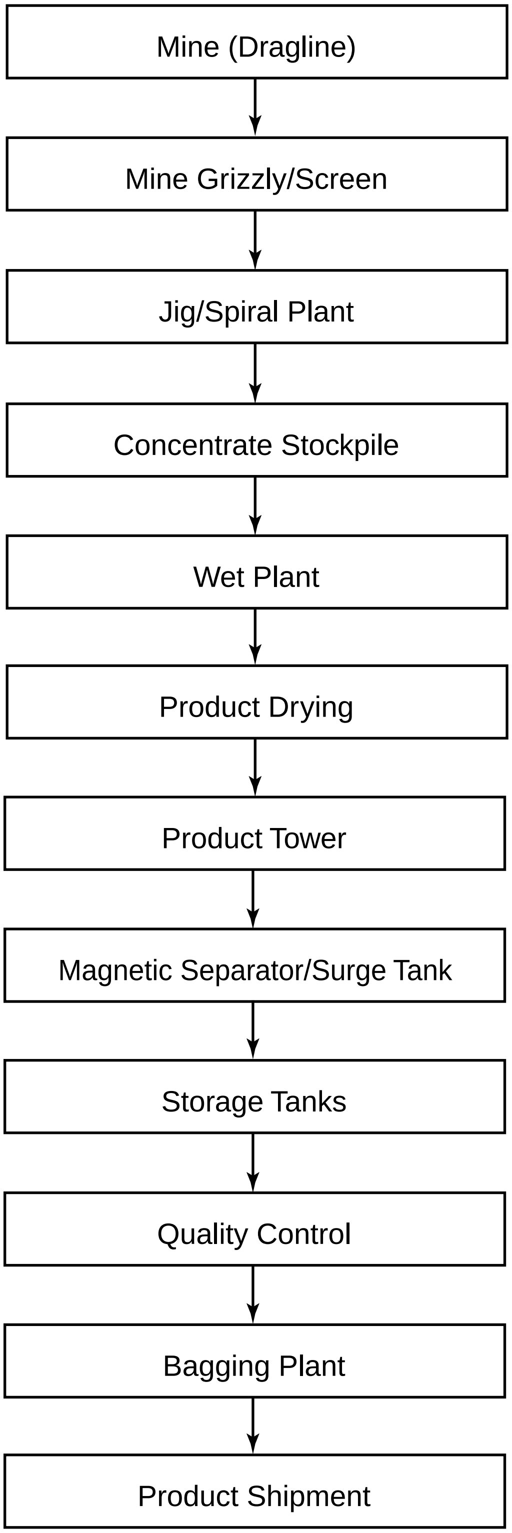

Figure 5. Mining/Processing flowsheet.

Markets

The almandine garnet from Ruby is characterized by the following commercial properties:

- Chemically inert
- Moh's hardness = 7.5–8
- Specific gravity = 3.8–4.2
- Angular to subangular particle shape
- Reusable
- Non-hydroscopic (no moisture gain)

These properties make garnet from Ruby useful in a number of applications. It is chemically inert and contains essentially no crystalline silica or leachable metals so health (silicosis) and environmental issues (metal dispersion) are minimized. The Ruby garnet is very hard, has a high specific gravity, and crystal fragments are angular to subangular. These characteristics yield fast waterjet cutting and rapid cleaning in abrasive blasting. The garnet gains no moisture ensuring free-flow during waterjet cutting. In abrasive blasting applications, three to four times as much silica sand is required compared to almandine garnet. Most of Ruby garnet sales are for waterjet cutting at a list price of $240/ton FOB mine; some has been sold for abrasive blasting and water filtration. Waterjet cutting has been the fastest growing market for garnet in the U.S. over the past few years. In waterjet cutting, garnet grains are entrained in a stream of high-velocity water (up to 55,000 psi). Waterjet cutting is used to shape-cut materials such as marble, granite, artificial stone, concrete, aluminum, titanium, steel, auto glass, textiles, corrugated box board, plastic laminates, and aerospace composites.

Abrasive blasting is a method to remove surface coatings and contaminates without changing the shape or texture of the surface being cleaned. It is used on structural steel (bridges, oil rigs, power station turbines, boilers, storage tanks, pipelines, ships, barges, railcars, aircraft, etc.) prior to painting.

Garnet is also used in multilayer water-filtration systems. It allows for more rapid and effective filtration and resets the bed faster than silica sand, resulting in a cost savings to end users.

North American garnet demand for 2002 is in table 2. Abrasive blasting is the largest demand sector at approximately 55,000 tons or about 2% of the estimated 2.75 million st annual abrasive mineral market in North America. Silica sand, at 1.55 million tons (56%), is the major abrasive utilized. Other materials that are used as abrasives include slags (coal, copper, nickel), staurolite, olivine, and steel. Garnet has high potential for replacing other blasting abrasives such as silica sand and slags. It does cost more than other blasting media, but this is justified through increased productivity and health and environmental benefits.

Growth in the waterjet sector will remain strong. The 15–20 % annual growth (partly tied to military spending) during the 1990s is probably gone, at least over the next few years.

Filtration demand for garnet will remain flat over the next few years. The "other uses" category in table 2 is mainly garnet for the electronics industry to polish television picture tubes. This sector may decline as emerging technologies, such as flat screens that require no garnet polishing, are widely adopted.

World annual garnet demand is estimated to be approximately 445,000 to 485,000 tons (Gorrill, 2003; Olson, 2003). North America is the largest market, followed by Australia, Europe, and Asia/Middle East respectively.

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Table 2. Garnet demand in tons in North America in 2002 (after Gorrill, 2003).

Abrasive blasting	55,000
Water-jet cutting	44,000
Filtration	16,500
Other uses	22,000
Total (tons)	137,500

High-Calcium Limestone Resources of Utah

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Abstract

Utah contains large deposits of high-calcium limestone, primarily in the western half of the state, which provide raw material for diverse mineral-processing operations. These limestone deposits are in Cambrian- to Holocene-age rocks; the most significant deposits are Cambrian, Devonian, and Mississippian shallow-marine rocks. These Paleozoic rocks generally do not crop out in eastern and southern Utah, where exposed units are predominantly clastic marine and terrestrial (including lacustrine). In eastern and southern Utah, Pennsylvanian, Permian, Triassic, and Jurassic units only locally contain high-calcium limestone. Tertiary lacustrine rocks in central and northeastern Utah contain a significant amount of moderate-quality limestone.

This report summarizes the results of a Utah Geological Survey compilation of 387 chemical analyses from 51 stratigraphic formations, which show that Utah contains large tonnages of high-calcium limestone. The compilation also contains information on 84 limestone quarries and prospects, many possibly containing high-calcium stone, that have been developed in Utah during the past 150 years. Many of these quarries were active in 2002, producing limestone for (1) portland cement raw material, (2) manufacture of masonry lime and quicklime, (3) flue-gas desulfurization, (4) smelter flux, (5) coal-mine rock dust, and (6) crushed stone and riprap.

Utah's above-average population growth rate should result in increasing demand for limestone; however, coal mine and smelter closures will eliminate some demand. Land-use conflicts, such as urbanization and withdrawal of federal land for special uses and environmental preservation, may locally preclude development of some high-calcium limestone deposits.

Introduction

Definition

High-calcium limestone (HI-CAL) is a sedimentary rock containing more than 95% calcium carbonate ($CaCO_3$). Limestone is a common rock type, forming 0.25% of the Earth's crust and 15% of the Earth's sedimentary rocks. The average limestone has the chemical composition listed in table 1. It has thousands of applications as a raw material constituent in construction, chemical, metallurgical, and other industries. It most commonly forms by precipitation of calcium carbonate from seawater by marine plants and animals. Limestone can also form in springs, in both fresh- and saltwater lakes, and as cave and vein-filling deposits, but volumes formed are often small and the limestone impure. Marine limestone deposits are the most economically important.

Table 1. Major oxide composition of average limestone in percent (from Carmichael, 1982).

SiO_2	5.19		Na_2O	0.05
TiO_2	0.06		K_2O	0.33
Al_2O_3	0.81		H_2O	0.77
Fe_2O_3	0.54		P_2O_5	0.04
MgO	7.89	(16.49 $MgCO_3$)	CO_2	41.54
CaO	42.57	(75.77 $CaCO_3$)	SO_2	0.05

HI-CAL is a high-purity form of limestone that is relatively uncommon. Even in Utah, which has abundant limestone, the percentage of HI-CAL that is economically exploitable is surprisingly small. To be commercially viable, HI-CAL deposits must be (1) readily mineable (large open-pit-mineable deposits in areas of low to moderate topographic relief are ideal), (2) close to transportation corridors and customers (HI-CAL is a low-unit-value commodity that cannot be economically shipped over great distances), (3) located on land that is available for mining (competing land uses such as residential development and government land mineral withdrawals often preclude limestone development), and (4) sufficiently large to support a mining operation for a long period of time (lime or cement plants, major users of HI-CAL, have life spans that often exceed 50 years and need reliable supplies of uniform raw material).

Uses for High-Calcium Limestone

Limestone has more uses than any other geologically derived material and is used in the manufacture of many of our material possessions. There is a voluminous body of literature dealing with these uses; good basic descriptions are contained in Buie and Robinson (1958), Stowell (1963), Rooney and Carr (1971), Boynton (1980), Carr and Rooney (1983), Boynton and others (1983), Carr and others (1994), Ciullo (1996), and Oates (1998). Most of Utah's limestone has been mined for the following uses: aggregate and construction stone, portland cement, chemical lime, metallurgical flux, coal-mine rock dusting, flue-gas desulfurization, masonry mortar, and sugar processing. A list of large Utah consumers, or potential consumers, of HI-CAL for non-aggregate use is presented in table 2 and their locations are plotted on figure 1.

Purpose and Scope of the Project

The Utah Geological Survey (UGS) compiled information on the limestone resources of Utah because: (1) little information has been published, (2) the available information is scattered throughout obscure and unpublished sources, (3) there is growing demand for HI-CAL, and (4) federal, state, and local resource managers need up-to-date

Table 2. Utah industrial operations that are current or potential large users of high-calcium limestone or lime. Information on coal mine locations is from the Utah Division of Oil, Gas and Mining (2003). Operations are arranged in geographic order from north to south. Location numbers correspond to those on figure 1.

Loc. No.	Facility	Owner	Sec	T	R	UTM(N)	UTM(E)	Operation Type
1	Nucor	Nucor	09	13N	03W	4637450	400840	Steel mini-mill
2	Devil's Slide	Holcim Inc.	19	04N	04E	4545420	455330	Cement plant
3	Lakeside	Utah Marblehead	02	01N	09W	4523780	345820	Dolo. refractory plant (inactive)
4	Kennecott	Kennecott Utah Copper Co.	20	01S	03W	4508650	399050	Copper smelter
5	Stansbury Mts.	Chemical Lime of Arizona	25	01S	07W	4506560	366960	Dolomitic lime plant
6	Geneva	Geneva Steel LLC	5, 8, 17	06S	02E	4463000	436800	Steel smelter (inactive)
7	Bonanza	Deseret Generation and Transmission	01	11S	24E	4417000	656000	Coal-fired power plant
8	Willow Creek	Cyprus Plateau Mining Co.	31	12S	10E	4398230	513120	Coal mine (inactive)
9	Carbon	Pacificorp	01	13S	09E	4397300	511700	Coal-fired power plant
10	Centennial	Andalex	07	13S	11E	4395100	523390	Coal mine
11	Horizon	Horizon Coal Co.	17	13S	08E	4393600	495570	Coal mine (inactive)
12	Skyline	Canyon Fuel LLC	13	13S	06E	4392440	482340	Coal mine
13	Dugout	Canyon Fuel LLC	23	13S	12E	4392380	539100	Coal mine
14	West Ridge	West Ridge Resources, Inc.	14	14S	13E	4384100	549100	Coal mine
15	Leamington	Ash Grove Cement	33	14S	03W	4379850	397300	Cement plant
16	Sunnyside	Sunnyside	06	15S	14E	4377600	552090	Coal-waste cogeneration
17	IPP	Consortium	24	15S	07W	4374040	364090	Coal-fired power plant
18	Crandall Canyon	Genwal Resource, Inc.	05	16S	07E	4367700	485680	Coal mine
19	Horse Canyon	Utah American Energy, Inc.	03	16S	14E	4368200	555500	Coal mine (inactive)
20	Bear Canyon	Co-op Mining Co.	24	16S	07E	4362130	491810	Coal mine
21	Huntington	Pacificorp	01	17S	07E	4358700	493320	Coal-fired power plant
22	Deer Creek	Pacificorp	10	17S	07E	4356260	490020	Coal mine
23	Hunter	Pacificorp	16	19S	08E	4335960	497520	Coal-fired power plant
24	Cricket Mts.	Graymont	01	22S	09W	4310750	343090	High-calcium lime plant
25	Sufco	Canyon Fuel LLC	12	22S	04E	4307280	463880	Coal mine
26	Emery Deep	C&P Coal Co.	33	22S	06E	4301110	477870	Coal mine

information for land-use management. Even though limestone production has been an important part of Utah's industrial sector since the arrival of settlers starting in 1847, very little published information is available on this commodity. As part of its mission, the UGS seeks to encourage prudent economic development of Utah's resources to help meet the needs of the rapidly increasing population in the western United States. Presently, exploration geologists who site new HI-CAL quarries must spend weeks winnowing through large volumes of general geological information to find relevant data. The UGS's limestone compilation is designed to shorten their library research and make it more productive. The State of Utah owns large limestone resources distributed across the state on School and Institutional Trust Lands and receives substantial revenue from them. The state-owned HI-CAL resources have not been thoroughly inventoried to allow the Utah School and Institutional Trust Lands Administration to maximize income from these resources for the benefit of Utah schools. Finally, federal, state, and local governments lack adequate information to critically evaluate the significance of their important land-use decisions on the potential development of limestone resources.

This compilation was designed to provide basic information on the most important geologic and infrastructure factors that should be considered when siting a new limestone quarry, such as: (1) data on existing pits and prospects, (2) chemical analyses of limestone from various geologic formations, (3) the extent and spatial distribution of geologic formations that have good potential for HI-CAL production, and (4) locations of cement and

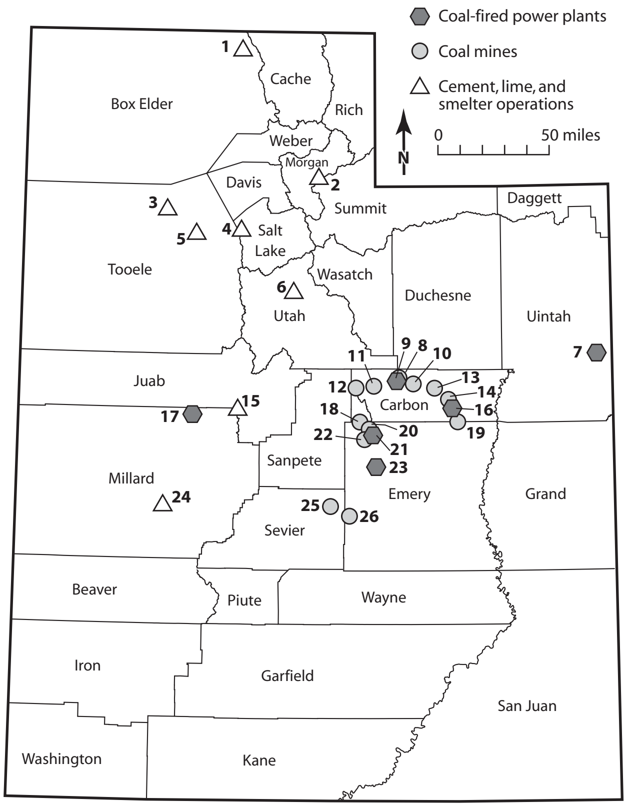

Figure 1. Large, non-aggregate industrial users or potential users of high-calcium limestone or lime in Utah. Numbering corresponds to information in table 2.

lime plants, electric power plants, coal mines, and metal smelters which are large consumers of HI-CAL.

The scope of the UGS study was limited due to the enormous volume of carbonate rock in the state; not every carbonate formation was evaluated. The UGS only compiled information on rock units that were thought to have potential for HI-CAL. Specifically, cement rock was not included in the study. Cement rock is a type of limestone that naturally contains the right amounts of calcium carbonate, alumina, silica, and iron to be used, with few additives, in the production of portland cement. Calcite-vein deposits also were not included. These are often high-purity calcium carbonate, but are usually small and are better suited for small niche markets such as poultry grit, terrazzo chips, rock mulch, and decorative stone in landscape use. Additionally, dolomite resources were not included. Dolomite is a rock type similar to limestone, but contains a large amount of magnesium carbonate. Some information on cement rock, calcite veins, and dolomite is contained in the following references: Eckel (1913), Dennis (1930), Buranek (1945), Crawford and Buranek (1948), Bullock and Okerlund (1951), Okerlund (1951), Nackowski and Levy (1959), Bullock (1962), Norman and Thompson (1963), Morris (1969), Doelling (1971), Minobras (1974), and Tripp (2001).

This report is a condensed version of a UGS report by Tripp (in prep.) which includes detailed analytical information for 387 limestone samples, a 1:750,000-scale map showing limestone and infrastructure data, and a CD containing spreadsheet and GIS versions of all data in the report. Most of the data for this report were compiled before 1997, so some data released later may not be included.

Methods

Data were gathered from publications, geologic maps, UGS databases and files, unpublished company files and reports, field investigations, and communications with industry personnel. Most of the limestone quarry and prospect data listed in table 3, and shown on figure 2, were extracted from the Utah Mineral Occurrence System database compiled by the UGS in cooperation with the U.S. Bureau of Land Management and the U.S. Geological Survey. Additional data were added from the Utah Division of Oil, Gas and Mining permitted mines database. The analytical data summarized in tables 4 and 5 were compiled from published and unpublished reports and UGS field sampling. The original analytical data are not included in this report due to space limitations. The Universal Transverse Mercator (UTM) locations for the sample points were measured manually from 1:24,000-scale topographic maps; inclusion of UTM coordinates allows accurate reporting of analytical data locations and use of this data in GIS systems. The figures in this report were compiled using ArcView (software from ESRI, Inc.) and (1) themes from the Utah Automated Geographic Reference Center, (2) the digital geologic map of Utah (Hintze and others, 2000), and (3) point data from tables 2 and 3.

Most of the analytical data included in the study were gleaned from published reports, UGS files, and unpublished company reports; some sampling and analysis was done by the UGS. No information is available for most of the analytical data concerning analytical methods used and the accuracy of those methods. Therefore mine development decisions should not be based solely on these data. Available analytical information for some samples containing 85 to 94% calcium carbonate are included in table 4 even though they are not HI-CAL. The rationale for including these analyses is that more detailed sampling around the original sample location could result in discovery of HI-CAL, and in areas where HI-CAL is rare, lower quality stone might be useable. A few samples containing less than 85% $CaCO_3$ were left in the database when they were part of a sampled stratigraphic section that had other samples exceeding 85% $CaCO_3$. The available assay data include a wide range of different major oxides and trace elements; however, each source of analytical data reported a different suite of major and trace elements. In some cases, only the percentage of acid-insoluble minerals in the sample was reported. Acid-insoluble data are inadequate to determine whether the limestone is useable in a specific process, but they may help limestone explorationists to focus their investigations.

Previous Work

Most of the specific data on HI-CAL in Utah were collected by prospectors and private companies; unfortunately, much of this information has been lost or is confidential. Available company and prospector information is contained in USX (1950, 1953, and 1957), Gin (1958), Hodgson (1974), Minobras (1974), Amodt and Sharps (1978), Madsen (1986), and Reed (1996).

Other data have been published by federal and state government agencies and universities. Federal government publications by the former U.S. Bureau of Mines for wilderness evaluation and other land-use planning efforts include Satkoski and Sokaski (1980), Almquist (1987), Brown (1987), Tuftin (1987), Wood (1987), Zelten (1987), Kness (1989), Munts (1989), Neumann (1989), and Hannigan (1990). Other federal government reports containing limestone information are Smith and others (1963), Morris (1969), and Abbay (1990). State data sources that discuss HI-CAL include Buranek (1945), Crawford and Buranek (1948), Godek (2003), Kaliser (1969), Pratt and Callaghan (1970), Tripp (1985, 1991, 1997, 2001), Willis (1994), and UGS file material. University theses and publications that discuss HI-CAL are Clark (1954), Kiersch (1955), and Eliason (1969).

Results of Investigation

Limestone Quarries of Utah

The 84 limestone workings documented in Utah are listed in table 3 and their locations are shown in figure 2. They range in size from small test pits that never were commercially produced, to large quarries that have been

Table 3. Limestone quarries and prospects in Utah, listed alphabetically by site name; only properties with workings are listed, and limestone properties developed for building stone, decorative stone, natural cement rock, or vein calcite are omitted. Crushed stone operations are included if they may have potential for HI-CAL. Locations of these workings are plotted on figure 2. "Site Names" of some of the more significant workings are emphasized with bold type. The table heading "Quadrangle" refers to the 7.5-minute U.S. Geological Survey topographic map where the working is located. Cadastral locations (Sec, T, R) are all related to the Salt Lake Base Line and Meridian survey. "UTM(N)" and "UTM(E)" headings represent the Universal Transverse Mercator (UTM) coordinate (northing and easting in meters) in zone +12. UTM locations are to the centers of the workings.

Loc. No	Site Name	Geologic Formation	Quadrangle	Sec, T, R	UTM(N)	UTM(E)
1	**Agnes and Betty Claims** (Alsop Claims)	Camb. Swasey, Dome, and Howell Ls.	Candland Spring	19, 21S, 09W	4314800	335000
2	**Asarco**	Miss. Great Blue Ls.	Fivemile Pass	10, 8S, 3W	4443690	399999
3	Ashley	Penn. Morgan Fm.	Dyer Mtn.	06, 02S, 21E	4503730	617080
4	Bear Lake	Camb. Bloomington Fm.	Garden City	26, 14N, 04E	4641350	461225
5	Beaver Mtn.	Camb. Bloomington Fm.	Tony Grove Creek	08, 14N, 04E	4645830	456230
6	Burnt Canyon	Penn. Oquirrh Gp.	Saratoga Springs	03, 06S, 01W	4463790	420290
7	Canyon Rim	Tri. Thaynes Fm. Jur. Twin Creek Ls.	Sugar House	25, 01S, 01E	4506000	433400
8	Cat Hill NE	Miss. undiff.	Soldiers Pass	07, 08S, 01W	4443600	415310
9	Cat Hill North	Miss. undiff.	Soldiers Pass	06, 08S, 01W	4443850	414920
10	Chaffin	Miss. Great Blue Ls. Miss. Humbug Fm. Dev. Victoria Fm.	Santaquin	08, 10S, 01E	4424000	427440
11	Cherry Hill Park (Beaver Creek)	Tert. Flagstaff Lst.	Kyune	36, 11S, 08E	4408210	501270
12	Chief Lime	Miss. Fitchville and Gardison Fms.	Eureka	04, 10S, 02W	4425670	407980
13	Chimney Rock	Tert. Flagstaff Ls.	Kyune	33, 11S, 09E	4407550	505850
14	Chocolate Peak	Miss. Great Blue Ls.	Honeyville	04, 11N, 02W	4619680	409970
15	Clyde Knoll	Miss. Humbug Fm.	Soldiers Pass	08, 08S, 01W	4443060	418000
16	Cottonwood	Tert. Green River Fm.	Richfield	24, 23S, 03W	4294100	405620
17	Cove Travertine (Travertine Cove)	Quat./Tert. marly ls.	Antelope Valley	05, 25S, 07W	4281070	354851
18	Cruz	Camb. White Marker Mbr. of the Wah Wah Summit Fm.	Cruz	04, 23S, 09W	4301000	338450
19	Deseret No. 1	Miss. Deseret Ls.	Fivemile Pass	09, 08S, 03W	4442820	398900
20	**Diamond Mtn. Resources**	Miss. Madison Ls.	Burnt Cabin Gorge	15,16,21, 01S, 22E	4509200	631250
21	Dodd's Hollow	Penn. Morgan Fm.	Dyer Mtn.	06, 02S, 21E	4502620	617860
22	Ekins East	Miss. Deseret Ls.	Santaquin	04, 10S, 01E	4424680	429290
23	Emigration Canyon	Jur. Twin Creek Ls.	Fort Douglas	11, 01N, 01E	4511400	432510
24	Enoch Ridge	Penn. Oquirrh Gp.	Soldiers Pass	01, 07S, 01W	4454800	423210
25	Evans	Quat. travertine	Jordan Narrows	27, 04S, 01W	4477480	419810
26	Flat Canyon	Miss. Great Blue Ls.	Honeyville	09, 11N, 02W	4617010	410270
27	**Flatiron**	Camb. Dome Ls.	Candland Spring	26, 21S, 10W	4313550	332100
28	Flux and South Flux	Miss. Great Blue Ls.	Flux	05, 08, 02S, 06W	4503100	368600
29	Georges Pass	Camb. White Marker Mbr. of the Wah Wah Summit Fm.	Cat Canyon	04, 23S, 09W	4300325	337150
30	Goshen Hill	Miss. Humbug Fm. Miss. Deseret Fm.	Santaquin	34, 09S, 01E	4427500	430160
31	Gracie D	Miss. Great Blue Ls.	Ophir	11, 06S, 04W	4463000	393450
32	Great Blue No. 1	Miss. Great Blue Ls.	Fivemile Pass	09, 08S, 03W	4443570	398710
33	Great Blue No. 2	Miss. Great Blue Ls.	Fivemile Pass	09, 08S, 03W	4443850	398950
34	Great Blue No. 3	Miss. Great Blue Ls.	Fivemile Pass	09, 08S, 03W	4444210	399400
35	Green Canyon No. 2	Ord. Garden City Fm.	Smithfield	19, 12N, 02E	4624450	436660
36	Gunnison Reservoir	Tert. Flagstaff Ls.	Sterling	21, 18S, 02E	4342240	438900
37	Hical #1	Tert. Sage Valley Ls. Mbr. of Golden's Ranch Fm.	Sugarloaf	24, 13S, 02W	4391300	414900
38	Ironton North	Miss. Humbug Fm. Miss. Deseret Ls.	Springville	17, 07S, 03E	4451400	446930
39	Ironton South	Miss. Deseret Ls.	Springville	17, 07S, 03E	4451200	447150
40	**Keigley**	Camb. Herkimer Ls. Camb. Teutonic Ls.	West Mountain	27, 09S, 01E	4429100	430900
41	Lakeside Mountain	Miss. undifferentiated	Puddle Valley Knolls	19, 03N, 09W	4538570	340550
42	Lakeside No. 1	Miss. Great Blue Ls.	Strongs Knob	21, 06N, 09W	4564900	342500
43	Lakeside No. 2	Miss. Great Blue Ls.	Lakeside	22, 06N, 09W	4564700	344250
44	**Leamington**	Camb. Swasey, Dome, and Howell Ls.	Champlin Peak	33, 14S, 03W	4379010	397950
45	**Lehi Quarry**	Miss. Great Blue Ls.	Jordan Narrows	16, 05S, 01W	4470896	418748
46	Limekiln Gulch North	Penn. Morgan Fm.	Fort Douglas	28, 01N, 01E	4515260	428980
47	Limekiln Gulch South	Penn. Morgan Fm.	Fort Douglas	33, 001N, 001E	4514640	429120
48	Lime Ridge	Penn. Honaker Trail Fm.	San Juan Hill	16, 41S, 20E	4119400	613000
49	Limestone Mesa	Tri. Moenkopi Fm.	Virgin	29, 41S, 12W	4118220	302280

continued

50	Little Canyon North	Miss. Great Blue Ls.	Soldiers Pass	31, 06S, 01E	4455610	425290
51	Little Creek	Tert. Green River Fm.?	Randolph	14, 11N, 06E	4615280	480400
52	Little Mountain	Miss. Great Blue Ls.	Flux	20, 02S, 06W	4498950	369450
53	Lofgreen No. 1	Miss. Humbug Fm.	Lofgreen	24, 08S, 05W	4439802	384350
54	Lofgreen No. 2	Miss. Great Blue Ls.	Lofgreen	35, 08S, 05W	4436310	383120
55	Lofgreen No. 3	Miss. Great Blue Ls.	Lofgreen	02, 09S, 05W	4436250	382950
56	Lofgreen No. 4	Miss. Great Blue Ls.	Lofgreen	35, 08S, 05W	4436530	383050
57	Lofgreen No. 5	Miss. Great Blue Ls.	Lofgreen	02, 09S, 05W	4436104	383100
58	Lofgreen No. 6	Miss. Great Blue Ls.	Lofgreen	02, 09S, 05W	4436203	383705
59	Lofgreen No. 7	Miss. Great Blue Ls.	Lofgreen	02, 09S, 05W	4436204	383530
60	Lofgreen Prospect	Miss. Humbug Fm.	Lofgreen	24, 08S, 05W	4440370	384480
61	Magcorp	Holo. oolites	Badger Island	02N, 07-08 W 03N, 06-07W	4531000	355300
62	Mammoth	Camb. Teutonic Ls.	Tintic Junction	25, 10S, 03W	4420450	403620
63	Mercur Canyon	Miss. Great Blue Ls.	Mercur	07, 06S, 03W	4463700	395650
64	**Metz Hollow**	Miss. Lodgepole Ls.	Morgan	31, 04N, 03E	4543554	444516
65	MH-1 Calcite	Tert. Salt Lake Fm.	Sabie Mtn.	35, 09S, 04W	4426696	392702
66	Midway Tufa	Quat. tufa	Heber City	35, 03S, 04E	4485520	460480
67	North Slope	Miss. Great Blue Ls.	Jordan Narrows	08, 05S, 01W	4471700	417459
68	**Papoose**	Penn. Honaker Trail Fm.	Lisbon Valley	36, 29, 5S, 24E	4231290	653890
69	**Pelican Point**	Miss. Deseret Ls.	Pelican Point	31, 06S, 01E	4456230	425940
70	**Poison Mtn.**	Camb. Dome Ls.	Candland Spring	25, 21S, 10W	4312875	333180
71	**Poverty Point**	Miss. Great Blue Ls.	Poverty Point	16, 21, 01N, 08W	4519110	353030
72	Powder Knoll	Miss. Great Blue Ls.	Fivemile Pass	03, 08S, 03W	4444840	400140
73	Providence	Miss. Brazer Ls.	Logan Peak	16, 11N, 02E	4615400	439000
74	**Redmond Limestone**	Tert. Flagstaff Ls.	Redmond	08, 21S, 01E	4317200	428020
75	Red Warrior (Beaver Dam)	Miss. Redwall Ls.	Jarvis Peak	02, 43S, 18W	4106060	248400
76	**Round Valley Rock**	Miss. upper mbr. of Doughnut Fm.	Morgan	29, 04N, 03E	4544793	446244
77	Sage Creek	Tert. Green River Fm.?	Sage Creek	13, 12N, 06E	4625410	482090
78	TAD 5,7	Miss. Redwall Ls.	Jarvis Peak	23, 42S, 18W	4111050	248740
79	The Goosenecks	Penn. Hermosa Gp.	Mexican Hat	10, 42S, 18E	4111710	595830
80	Three Sisters	Miss. Deseret Ls. and Humbug Fms.	Springville	27, 07S, 03E	4447700	449550
81	Topaz Valley	Ord. Garden City Fm. of the Pogonip Gp.	Topaz Mtn. 15'	21, 13S, 11W	4393200	320750
82	**Travertine #1**	Holo. travertine	Champlin Peak	14, 14S, 03W	4383981	400802
83	**USSR & M**	Miss. Great Blue Ls.	Fivemile Pass	05, 08S, 03W	4444780	398180
84	Victory Road	Miss. Madison Ls.	S. L. City N.	25, 01N, 01W	4516100	42420

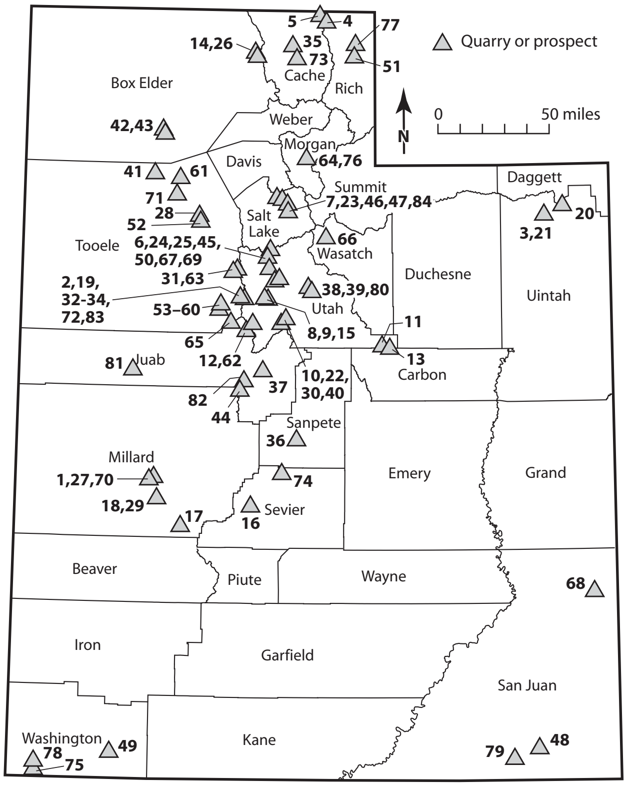

Figure 2. Limestone quarries and prospects of Utah. Numbering corresponds to information in table 3.

mined for decades. A substantial number of small, obscure, abandoned limestone prospects, especially from the era of European immigration, are not included in table 3.

Geologic Units with High-Calcium Limestone Potential

Tables 4 and 5 list more than 50 known or probable HI-CAL limestone-bearing formations based on 387 chemical analyses and general knowledge of the lithologies of these formations. Approximate areal extent of these formations is shown on figure 3. Paleozoic units have the best potential for HI-CAL, followed by Cenozoic rocks; Mesozoic rocks have the lowest potential. The outcrops on figure 3 are derived from a 1:500,000-scale digital geologic map of Utah (Hintze and others, 2000), which "lumps" individual formations into packets, such as Lower Mississippian. This lumping causes the HI-CAL outcrops to appear more extensive than they actually are. This is especially true of the Mesozoic units; only a small percentage of the Mesozoic outcrops shown in figure 3 probably contain HI-CAL.

Of the Paleozoic rocks, the Cambrian, Devonian, and Mississippian units contain most of the best HI-CAL resources in Utah. These units are exposed at the surface primarily in western Utah and on the flanks of the Uinta Mountains of northeast Utah. Some of these units have hundreds of feet of strata that assay more than 95% $CaCO_3$ with mineable thicknesses exceeding 97% $CaCO_3$. Outcrops

Table 4. Geologic formations known or inferred to contain HI-CAL resources based on $CaCO_3$ content. The formations are organized from youngest to oldest.

Fm. Age and Name	No. of Samples	Percent $CaCO_3$ High	Low	Mean
Holo. Spring tufa	1	89.23	89.23	89.2
Holo. Great Salt Lake oolites	1	91.47	91.47	91.5
Tert. Salt Lake Fm.	3	96.4	88.6	92.8
Tert. Green River Fm.	3	97.69	94.7	95.9
Tert. Flagstaff Ls.	24	98.61	91.0	95.6
Jur. Carmel Fm.	13	94.57	86.7	89.9
Jur. Kayenta Fm.	1	85.64	85.64	85.6
Tri. Moenkopi Fm.	2	89.2	88.6	88.9
Pal. undiff.	1	86.2	86.2	86.2
Perm. Park City Fm.	1	94.62	94.62	94.6
Perm. Kaibab Fm.	2	91.7	91.1	91.4
Perm./Penn. Oquirrh Gp.	1	92.63	92.63	92.6
Penn. Wells Fm.	1	93.63	93.63	93.6
Penn. Honaker Trail Fm.	4	92.1	87.8	89.7
Miss. Doughnut Fm.	5	98.4	90.8	93.6
Miss. Great Blue Ls.	18	100.05	72.9	90.9
Miss. Fm. of Rose Spring Cyn.	2	94.2	84.7	89.5
Miss. Humbug Fm.	11	99.9	90.0	95.7
Miss. Brazer Dol.	1	89.8	89.8	89.8
Miss. Deseret Ls.	8	97.9	91.63	95.2
Miss. Gardison Ls.	55	98.61	87.2	92.1
Miss. Joana Ls.	2	98.4	97.4	97.9
Miss. Lodgepole Ls.	11	100.0	91.0	95.6
Miss. Redwall Ls.	1	99.4	99.4	99.4
Miss./Dev. Fitchville Fm.	8	97.79	86.9	94.4
Dev. Beirdneau Ss.	6	98.0	89.8	94.3
Dev. Hyrum Dol.	11	99.1	90.0	96.0
Dev. Guilmette Fm.	10	99.4	91.3	96.6
Ord. Pogonip Gp.	2	94.5	93.94	94.2
Ord. Garden City Fm.	2	89.21	94.50	91.9
Ord. Opohonga Ls.	1	91.4	91.4	91.4
Ord./Camb. St. Charles Fm.	1	90.14	90.14	90.1
Camb. undiff.	31	95.05	87.9	91.1
Camb. Orr Fm.	3	94.6	92.3	93.7
Camb. Wah Wah Summit Fm.	18	98.1	91.0	96.6
Camb. Trippe Ls.	1	86.2	86.2	86.2
Camb. Trippe Ls. and Pierson Cove Fm. undiff.	2	92.84	90.80	91.8
Camb. Cole Canyon Dol.	1	96.9	96.9	96.9
Camb. Marjum Fm.	1	89.00	89.00	89.0
Camb. Pierson Cove Fm.	2	94.0	86.9	89.6
Camb. Bluebird Dol.	1	97.9	97.9	97.9
Camb. Eye of Needle Ls.	1	96.7	96.7	96.7
Camb. Dome Ls.	19	99.36	88.9	96.0
Camb. Howell Ls.	4	98.56	95.76	97.2

Table 5. Geologic formations known or inferred to contain HI-CAL resources based on acid-insoluble mineral content. The formations are organized from youngest to oldest. Generally the lower the acid-insoluble residue, the greater the possibility that the rock is HI-CAL.

Fm. Age and Name	No. of Samples	Percent Insolubles High	Low	Mean
Tert. Brian Head Gp.	7	2.68	7.07	5.1
Tert. Claron Fm.	43	1.73	9.15	4.7
Jur. Carmel Fm.	6	3.29	9.94	7.1
Tri. Moenkopi Fm.	28	3.40	9.39	7.2
Miss. Deseret Ls.	1	3.17	3.17	3.2
Miss. Gardison Ls.	3	1.15	3.64	2.5
Miss./Dev. Fitchville Fm.	2	0.88	1.16	1.0

in southeastern Utah are predominantly of Pennsylvanian age or younger and thus have limited HI-CAL potential. Pennsylvanian and Permian marine limestones in the area are mostly impure, but contain some thin, lower grade beds that have been mined to supply local needs. An example is the Papoose quarry (see quarry no. 68, table 3 and fig. 2) in Lisbon Valley that exploits a unit in the Pennsylvanian Honaker Trail Formation of the Hermosa Group. This deposit is not impressive, but the scarcity of limestone in the area and its proximity to a point of use (the Nucla, Colorado electric power plant) make it economically viable.

Mesozoic rocks primarily occur in central, southern, and eastern Utah and contain only a few, mostly impure limestones such as the Triassic Virgin Limestone and Sinbad Limestone Members of the Moenkopi Formation and parts of the Jurassic Carmel and Curtis Formations. No Cretaceous formations are known to contain HI-CAL.

Cenozoic rocks contain some significant HI-CAL resources. Tertiary lacustrine sediments contain large volumes of limestone in central and northeastern Utah. The principal Tertiary units are the Flagstaff Limestone, Claron Formation, and Salt Lake Formation; these units are not generally as pure as Paleozoic marine limestones. Few beds in Tertiary units exceed 95% $CaCO_3$. There are also small Quaternary limestone resources in Utah that are locally important, such as MagCorp's use of Holocene oolites from Great Salt Lake.

There is no complete list of all formations known to host HI-CAL because no systematic sampling of limestone has been done in Utah. Tables 4 and 5 list all geologic formations known or inferred to have potential for HI-CAL production based on limited, available analytical data. Some other formations, explored by the pits and quarries listed in table 3, probably also contain HI-CAL, but no analytical data are available.

Future of Utah Limestone Development

Because limestone usage closely tracks residential and commercial construction, the amount of limestone mined in Utah should steadily increase to match the trend of increasing population in the western U.S. The Utah Governor's Office of Planning and Budget projects that Utah's population will increase about 60% between 2003 and 2030 (Governor's Office of Planning and Budget, 2003). One potential negative factor affecting limestone production is the eventual decrease in coal mining in Utah and the decline in metal mining and refining in the western United States. Most of the thick coal with moderate overburden that can be mined economically under current conditions will be mined out by about 2050 (David Tabet, UGS, personal commun., April 2003). Mining will continue, probably at a reduced rate, on thinner, deeper coal, so the market for coal-mine rock dust will be flat to slightly down for the long term. Geneva Steel LLC is in bankruptcy and has ceased making steel, so the local market for limestone flux disappeared. Kennecott Utah Copper Company announced that the Bingham Mine has enough reserves that can be mined by open-pit methods to permit open-pit mining to continue at its present rate until 2013.

Kennecott may then turn to underground mining of higher grade vein and skarn copper ore, probably with a sizable drop in tonnage of ore processed and consequently the amount of limestone needed for treatment of tailings pond water. Some additional limestone, however, will be used for Kennecott's groundwater pumping and treatment program. The underground mining is anticipated to last until 2028 (Rio Tinto, 2001). Heap leaching of gold in Nevada uses large amounts of lime mainly for controlling pH of the leach liquor; many large Nevada gold mines will be exhausted in the next 20 years and the market for chemical lime will decrease. Another potential negative for limestone quarry development is government withdrawal of land from mineral development. Figure 4 shows mostly federal land in Utah unavailable for limestone development.

Summary

More than 350 samples taken from 51 sedimentary formations across Utah show that the state has large tonnages of high-calcium limestone. The best material is contained in Cambrian, Devonian, and Mississippian formations of

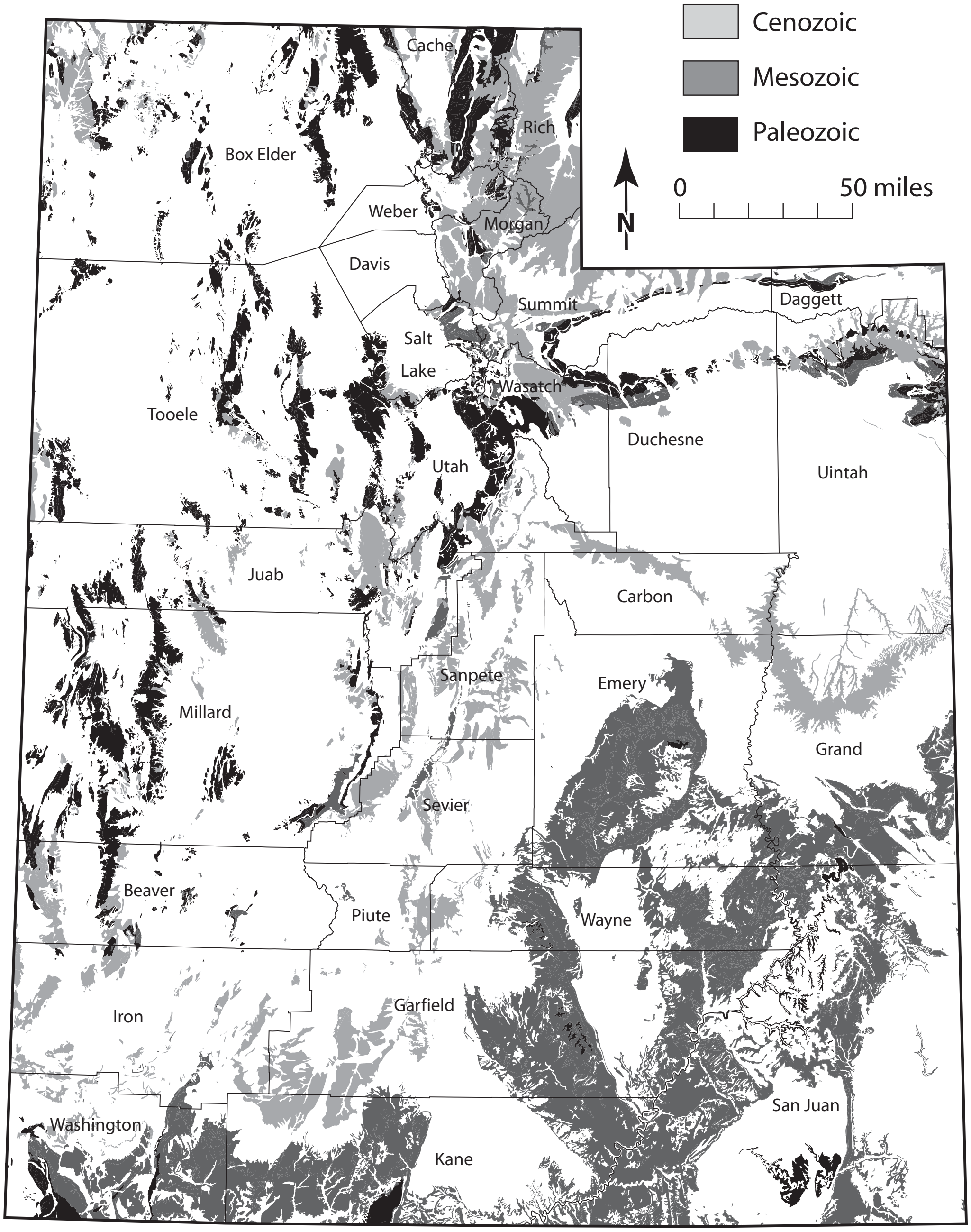

Figure 3. Extent of strata in Utah that potentially contain high-calcium limestone (after Hintze and others, 2000).

western Utah. Tertiary lacustrine formations contain a significant resource of moderate-quality limestone in the central and northeast parts of the state. Upper Paleozoic and Mesozoic rocks of Utah locally contain a small amount of moderate-quality limestone. Limestone has been prospected or produced from more than 84 quarries and pits across Utah for use in (1) portland cement raw material, (2) manufacture of masonry lime and quicklime, (3) flue-gas desulfurization, (4) smelter flux, (5) coal-mine rock dust, and (6) crushed stone and riprap. While some industrial uses for limestone may decrease in the future, overall demand for limestone is expected to increase because of commercial and residential construction that will track Utah's above-average rate of population growth.

Acknowledgments

Much of the examination and description of the limestone quarries and prospects took place during the U.S. Geological Survey and U.S. Bureau of Land Management sponsored Computerized Resources Information Bank (CRIB) mineral inventories from 1975 to 1987; the geologists who conducted the examinations are listed as follows (in order of number of properties described): Bryce Tripp, Charles

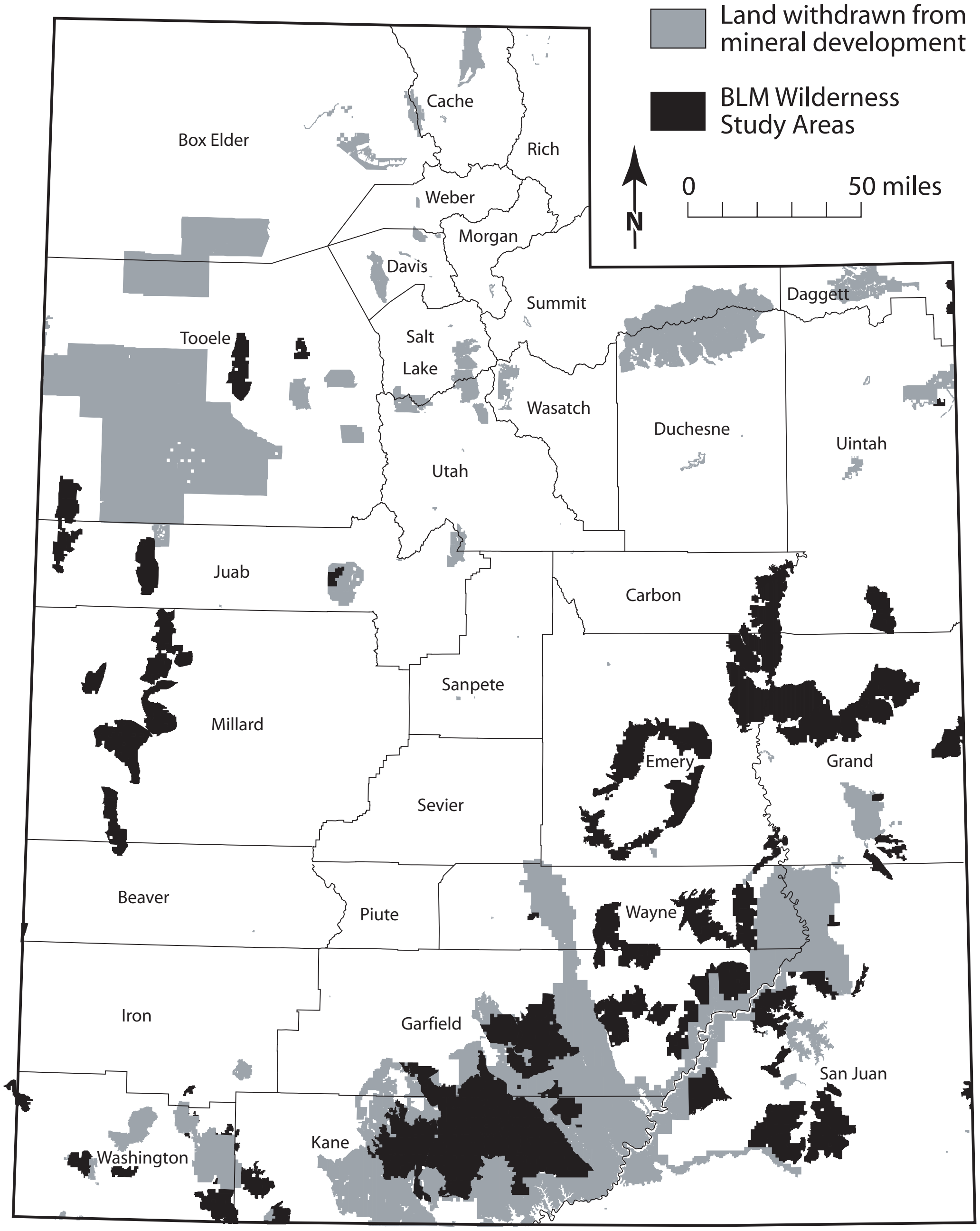

Figure 4. Areas of Utah currently withdrawn from mineral development and U.S. Bureau of Land Management Wilderness Study Areas, currently managed for no mineral development.

Bishop, Mike Everts, Hasan Mohammad, Blair McCarthy, Hellmut Doelling, Robert Dollar, Larry James, Harry Messenger III, Steve Sommer, and Larry Trimble.

A number of geologists provided information on Utah limestone including: Keith Hayes, Thomas Sharps, Jack Madsen, Henry Reed, and Stanley Krukowski. Reviews by Dennis Bryan, Jon King, Stanley Krukowski, Terry Massoth, Dick Meeuwig, and David Tabet improved the quality of this report.

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Asbestos-Bearing Talc Deposits, Southern Death Valley Region, California

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Abstract

Beginning in 1910, at least 43 talc deposits have been prospected and mined from occurrences scattered throughout several mountain ranges that surround the southern part of Death Valley, California. Until 1988, talc was mined from deposits that are now part of Death Valley National Park. Talc mining is still being conducted in the Kingston Range, east of the Park. Death Valley talc has been used in wall tile, as an extender in paints, and in cosmetics.

The southern Death Valley talcs are talc-tremolite deposits that are geologically similar across the region; they are consistently associated with a carbonate horizon of the Crystal Spring Formation of Proterozoic age. In this interval, thick regionally persistent gabbroic sills intruded dolomite during the Mesoproterozoic, and formed laminated talc-tremolite-rich rock along the sill-dolomite contacts. Metasomatic reactions during sill emplacement caused the massive replacement of dolomite by talc-tremolite-rich bodies, which are approximately 500 to 5,000 feet long and 10 to 100 feet thick. Relative proportions of talc versus tremolite vary across the deposits and either mineral can predominate within any particular deposit. Our petrographic examinations of the ore suggest the talc and tremolite were co-genetic.

Samples of talc-tremolite rock were collected by the lead author in the Alexander Hills-Kingston Range region, located east of southern Death Valley National Park. The samples were analyzed by X-ray diffraction and examined by scanning electron microscopy accompanied by energy-dispersive x-ray analyses. Our examination found asbestiform tremolite, including bundles of fibers and loose fibers, to be common in talcose rock from all of the sample sites. Asbestiform winchite and/or asbestiform richterite were identified in 5 of 13 talcose samples examined by this study. These observations suggest that mining and milling of the southern Death Valley talc deposits could produce asbestos-bearing dusts.

Introduction

Collectively, the talc mines of the southern Death Valley region of California (fig. 1) supplied a large proportion of the talc production from California during the 20th century. Today (2003), small sporadic production apparently is ongoing at one and possibly two of these mines.

The talc deposits mined in the southern Death Valley region are complex mixtures of talc and amphiboles, especially tremolite. These deposits were well described by Wright (1968) at eyeball and microscopic scales. Our mineralogical study of these historically important talc deposits was undertaken to examine the morphology and composition of their amphibole minerals using micron-scale analytical techniques, such as a scanning electron microscope complemented by energy-dispersive x-ray spectrometry and X-ray diffraction data.

Recently, tremolitic talc deposits have been receiving more attention, due to a focus by U.S. regulatory agencies on industrial mineral deposits that may contain naturally occurring asbestos as accessory minerals. As an example, unusually high incidences of asbestos-related mortality and respiratory disease in Libby, Montana, have been linked to amphibole asbestos intergrown with the vermiculite deposits mined and milled near the town from 1923 to 1990 (106th Congress, 2000; Dearwent and others, 2000). Tremolite, when it occurs in the asbestiform mineral habit, is regulated in the U.S. as asbestos (Occupational Safety and Health Administration, 1992; Perkins and Harvey, 1993). Because previous descriptions of the southern Death Valley talc-tremolite deposits lacked the submicroscopic scale of observations necessary to distinguish amphibole asbestos, our reconnaissance study focused on detailed analyses of the amphiboles, especially tremolite, found within representative talc ores of this region. It is emphasized that this study was a reconnaissance examination of these orebodies; a quantitative assessment of the asbestos content in these deposits was beyond the scope and design of this study.

Talc-Tremolite Deposits of Southern Death Valley

Several mountain ranges that border southern Death Valley, California (fig. 1), contain exposures of talc-tremolite bodies, which formed at the contact zones of gabbroic sills and dolomitic metasedimentary rocks, both of Mesoproterozoic age. The talc-bearing belt is about 75 miles (120 km) long by 15 miles (24 km) wide, and includes at least 43 talc mines and prospects (fig. 1). The geology of the region, the geology and workings at the mine sites, and their mining history are well documented by Wright (1968); thus, the geologic descriptions that follow are only a general overview.

Geologic Setting

The talc-tremolite deposits of the southern Death Valley National Park region are similar in occurrence and geologic setting (Wright 1957, 1968; Evans and others, 1976). Thick gabbroic sills, mostly medium- to coarse-grained, intruded a cherty dolomitic horizon at or near the base of the carbonate section of the Crystal Spring Formation, the lowest of three formations of the Late Precambrian Pahrump Group in southeastern California. The sills are exposed in each of the mountain ranges shown in figure 1. The intrusion of the sills and the associated metasomatism formed talc-tremolite rock along the sill-carbonate metasedimentary rock contacts. Ages of 1087 ± 3 and 1069 ± 3 Ma were determined by the U-Pb method from baddeleyite crystals in two gabbroic sills of this area (Heaman and Grotzinger, 1992); these age determinations indicate that the sills and the intruded Crystal Spring Formation (minimum estimate of depositional age) are Mesoproterozoic in age. The talc-forming event, as explained below, is interpreted to be the direct result of the intrusion of the gabbroic sills.

The consistent stratigraphic position of the sills at or near the base of the carbonate interval of the Crystal Spring Formation, but not higher, suggested to Wright (1968) and Hammond (1986) that the sills were emplaced before deposition of much overlying strata. Wright (1968) estimated that the overlying sediment during sill emplacement is represented by 200 to 2,500 feet of the overlying metasedimentary rock now present. Wright (1968) and Hammond (1986) suggested that during sill intrusion, the limy sediments were poorly consolidated and saturated, perhaps by marine water from an overlying sea. Whole-rock geochemical analyses of the sills and adjacent metasedimentary rock are provided in table 1.

Talc-Tremolite Deposits and Mines

The talc-tremolite rocks are replacement bodies that formed exclusively along the sill-carbonate metasedimentary rock contacts. The bodies are typically 500 feet to 5,000 feet long and 10 to about 100 feet thick, consisting of friable, laminated talc-tremolite rock. The deposits contain talc or tremolite in greater proportion than other minerals, and locally either talc or tremolite can be the predominant mineral. Most commonly, acicular amphiboles (mostly tremolite) and platy particles of talc are intergrown on a microscopic scale. Other major to minor constituents of the ore as determined by XRD (table 2), include calcite,

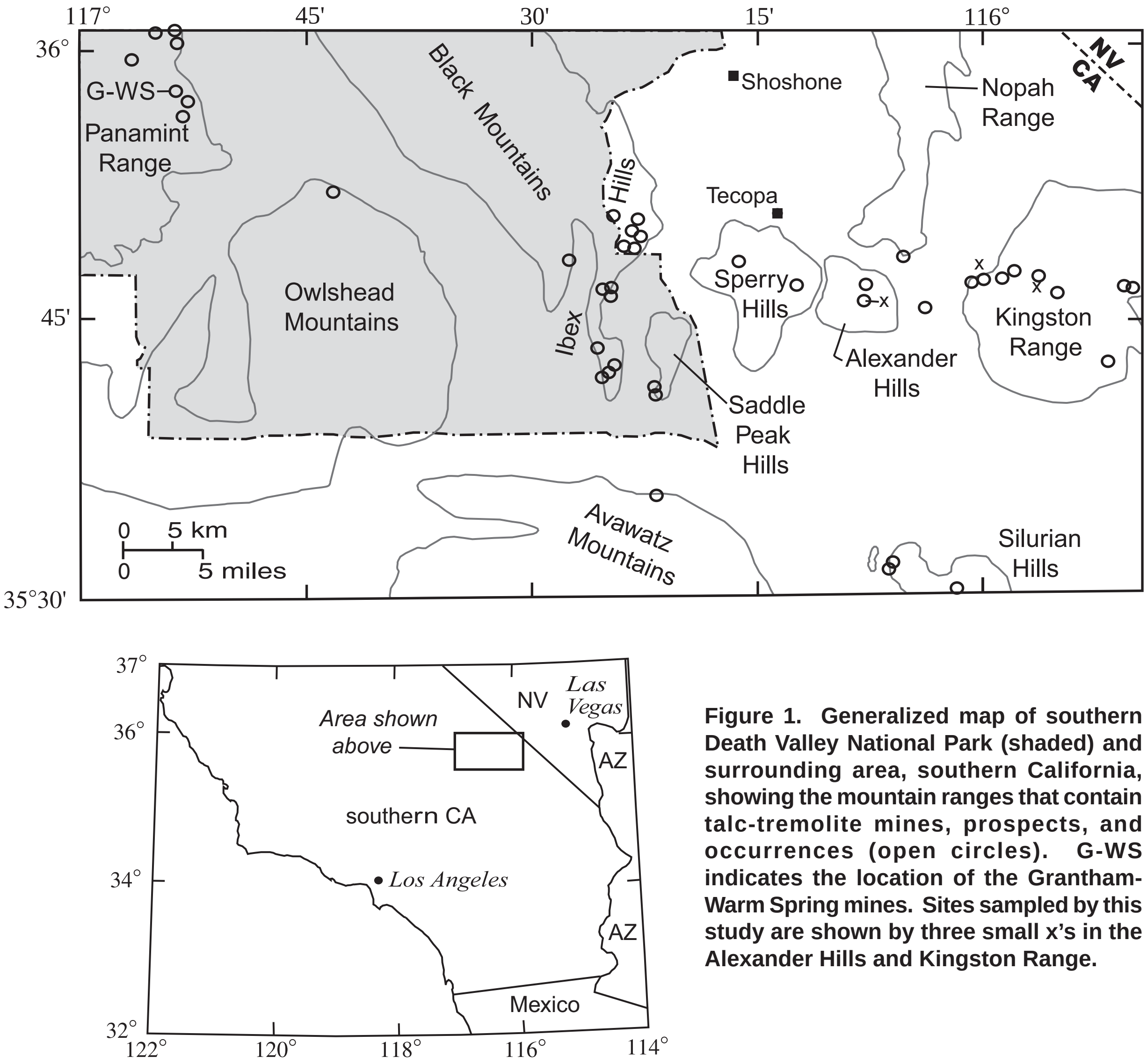

Figure 1. Generalized map of southern Death Valley National Park (shaded) and surrounding area, southern California, showing the mountain ranges that contain talc-tremolite mines, prospects, and occurrences (open circles). G-WS indicates the location of the Grantham-Warm Spring mines. Sites sampled by this study are shown by three small x's in the Alexander Hills and Kingston Range.

Table 1. Major-element chemistry (in weight percent) of gabbro sills, dolomitic limestone host rock, and talcose rocks associated with talc-tremolite ore bodies in the Alexander Hills and Kingston Range, near Tecopa, California. Analyses by wavelength-dispersive X-ray fluorescence spectrometry, conducted by Joseph E. Taggart, USGS laboratories in Lakewood, Colorado. See Taggart and others (1981, 1987) for descriptions of methods. LOI, loss-on-ignition; total Fe calculated as Fe_2O_3.

Sample No.	*Rock type*	SiO_2	Al_2O_3	Fe_2O_3	*MgO*	*CaO*	Na_2O	K_2O	TiO_2	P_2O_5	*MnO*	*LOI*
Alexander Hills												
24ADV02	gabbroic sill	45.6	14.7	15.5	6.47	2.69	4.24	3.07	3.72	0.69	0.22	2.70
27DDV03	gabbroic sill	39.5	13.0	14.4	10.6	3.78	2.10	5.82	3.91	0.67	0.14	2.54
26BDV02	dol. limestone	57.0	0.21	1.27	8.33	12.7	<0.15	0.10	0.03	<0.05	0.06	19.6
24CDV02	talc ore	60.3	0.57	0.38	28.4	3.51	0.72	0.32	0.08	<0.05	0.02	4.67
25BDV02	talc ore	44.8	1.20	0.46	25.0	9.98	0.59	0.93	0.06	<0.05	0.03	16.1
26ADV02	talc schist	48.0	0.43	0.33	23.8	13.0	<0.15	0.43	0.04	<0.05	0.04	12.4
27BDV03	talc ore	53.9	0.31	0.29	24.6	11.4	0.58	0.24	0.04	<0.05	0.02	7.84
27CDV03	talc ore	49.8	1.26	1.32	23.2	11.3	1.85	1.09	0.07	<0.05	0.04	8.98
27EDV03	talc schist	56.9	0.72	0.61	24.9	9.41	2.59	0.43	0.06	0.06	0.03	3.15
27FDV03	talc ore	55.0	0.51	0.37	25.3	10.5	1.83	0.31	0.05	<0.05	0.03	5.40
Road cut, Kingston Range												
28ADV02	talc rock	58.7	0.17	2.95	26.2	6.33	<0.15	0.02	0.07	0.05	0.08	4.30
Ore pile, Kingston Range												
29ADV02	talc ore	57.1	0.44	0.34	24.9	11.5	<0.15	0.21	0.05	<0.05	0.03	3.77

Table 2. Mineralogic and morphologic analyses of samples of talcose rock collected from the Alexander Hills-Kingston Range region. In regard to the x-ray diffraction results (see text), "major" minerals are estimated to comprise >25 wt. % of the sample analyzed; "minor" minerals form 5-25 wt. %; and "trace" minerals comprise <5 wt. %. Mineral abbreviations: amph, amphibole of the tremolite-actinolite series; ct, calcite; phlog, phlogopite; dol, dolomite; sep, sepiolite; hb, ferroan magnesiohornblende (best fit identification according to mineral structure by XRD analyses). Asbestiform amphibole particles were identified by visual scans of the sample by SEM and analyses of the particle by EDS (see text); asbestiform amphiboles were described as "common" in occurrence (easily found), "present, not common" (widely scattered and found occasionally), or in one sample "none were found."

Site name,		**Minerals identified by x-ray diffraction**		**Asbestiform amphiboles**
Sample number	**Major**	**Minor**	**Trace**	**found by SEM/EDS**
Alexander Hills				
24CDV02	talc		amph, ct, phlog	common
24DDV02	talc, dol	ct, amph	phlog	common
25ADV02	ct	talc	amph, phlog	common
25BDV02	talc	ct, dol, sep	phlog, amph	present, not common
26ADV02	talc	ct	amph, phlog	common
27ADV02	ct	talc	phlog, dol, amph	none were found
27BDV03	amph, hb	talc, dol	ct	common
27CDV03	amph, hb, talc	quartz, dol	antigorite	present, not common
27EDV03	amph, hb		talc, ct, antigorite, muscovite	present, not common
27FDV03	amph	talc	antigorite, dol, ct, clinochrysotile	common
road cut, Kingston Range				
28ADV02	amph	talc	ct, kaolinite(?)	common
28BDV02	quartz	amph, talc		common
ore pile, west foot of Kingston Range				
29ADV02	talc, amph, ct		quartz, K-feldspar	common

phlogopite, dolomite, quartz, antigorite, sepiolite, clinochrysotile, kaolinite, muscovite, K-feldspar, and ferroan magnesiohornblende (best fit according to mineral structure by XRD analyses). Petrologic and petrographic descriptions of talc bodies of this region are provided by Wright (1968).

The mining of talc began in the southern Death Valley region as early as 1910. At least 43 talc mines and prospects are known in the southern Death Valley-Kingston Range region (fig. 1); Tucker and Sampson (1943), Norman and Stewart (1951), Wright and others (1953), and Wright (1968) provided descriptions of these sites and their history. The largest talc-mining district of the southern Death Valley area, and likely the largest producer, was the Grantham-Warm Spring district (fig. 1), which consisted of a number of adits and open pits scattered for slightly over 2 miles (3.2 km) along Warm Spring Canyon in southwestern Death Valley National Park (Franklin, 1965; Wright, 1968; Papke, 1975). Talc mining was active in Warm Spring Canyon and in Galena Canyon, one mile to the north, until 1988. These mining districts and several others are now part of Death Valley National Park (fig. 1). The second largest talc-mining complex, composed of large open pits and older adits, was the Western-Acme mine in the Alexander Hills located southeast of Tecopa, California (Wright, 1968). Apparently, one talc mine, located in the Kingston Range east of the Park (fig. 1) is still active to at least a limited extent. Southern Death Valley talc has apparently been used mainly in the manufacturing of wall tiles and to a lesser extent as an extender in paints. Wright (1968) indicated that some of the talc produced from the Death Valley mine was sold as cosmetic talc.

Genesis of the Talc-Tremolite Deposits

The talc-tremolite orebodies of the southern Death Valley region clearly formed by contact metasomatism caused by intrusion of the gabbroic sills and massive replacement of the contacted dolomitic carbonate rocks or sediment. Wright (1968) determined that the gabbroic sills intruded the lower horizons of the carbonate section of the Crystal Spring Formation before much of the overlying strata preserved today were deposited. As noted earlier, Wright (1968) and Hammond (1986) concluded that during sill intrusion the limy strata were likely unconsolidated and saturated with marine waters. Thus, during sill emplacement (and talc-tremolite formation) the pore fluids were likely as saline as ocean waters or perhaps more saline.

The mineral-fluid equilibria in an environment of contact metasomatism may be represented by the saline fluid-siliceous dolomite reactions described by Labotka (1991, p. 86–88). Siliceous waters of >400°C react with dolomite to form talc, calcite, and CO_2 vapor, through the reaction:

$$3\text{ dolomite} + 4\text{ quartz(aq)} + H_2O = \text{talc} + 3\text{ calcite} + 3\ CO_2$$

The calcite formed by this reaction may react with the newly formed talc (and/or silica still in solution) to form tremolite, dolomite, and CO_2 vapor at slightly higher fluid temperatures, as follows:

$$2\text{ talc} + 3\text{ calcite} = \text{tremolite} + \text{dolomite} + H_2O + CO_2$$

Notice that the minerals identified by X-ray diffraction in samples of these orebodies (table 2) include talc, tremolite, calcite, dolomite, and quartz. Thus, cherty, dolomitic limestone saturated with heated silica-rich waters can explain the coexisting talc-tremolite intergrowths that are common within the Death Valley deposits. Silica saturation is evidenced by the silicification of the dolomitic limestones that directly overlie the deposits (sample 26BDV02, table 1). The temperature of the heated silica-rich waters most likely controlled the extent of talc and tremolite development at any particular site. At some distance from the sills these metasomatic fluids were cooled below the equilibria conditions for talc and tremolite precipitation, due to wall rock interaction, and then only silica would remain in solution and talc-tremolite deposition would cease. The gabbroic sills provide an obvious source for the heat and additional silica required to drive the talc-tremolite reactions.

USGS Reconnaissance Study

Study Methods

Samples of talcose material were collected in three areas of the Alexander Hills-Kingston range region, to the east of the southern part of Death Valley National Park (fig. 1). The sample sites were selected because they are abandoned properties that allowed access and sampling—they lie on public lands administered by the Bureau of Land Management. Sample sites included (1) a roadcut exposing talc-tremolite rock in the Kingston Range, (2) a talc ore pile left on public lands near the western foot of the Kingston Range, and (3) outcrop, abandoned pits, mine dumps, and ore piles in the Alexander Hills. Each sample was collected as a composite, containing at least 30 pieces of randomly selected talcose rock at each particular sample spot. The samples analyzed by this study (table 2) are presumed to represent the ores that were mined in this region. All of the talc samples collected by the lead author from the study area are described in this report; thus, this report does not represent the results of selected pieces from each sample spot.

Dust coating the inside of the plastic sampling bag was examined using a JEOL 5800-LV scanning electron microscope (SEM), equipped with an Oxford ISIS energy-dispersive system (EDS) with ultra-thin window detector. The EDS provided semi-quantitative chemical data that was reduced using the Oxford ISIS standardless software with the ZAF correction procedure selected. Analyses were performed on single, isolated structures, not on fibers that lay across other mineral particles. The operating conditions of the instrument were 15 kV, 0.5–3 nA (cup), and approximately 30% dead time. These conditions would excite an analysis volume of approximately 2 µm.

The matrix corrections used do not account for particle geometry. However, Small and Armstrong (2000) demonstrated that at 10–15 kV (utilized by this study) geometry-induced errors in the analyses of particles can be relatively small. We compared the analyses of individual grains of tremolite by our EDS instrument versus analyses of the same grains by electron probe microanalysis with wavelength dispersive spectroscopy (WDS). Table 3 shows our comparison of analytical results by EDS and WDS. The amphibole nomenclature used in this study follows the recommendations of Leake and others (1997).

Samples were pulverized and mechanically split for XRD analyses. The minerals identified by XRD in the samples were categorized as major, minor, and trace mineral constituents of the analyzed split (table 2). "Major" minerals are estimated to comprise >25 wt. % of the sample, "minor" minerals form 5–25 wt. % of the sample, and "trace" minerals form <5 wt. % of the sample (table 2). These estimates were based on the experience of the XRD operator with his instrumentation and its data output. The pulverized splits examined by this study provide snapshots of the mineralogy and variability in the talcose ores. However, quantitative estimates of the talc, amphibole, or asbestiform amphibole content should not be interpreted from the results shown in table 2.

The XRD technique can identify the amphibole minerals within a sample as members of the tremolite-actinolite-ferroactinolite series, but is not able to determine the specific amphibole species. It is also not possible to positively distinguish between tremolite and the sodic-calcic amphiboles winchite and richterite by XRD.

Study Results

Our reconnaissance sampling and analyses indicate that talc is the predominant mineral in the Death Valley deposits; however, as noted by earlier studies, tremolite is a major constituent of these deposits (tables 2 and 4). The tremolite particles in the Death Valley ores, as is typical in tremolitic talc deposits, range in habit from blocky to prismatic to acicular to asbestiform, commonly within a single sample. Accessory minerals identified in the talc-tremolite rock (table 2) include calcite, phlogopite, dolomite, quartz, antigorite, sepiolite, clinochrysotile, kaolinite(?), muscovite, K-feldspar, and ferroan magnesiohornblende (best fit identification according to mineral structure by XRD analyses).

Our examination of 13 talc-rich samples by SEM/EDS (table 2) found that amphibole particles with prismatic to acicular habits are most common; however, particles with asbestiform morphologies are also present. This observation has apparently not been noted previously in the literature. Much of the tremolite in the Death Valley talc deposits meet the criteria of regulatory amphibole asbestos as defined by the U.S. Environmental Protection Agency (Perkins and Harvey, 1993) and the Occupational Safety and Health Administration (1992). That is, many amphibole particles more than 5 micrometers in length are ~1 micrometer or less in width, have aspect (length:width) ratios of 20:1 or higher (table 4), are present in bundles with splayed ends (fig. 2), and display curvature (fig. 3).

EDS analyses of individual particles indicated that many of the asbestiform particles in the talcose rocks have compositions consistent with winchite and (or) richterite (figs. 3 and 4, table 4), which are sodic-calcic amphiboles related to the tremolite-actinolite series (Leake and others, 1997). Recognizing that some analytical variance is inherent in the EDS analyses of thin fibers, our EDS analyses of fibrous particles in the study samples produced data that appear consistent with tremolite, winchite, and richterite compositions and with the solid-solution compositional ranges of these minerals (Zoltai, 1981; Leake and others, 1997).

The EDS analyses of a number of talc particles revealed compositions that were usually close to that of ideal talc [$Mg_3Si_4O_{10}(OH)_2$]. A few of the talc particles contained ~0.3 cations of Fe substituting for Mg. The talc particles were typically flat and platy, occurring on a sub-microscopic scale with the acicular amphiboles (figs. 3 and 4).

Table 3. Comparison of the analyses of tremolite particles within one tremolite-rich study specimen from the Death Valley region, as measured by two techniques: (1) energy dispersive x-ray analysis (EDS) on polished and single unpolished grains, and (2) electron probe microanalysis with wavelength dispersive spectroscopy (WDS) on polished grains. Data are expressed in cation proportions. bdl = below the detection limit of the analytical technique.

Mount type	Particle L x W (µm)	Analysis method	K	Na	Ca	Mn	Fe	Mg	Ti	Al	Si
Polished	203 x 106	WDS	0.01	0.06	1.88	0.01	0.04	4.93	bdl	0.03	7.99
		EDS	bdl	bdl	1.7	bdl	0.1	4.9	bdl	bdl	8.1
Polished	362 x 226	WDS	0.01	0.06	1.88	0.01	0.05	4.94	bdl	0.03	7.97
		EDS	bdl	bdl	1.7	bdl	bdl	5.0	bdl	bdl	8.1
Polished	140 x 14.3	WDS	0.01	0.05	1.85	0.02	0.06	4.93	bdl	0.04	8.00
		EDS	bdl	bdl	1.8	bdl	0.1	5.0	bdl	bdl	8.1
Loose	18.5 x 0.9	EDS	bdl	bdl	1.8	0.1	0.1	5.2	bdl	bdl	7.9
Loose	5.8 x 0.8	EDS	bdl	bdl	1.7	0.1	0.2	5.1	bdl	0.1	7.9
Loose	6.7 x 1.1	EDS	bdl	bdl	1.9	bdl	0.1	5.3	bdl	bdl	7.8
Loose	3.9 x 1.5	EDS	bdl	bdl	1.8	bdl	bdl	5.0	bdl	0.1	8.0
Loose	13.4 x 1.0	EDS	bdl	bdl	1.8	0.1	0.1	5.1	bdl	0.2	7.9

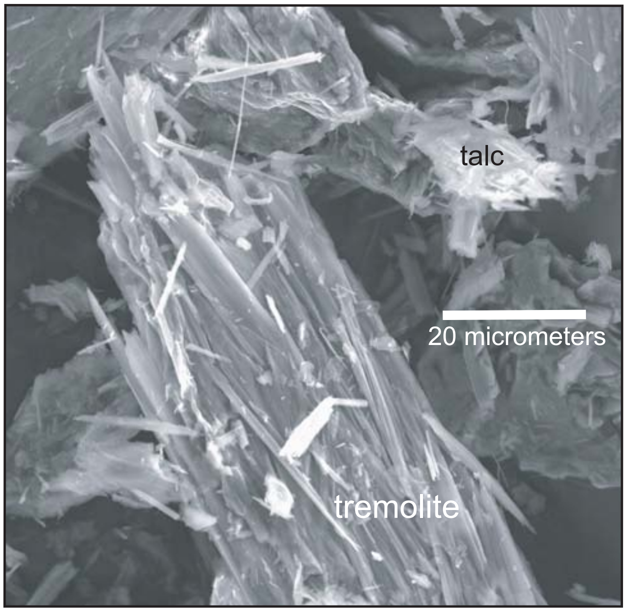

Figure 2. SEM photomicrograph of a bundle of tremolite alongside platy talc in sample 28BDV02 (table 2); from talcose rock in a roadcut in the Kingston Range.

Table 4. Representative compositions of fibrous amphibole particles in study samples as calculated from EDS analyses. Cation ratios were calculated by stoichiometry using 23 oxygen atoms for amphibole. (OH) was assumed to be 2. The EDS technique cannot distinguish the oxidation state of Fe (Fe^{3+} versus Fe^{2+}). Most of the amphibole analyzed in this study had neglible Fe; therefore, the oxidation state of Fe would not greatly affect the compositional calculations. Amphiboles are identified as the most likely amphibole species based on semi-quantitative results. Amphibole nomenclature used is based on the recommendations of Leake and others (1997). bdl = below the detection limit of the EDS analytical method.

Sample area Sample no.	Fiber shape L x W (µm)	Probable Amphibole	K	Na	Ca	Mn	Fe	Mg	Ti	Al	Si
Alexander Hills											
24CDV02	62.2 x 1.5	richterite	0.2	1.3	1.0	bdl	bdl	5.0	bdl	bdl	8.1
24CDV02	22.0 x 0.8	tremolite	0.1	0.3	1.6	bdl	bdl	5.1	bdl	bdl	8.0
24DDV02	24.5 x 0.9	richterite	0.1	2.1	0.5	bdl	0.2	5.1	bdl	0.1	7.9
25ADV02	34.7 x 1.6	richterite	0.2	1.5	0.8	bdl	0.2	4.9	bdl	bdl	8.1
25ADV02	22.4 x 1.6	winchite	0.3	0.9	1.0	bdl	0.1	5.1	bdl	bdl	8.1
25BDV02	22.5 x 1.3	richterite	0.1	1.8	0.7	bdl	0.1	5.4	bdl	bdl	8.0
25BDV02	29.5 x 1.3	richterite	0.2	1.7	0.7	bdl	0.1	5.1	bdl	bdl	8.1
26ADV02	19.2 x 1.8	tremolite	0.1	0.4	1.5	bdl	bdl	5.0	bdl	bdl	8.0
26ADV02	27.8 x 1.9	winchite	0.2	0.5	1.0	bdl	0.1	5.3	bdl	bdl	8.1
26ADV02	12.9 x 1.3	richterite	0.4	1.6	0.9	bdl	0.1	5.2	bdl	bdl	7.9
27BDV03	19.6 x 0.9	tremolite	bdl	bdl	1.9	bdl	0.1	4.6	bdl	0.1	8.0
27BDV03	59.0 x 0.7	tremolite	bdl	bdl	1.7	bdl	0.2	5.1	bdl	bdl	8.0
27BDV03	28.9 x 0.9	tremolite(?)	0.1	0.2	1.4	bdl	bdl	5.3	bdl	0.1	8.0
27CDV03	18.8 x 0.6	tremolite	bdl	bdl	1.7	bdl	0.2	5.2	bdl	0.1	7.8
27CDV03	16.2 x 1.6	tremolite	bdl	bdl	2.1	bdl	0.3	4.6	bdl	bdl	8.0
27CDV03	20.3 x 0.7	tremolite	bdl	bdl	1.8	bdl	0.4	5.1	bdl	0.1	7.8
27EDV03	32.0 x 1.1	tremolite	bdl	bdl	1.7	bdl	bdl	5.0	bdl	0.1	8.1
27EDV03	13.3 x 0.4	magnesio-hornblende	bdl	0.1	2.2	0.1	2.1	3.1	bdl	0.5	7.4
27EDV03	24.1 x 1.0	tremolite	0.1	0.1	1.9	bdl	0.1	5.1	bdl	bdl	7.9
27FDV03	20.6 x 0.3	tremolite	0.1	bdl	1.5	bdl	0.1	5.2	bdl	0.1	8.0
27FDV03	19.6 x 1.2	tremolite	0.1	0.2	1.6	bdl	0.1	5.0	bdl	bdl	8.0
27FDV03	15.9 x 0.7	tremolite	bdl	bdl	1.8	bdl	0.1	5.1	0.1	bdl	7.9
Road cut, Kingston Range											
28ADV02	20.3 x 1.1	tremolite	bdl	bdl	1.8	bdl	0.3	5.0	bdl	bdl	8.0
28BDV02	92.0 x 1.4	tremolite	0.1	0.2	1.7	bdl	0.1	4.9	bdl	bdl	8.1
Ore pile, Kingston Range											
29ADV02	22.9 x 1.6	winchite	0.2	0.6	1.4	bdl	bdl	4.9	bdl	bdl	8.1

A quantitative assessment of the "asbestos" content in the ore material was beyond the scope of this study. Our SEM/EDS analysis of the mineral residues caused by light handling of the ore samples suggests that prismatic particles are the most common amphibole habit in the talcose rocks. Blocky, prismatic, and acicular examples of the amphiboles in each sample yielded compositions similar to those measured in the fibrous particles (representative fiber compositions shown in table 4). No obvious correlation between particle composition and morphology was found—tremolite, richterite, and winchite compositions were found in crystals that range from non-fibrous to highly fibrous in habit.

We emphasize that our sampling and SEM/EDS studies of these talc deposits were reconnaissance in fashion. Importantly, asbestiform amphiboles in the ore samples were often encountered in SEM scans of the ore material; fibrous particles locally occur in amounts as high as one percent (by volume) in many of the ore samples (table 2). This observation suggests these talc ores should be handled with care and they require sampling and analytical techniques performed by protocol methods to properly assess their asbestos content (Beard and Rooks, 2000).

Implications of the Study Results

Based on the reconnaissance sampling and mineralogical analyses of samples from talc deposits of the Alexander Hills-Kingston Range region, we conclude that the mining and milling of these deposits could produce asbestos-bearing dusts. While a quantitative estimation of the amphibole asbestos content in the deposits was beyond the scope and intent of this study, our observations indicate that asbestiform amphiboles are present in more than trace amounts. The consistency in geology at each of the known talc deposits of the southern Death Valley region (Wright, 1968) suggested that their mineralogy is also likely to be similar.

Occupational exposures to tremolite asbestos have been implicated with respiratory disease, such as high rates of asbestosis and mesothelioma in asbestos miners and mill workers (see discussions in Ross, 1981, 1984; Stanton and others, 1981; Skinner and others, 1988; Mossman and others, 1990; Guthrie, 1993; Nolan and others, 2001). More recently, winchite, and to a lesser amount richterite, have been identified as the asbestiform amphiboles within the vermiculite deposit mined near Libby, Montana, from 1923 to 1990 (Wylie and Verkouteren, 2000; Meeker and others, 2002). These amphiboles have been linked to very high rates of lung disease in Libby mine and mill workers and residents (Dearwent and others, 2000). Thus, the talc-tremolite-winchite-richterite deposits of the southern Death Valley region of California should be handled with caution and warrant further evaluation.

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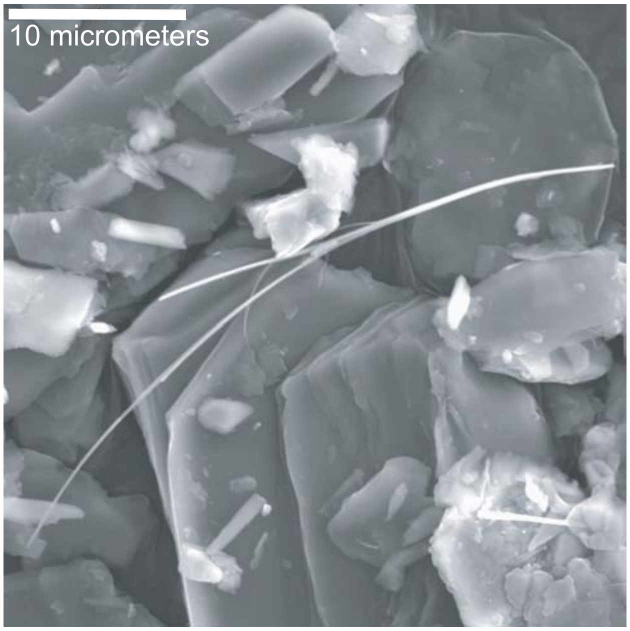

Figure 3. SEM photomicrograph of an asbestiform amphibole particle (likely winchite) with platy talc in sample 26ADV02 (tables 2 and 4); from talcose rock outcrop in the Alexander Hills.

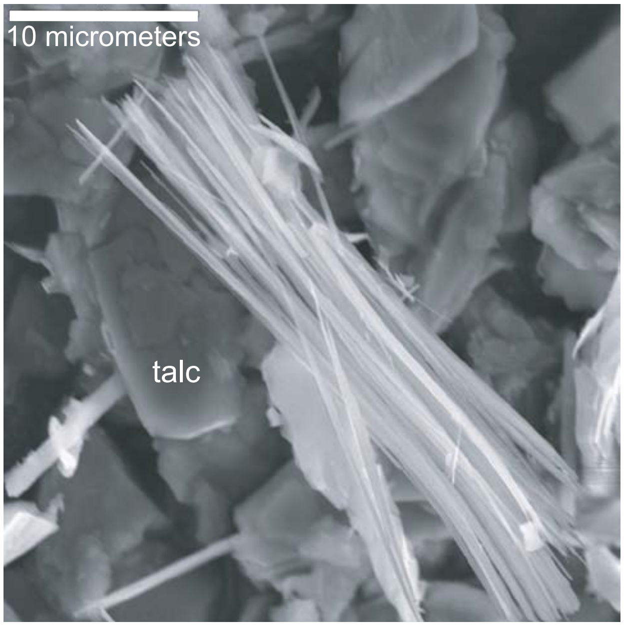

Figure 4. SEM photomicrograph of a fibrous amphibole bundle (likely richterite) in sample 24CDV02 (table 2); from talcose rock in an ore pile in the Alexander Hills.

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The IMV Story—Sepiolite and Saponite

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Abstract

Unique deposits of sepiolite and saponite in a desert valley in southern Nevada are mined and processed by IMV Nevada. These magnesium clay minerals occur in and near a modern playa called Amargosa Flat. Older, partly buried playa deposits of Pliocene age have a thick section of magnesium-rich claystones and subordinate carbonate rocks. Most of the waters that fed the earlier playa lake and adjacent marshes came from an extensive and prolific spring system with a recharge area that includes much of south-central Nevada. The magnesium-rich spring waters were additionally concentrated by solar evaporation, and sepiolite, saponite, dolomite, and calcite were precipitated. Mining is by open pit using scrapers, and the sepiolite is stockpiled into three grades. Processing includes crushing and screening, extruding, drying, and grinding to product specifications. The sepiolite market includes the construction industry, exports to the Far East, drilling mud, suspension aids, animal feed, and paint. The saponite market includes stucco applications and use in the wet end of paper manufacture. Both clays are used to make clumping pet litter.

Introduction

Unique deposits of sepiolite and saponite occur in Ash Meadows, Nye County, southern Nevada (fig. 1). Ash Meadows is near the southeastern end of the Amargosa Desert, a northwestward trending, irregular valley near the southern end of the Basin and Range province. Lakes occupied much of the valley during Pliocene time, and it contains a great thickness of sediments that were deposited in these lakes.

Ash Meadows is the only locality in the United States where sepiolite has been produced. Elsewhere in the world, most of the production is from a single deposit in Spain. Small amounts are also mined in Turkey and east Africa (Heivilin and Murray, 1994, p. 251–253). Saponite is a more common mineral than sepiolite in the western United States, but none of the other deposits of saponite are reported as extensive or pure as those in Amargosa Valley, and none are mined commercially.

The occurrence of sepiolite and saponite in this area is extremely unusual. The presence of sepiolite in sediments generally is considered diagnostic of a highly saline and alkaline environment. However, sepiolite has seldom been reported in playa sediments in the western United States and those reported are thin, impure, and of no possible economic importance.

History

Clays were produced in large quantities in Ash Meadows from 1918 through 1952. The clay mined during that period was nonswelling montmorillonite (fuller's earth) that was used to decolorize and purify oils. Since the early 1960s, small quantities of swelling bentonite have also been produced in the district (Papke, 1970, p. 30, 32; Mayhew, and others, 1979, p. 1).

Louis Moretti, a mineral prospector, located the Meerschaum Quarry placer claim in 1946. Meerschaum is a name for the hydrothermal form of sepiolite that is used for tobacco pipes. In 1955, Moretti located more placer claims that have been commercially mined since the late 1970s. Industrial Mineral Ventures was formed in 1966 (first as a partnership and later as a company), and under the direction of E.J. Mayhew begin prospecting in the Ash Meadows area. By 1974, sufficient clays had been discovered by IMV to justify construction of a mill and to later acquire Moretti's claims. The mill processed hectorite, bentonite for drilling mud, and sepiolite. Ownership changed to Gulf Resources and Chemical Corp. in 1978, to U.S. Borax Inc. in 1989, and to Mud Camp Mining Co. (the present owner) in 1997. The Ash Meadows sepiolite became profitable as a stand-alone commodity only during the last 10 years, more than 40 years after the discovery of these rare and valuable clay deposits (Mayhew and others, 1979, p. 1; Papke, 1999).

General Geology

The sepiolite and saponite occur mostly in or near the Amargosa Flat playa in the northeastern part of Ash Meadows (fig. 1). The exposed part of the playa covers about 6 square miles. An earlier playa, now mostly buried beneath as much as 25 feet of Pleistocene and Holocene sediments, had an area of at least 22 square miles and is characterized by the presence of high-magnesium clays. Where exposed, the older playa sediments are nearly horizontal and relatively undeformed. Drilling as deep as 115 feet shows that the sought-after clay deposits occur in claystone with some carbonates as nodules and beds, and less than 1% of unaltered volcanic glass. The claystone is almost all magnesium-rich, massive, brown to green, and generally forms units less than 3 feet thick. Thicker, nearly pure beds of sepiolite and saponite are present near the surface in the mine areas (Hay and others, 1986, p. 1489–95: Papke, 1999).

Sepiolite

Sepiolite is a hydrous magnesium silicate clay mineral that is commonly included with attapulgite-palygorskite in the hormite group. These minerals have chain-like structures and form elongated crystals with open central channels. Sepiolite has large surface area—larger than any other mineral-and thus has high absorptive capacity. (Heivilin and Murray, 1994, p. 249–250) The low density, high absorption, ability to absorb odors, and non-powdery nature make sepiolite an ideal agent in cat litter and other water- or oil-absorption products. When dispersed in liquids, the inert and non-swelling crystals form a random lattice that gives good thickening, gelling, and suspension properties. Unlike minerals of the smectite group, the hormites gel in salt water and make excellent viscosity agents for drilling in saline environments. The hormites also retain their viscosity and gelling characteristics at high temperatures, allowing their use in geothermal drilling where smectites cannot be used. Unlike the smectites, the hormites have relatively low cation-exchange capacity, about 20 to 50 meq/100g.

The sepiolite mined by IMV Nevada forms an extensive deposit. It occurs in an almost continuous bed as much as 20 feet thick that averages about 6 feet. It is covered by 10 to 25 feet of younger sediments. Except in transitional areas to the north and northwest, the sepiolite-rich unit rarely contains saponite, but saponite beds underlie or overlie it in places (fig. 2).

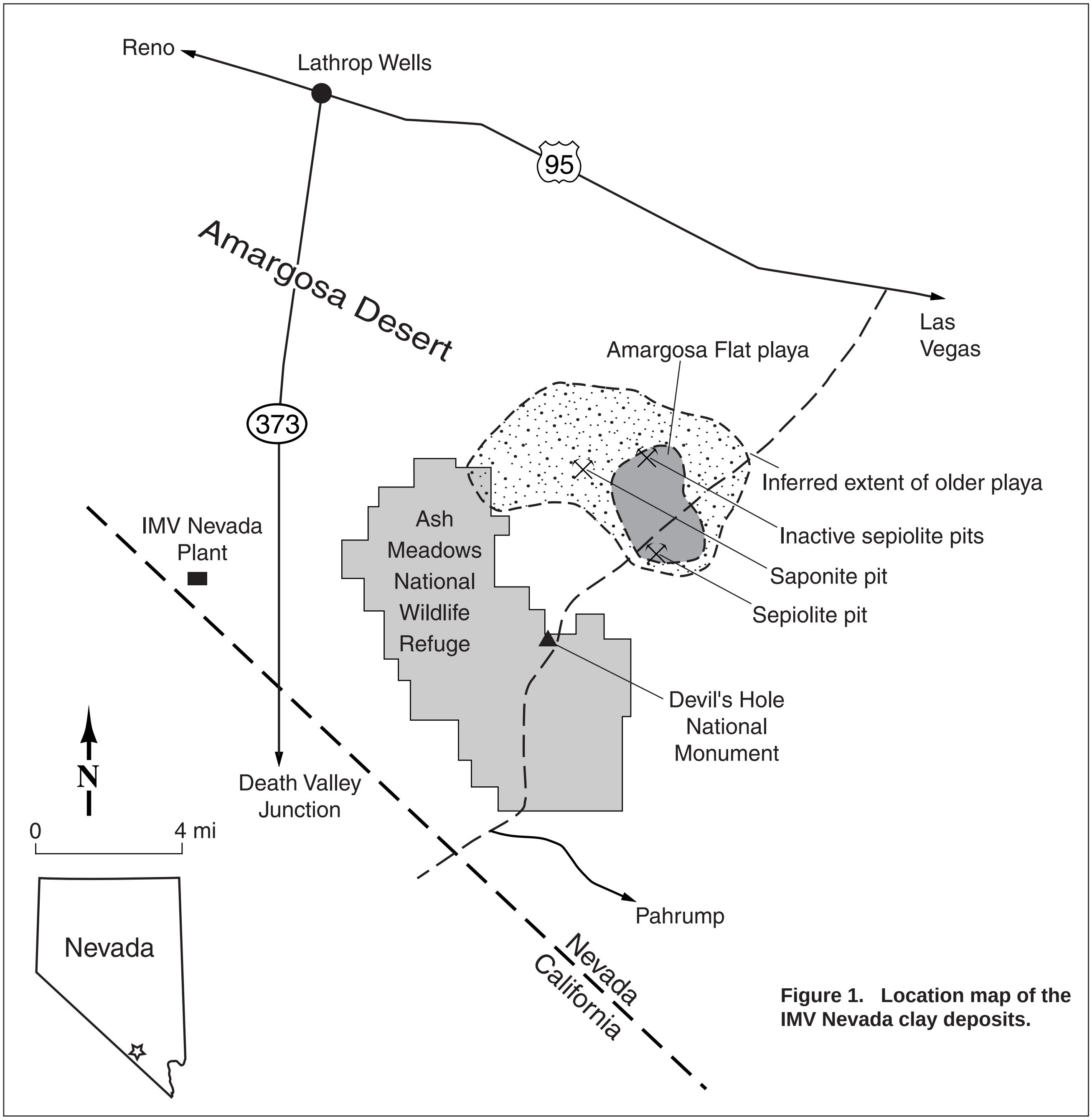

Figure 1. Location map of the IMV Nevada clay deposits.

The sepiolite-rich unit is essentially horizontal. Minor variations in attitude or thickness are attributed to an uneven underlying surface, a slightly eroded upper surface, or differential compaction. The clay has sharp lower and upper contacts and generally has no internal bedding. Root marks are common, and a breccia texture, indicating shallow-water disturbance, is locally present, mostly near the base of the unit. Individual units are thinned or terminated by interfingering with other clays. Faults are relatively uncommon and are of small magnitude (fig. 3). The material is white to pale gray with a dull luster. It is compact, homogeneous, and has a low specific gravity. It slakes rapidly in water to form curved chips. After a few weeks exposure to air, the material becomes brittle and somewhat harder. In general the sepiolite crystals are 1 to 2 microns long and 0.2 micron wide. A solution of methyl orange stains the sepiolite red, and the intensity of the color generally is proportional to the purity of the sample; such testing is used extensively during exploration and mining. Associated minerals are dolomite and calcite, small amounts of quartz and feldspar, trace amounts of saponite and illite, and occasional fragments of volcanic glass. The dolomite and calcite, in crystals that average about 2 microns across, are believed to be chemical precipitates along with the sepiolite, saponite, and perhaps the illite. The quartz, feldspar, and volcanic glass are of detrital origin (Papke, 1972).

Saponite

Saponite is the magnesium-rich end member of the smectite group of hydrous aluminum-magnesium-iron silicates. These clay minerals are sheet silicates that have high cation-exchange capacity and many varieties swell in water. Their swelling, viscosity, and gelling ability as well as their cation-exchange capacity make them commercially valuable (Grim, 1968, p. 40, 86, 112).

The saponite-rich units in Ash Meadows occur in an extensive area and appear to be nearly continuous. The purer beds range in thickness from a few inches to more than 20 feet, averaging about 5 feet. In places two mineable saponite beds are separated by saponite that does not meet the physical test standards. Some saponite crops out at the surface and the average overburden thickness is about 7 feet (fig. 4). The associated minerals are similar to those in the sepiolite. Due to the presence of iron compounds, the saponite commonly is light brown to light green. It has been noted that the quality of the saponite can be judged by its saltiness; the purer material has a distinctly stronger taste.

Origin of the Deposits

Surface drainage into the Amargosa Flat playa comes from a region of more than 300 square miles to the north, east, and southeast, and this drainage area has not changed substantially since Pliocene time. Bedrock in the drainage area consists of limestone, dolomite, and clastic sedimentary rocks of Precambrian through Devonian age. Although the playa is not now a topographically closed basin, it and the

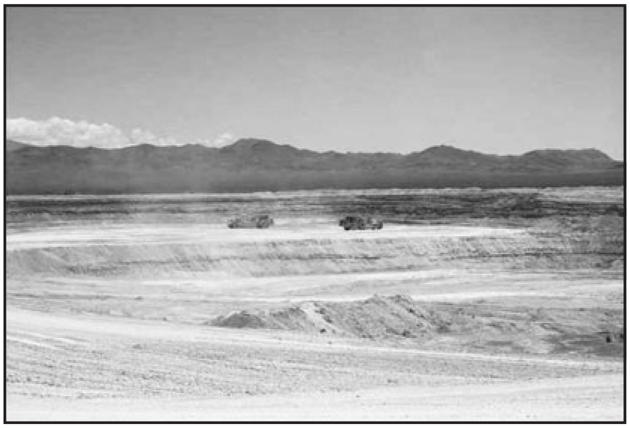

Figure 2. The Moretti sepiolite pit, looking east.

Figure 3. Sepiolite bed (light colored) in Moretti pit. Bed averaging about 5 feet is offset by a fault on the right.

Figure 4. Saponite pit area, looking south. The pure saponite lies below a thin veneer of surficial material.

surrounding area was at least periodically closed during Pliocene time and was the site of a saline, alkaline lake. Ash Meadows is the discharge point for a large regional groundwater system with a source area of at least 4,500 square miles to the north and northeast. Movement of the recharge waters is through deeply buried, fractured Paleozoic rocks, mostly dolomites (Winograd and Thordarson, 1975). A groundwater dam in the southwestern part of Ash Meadows created by a northwest-trending normal fault is responsible for about 20 large flowing springs on the northeastern side of the fault. Before pumping began in the late 1960s, the total discharge of these springs was about 17,000 acre-feet annually (Naff and others, 1974, p. 17).

The intimate mixture of the fine-grained clays, dolomite, and calcite in the sediments suggests that all had a similar origin. The origin of dolomite has been controversial: whether it ever formed as a primary mineral or only formed by replacement of calcite. There is now considerable evidence that dolomite can be a primary mineral formed as a chemical precipitate in some saline lakes or marshes. The presence of sepiolite in sediments generally is considered diagnostic of a highly saline, alkaline environment. We conclude that the clays, dolomite, and calcite were formed by chemical precipitation in a shallow playa lake and in adjacent marshland. The saline, alkaline waters were derived from runoff of abundant springs in the vicinity and, to a much lesser extent, from surface inflow from the drainage basin. The fluids, already magnesium-rich, were further concentrated by evaporation and the chemical precipitates resulted. The sparse amount of detrital minerals in the clays indicates that the water contribution from the drainage area was quite small. It has been suggested that saponite requires more saline solutions than sepiolite. This is supported by the field observation that the saponite generally has a salty taste whereas the sepiolite does not. The chemical composition of the water was the principal factor in controlling the mineral deposition, but temperature, pH, and availability of silica may also have been important (Papke, 1972, p. 212–215; Hay and others, 1986; Papke, 1999).

Because of the relatively great thickness of pure clays, we believe that the playa existed for a relatively long time. The almost complete absence of internal bedding suggests rapid deposition of the clays or, at least, constant conditions during deposition. The existence of the lake and marshes and the deposition of the clays may have ended when precipitation decreased sharply following the uplift of the Sierra Nevada far to the west which created a rain shadow, an event generally believed to have occurred about 3 million years ago. Before that time the amount of precipitation was much higher and springs were more abundant and prolific. Annual rainfall in the region is only about four inches at the present time. This age is supported by a 3.2-million-year-old tuff that is present less than 3 feet below the top of the Pliocene section in the Amargosa Valley (Hay and others, 1986, p. 1490).

Mining and Processing

As in much industrial-mineral mining, sampling and testing at the IMV Nevada operation are critical from the mining stage, through the processing, to the final product. The customer wants consistency. Product consistency is achieved here by repeated blending and testing.

Before each 5-acre pit for sepiolite is stripped, auger holes on 100- by 200-foot centers are used to delineate the orebody. After the 15 to 25 feet of overburden is removed, 5-foot deep holes reconfirm the initial drilling results. During mining, samples are taken at the end of the day to the IMV laboratory and the results are reported back when the mining crew starts work the next morning. The sepiolite is mined by scraper and is stockpiled into three grades as determined by the results of the Salt Fann test for viscosity. The clay is tested again as it goes into the mill stockpile.

Figure 5 is a flow diagram for the operation. After further blending and mixing, the extruded clay noodles are either dried in a rotary dryer and milled or flash dried in an IMP mill to obtain the required particle size. Both grinding methods give materials with similar rheological properties but provide different particle sizes. Saponite, which is produced in much smaller tonnage than the sepiolite, generally undergoes similar testing, mining, and processing.

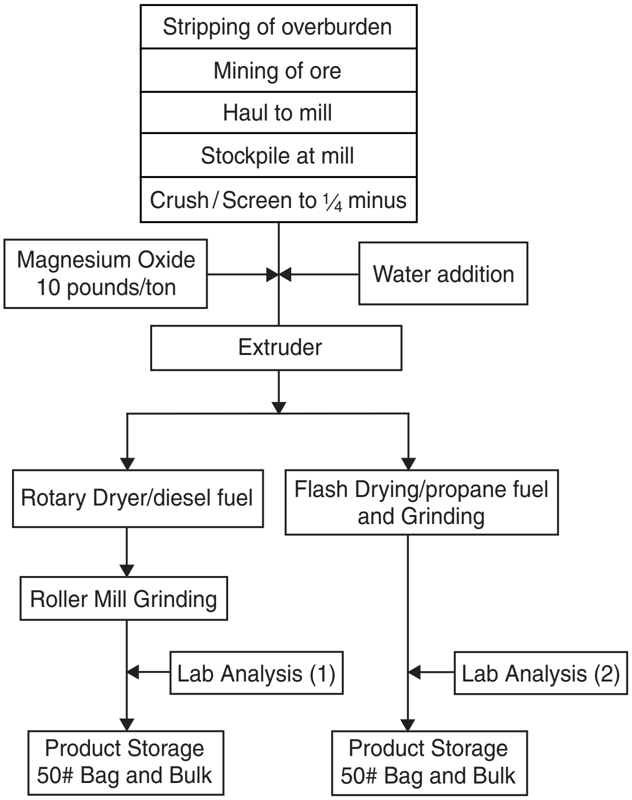

Figure 5. Simplified flow diagram for the IMV Nevada operation.

Markets

Like many industrial-mineral operations, IMV has supplied a variety of markets. Initially, the mill was built to recover hectorite, a lithium clay with great market appeal from a California deposit, and a calcium carbonate whiting agent. Low-grade ore, recovery problems, and lack of an established market limited the success of this early venture.

Demand for drilling mud in the late 1970s and early 1980s was the basis for most of the production for several years. A varied line of organo-clad clays, sepiolite, and modified bentonite were produced successfully for more than ten years. Currently, the use of sepiolite in animal-feed suspensions, as a binder in tape-joint compounds, as a replacement for asbestos in asphalt repair compounds, and as an absorbent of ammonia in the clumping pet litter, as well as the continued use as a salt water drilling mud are the major markets.

Until several years ago, the market for saponite was limited to its use as a minor constituent in stucco wall mixes, as a slurry wall sealer, and as the clumping agent in pet litter. The strong clumping characteristics of the saponite have recently yielded great success in IMV's clumping pet litter. In the last few years, additional applications for saponite have been found in the wet end processing at paper plants. Table 1 shows the current clay production and marketing information.

Table 1. Current production and marketing information for IMV Nevada.

Annually Mined and Processed:

Sepiolite	25,000 tons
Saponite	3,000 tons
Calcium bentonite	2,000 tons

Markets Geographically:

- 24,000 tons domestically with most west of the Mississippi
- 6,000 tons exported to Japan, Korea, and a lesser amount to Brazil, Mexico, Chile, and Australia

Markets by Mineral:

- Sepiolite
  - Agriculture: Animal feed and fertilizer suspension
  - Construction: Tape joint compounds, asbestos replacement, asphalt repair, binding agents
  - Drilling mud
  - Cat litter (absorbs ammonia)
- Saponite
  - Construction: Stucco wall mix and slurry wall sealing
  - Wet end paper mills
  - Cat litter

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Processes Related to the Formation of Neogene Lacustrine Diatom-Rich Sediments and Diatomite Deposits, Great Basin Region

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Abstract

Favorable time-space intersections of climate, tectonism, sedimentation, and volcanism promoted the formation of Neogene diatom-rich sediments in the Great Basin. The climate became cooler and drier from 15 Ma to the present, which influenced runoff, erosion, and nutrient transport. Fault-controlled sedimentary basins formed at various times and in various places, and local-scale processes varied from basin to basin throughout the region. Between 17 and 14 Ma, clastic-rich basins formed near detachment faults in eastern Nevada, whereas broad, lake-filled basins formed in northern and western Nevada. Fault-controlled basins began to form along the Walker Lane in western Nevada at about 17 Ma, with additional basins forming later in the Miocene. Post-6 Ma basins formed during incipient basin-and-range faulting. The style and age of volcanism varied throughout the region, with equally variable effects of volcanism on basins. Volcanism contributed Si and nutrients to the basins and locally blocked drainages to form lakes. Local basin morphology, hydrology, ecology, and nutrient sources influenced the local formation of diatom-rich sediments within a basin. Only certain combinations of these global to local processes produced large, in places commercial, lacustrine diatomite deposits.

Various combinations of post-depositional processes preserved, modified, or destroyed lacustrine sediments in some basins. Fault-induced uplift and erosion eroded parts or all of some sedimentary basins or buried diatom-rich sediments beneath coarse clastic sediments. Similarly, volcanic tuffs and flows blanketed some sedimentary basins. Local changes in hydrology due to burial or faulting both induced and prevented diagenetic alteration of the sediments and diatoms. As with the formation of diatom-rich sediments, only certain combinations of processes led to their preservation in this geologically active region.

Introduction

Neogene diatom-rich lacustrine sedimentary rocks are common in parts of the Great Basin and other western states (fig. 1), and some of them have been mined for diatomite. Sedimentary basins developed in the Great Basin and surrounding regions at various places and times during the past 17 million years. Many of these basins contained small to large lakes, and conditions in and around some of these lakes, or even just parts of a lake, favored the formation of thick, diatom-rich beds in the lake-bottom sediments. Other contemporaneous basins in the region contain only small amounts of lacustrine or diatom-rich sediments, or none at all. Overall, diatom-rich sediments comprise only a minor percentage of the late Cenozoic basin-filling sedimentary rocks in the region, indicating that special conditions were needed to form the deposits. In addition, post-depositional processes variably preserved or destroyed the diatom-rich sediments.

By definition, diatomite is a "light-colored soft friable siliceous sedimentary rock, consisting chiefly of opaline frustules of the diatom" (Bates and Jackson, 1987). The term also refers to diatom-rich sedimentary rocks that are of commercial value. For this paper, diatomite refers to the diatom-rich material that has been mined, whereas diatom-rich and diatomaceous sediments refer to all diatom-bearing sediments, regardless of their commercial value. The term deposit generically refers to the diatom-rich sediments unless stated otherwise.

In terms of total production, lacustrine diatom-rich sediments are the largest source of commercial diatomite in the United States. Diatomite is or has been mined from lacustrine deposits in all of the western states, and Nevada is the largest producer from this type of deposits (Dolley, 1999). Diatomite and diatoms have a wide variety of commercial uses that depend on the diatom genera (and their physical properties) in the deposit, deposit purity, degree of preservation of the diatoms, and specific needs of the end users.

Getting from a sedimentary basin in the past to a commercial diatomite deposit in the present requires a serendipitous sequence of events that both formed and preserved the diatom-rich sediments. Deviations from this path contributed to the current absence of diatom-rich sediments, commercial or otherwise, in many parts of the Great Basin. This paper presents a brief overview of Neogene lacustrine basins in the Great Basin, and it describes various processes that may have contributed to the formation and preservation of diatom-rich sediments in those basins. These processes were both regional and local in scale, and they included aspects of tectonics, volcanism, erosion, sedimentation, and climate that varied in space and time. Characteristics of these diatom-rich deposits that affect their commercial value, such as size, purity, diatom assemblage, and end uses, are beyond the scope of this paper, although the processes described here contributed to those qualities. Information on the attributes and uses of diatomite in the Great Basin and the U.S. is available in Lenz and Morris (1993) and Dolley (1999).

Regional Geologic Setting

Neogene sedimentary basins in the Great Basin formed in response to various tectonic, volcanic, and climatic events that developed and evolved over the past 15 to 20 million years. Each of these events varied both in time and space throughout the region, and different subregions therefore had significantly different Neogene geologic histories. Most of these events were unique to the Neogene, but some processes, as described below, started in the Oligocene and continued into at least the middle Miocene.

Tectonic Setting

The effects of Neogene tectonism varied spatially and temporally throughout the Great Basin. In some parts of the southern and eastern Great Basin, late Oligocene extension continued into the early to middle Miocene. This extension led to the formation of extensive detachment structures in the Grant, Snake, and East Humboldt Ranges and the Ruby Mountains of eastern Nevada, and to other structures related to low-angle faulting in southeastern Nevada (Axen and others, 1993). Most of this fault activity continued to about 15 to 13 Ma (Dumitru and others, 1997).

In many parts of the Great Basin, west-southwest-directed regional crustal extension began in the middle Miocene and continued into the late Miocene, possibly as late as 6 Ma (fig. 2; Zoback and Thompson, 1978). This extension produced abundant high-angle normal faults and small to moderate uplifted areas separated by broad basins. At about 6 Ma, the regional extension direction shifted to the northwest (fig. 2; Zoback and Thompson, 1978; Christiansen and Yeats, 1992), forming high-angle normal faults that produced much of the modern basin and range topography.

In western Nevada, extension began along the Walker Lane structural zone (fig. 2) as early as the Oligocene, but basin formation did not start until about 16 to 17 Ma (Hardyman and Oldow, 1991; Stewart, 1992a). The Walker Lane has an overall dextral sense of displacement, and it is divided into several structural domains. Each domain has different dip- and strike-slip fault patterns, and the resulting basins have distinctly different ages and structural and stratigraphic histories (Stewart, 1992a, b).

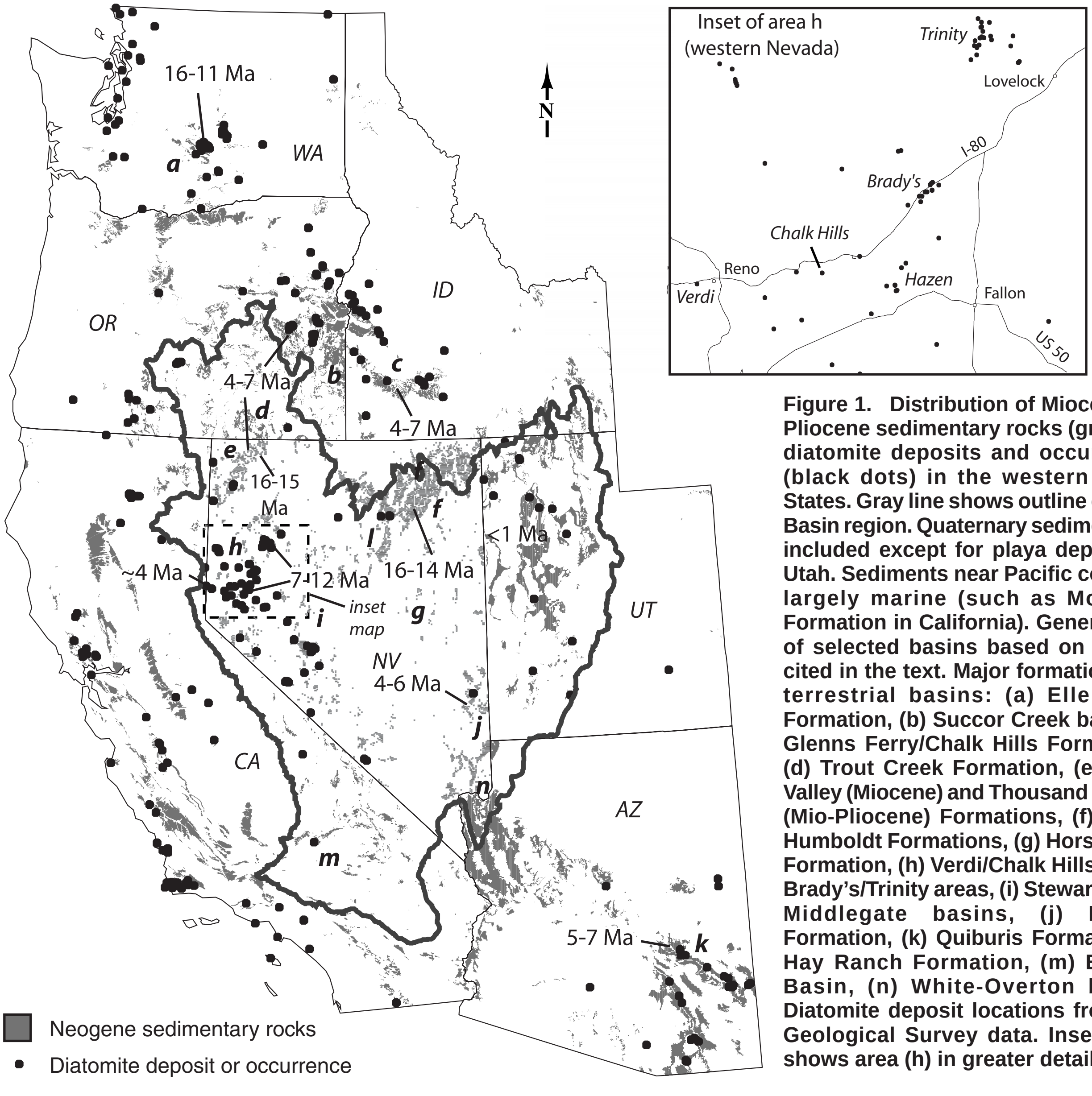

Figure 1. Distribution of Miocene and Pliocene sedimentary rocks (gray) and diatomite deposits and occurrences (black dots) in the western United States. Gray line shows outline of Great Basin region. Quaternary sediments not included except for playa deposits in Utah. Sediments near Pacific coast are largely marine (such as Monterey Formation in California). General ages of selected basins based on studies cited in the text. Major formations and terrestrial basins: (a) Ellensburg Formation, (b) Succor Creek basin, (c) Glenns Ferry/Chalk Hills Formations, (d) Trout Creek Formation, (e) Virgin Valley (Miocene) and Thousand Springs (Mio-Pliocene) Formations, (f) Carlin/Humboldt Formations, (g) Horse Camp Formation, (h) Verdi/Chalk Hills/Hazen/Brady's/Trinity areas, (i) Stewart Valley/Middlegate basins, (j) Panaca Formation, (k) Quiburis Formation, (l) Hay Ranch Formation, (m) El Paso Basin, (n) White-Overton basins. Diatomite deposit locations from U.S. Geological Survey data. Inset figure shows area (h) in greater detail.

Volcanism

Two regional volcanic systems (western andesite and bimodal) were active in the Great Basin and surrounding regions during Neogene and Quaternary times (Ludington and others, 1996). Early to late Miocene volcanism related to the early Cascades volcanic arc produced the western andesite assemblage. This volcanic arc included stratovolcanoes and shield volcanoes that were erupted in the western part of the Great Basin and to the north-northwest beneath the modern Cascade volcanic chain (fig. 2).

Bimodal mafic-felsic volcanism, in part related to the Yellowstone mantle plume (Pierce and Morgan, 1992), influenced much of the north-central Great Basin (fig. 2), and it produced widespread mafic flows and more localized rhyolite domes, flows, and tuffs. Volcanism began at about 17 Ma with the eruption of voluminous and regionally extensive basalt sequences, including the Steens Basalt in the northwestern Great Basin and the Columbia River Basalt Group in eastern Oregon and Washington. Activity waned after about 14 Ma but has continued weakly to the present. Bimodal volcanism in the southern Great Basin produced widespread middle Miocene rhyolites and less-extensive related mafic flows (fig. 2; Best and others, 1989; Ludington and others, 1996), as well as Quaternary basalt flows and cones.

The Great Basin also contains a third volcanic suite, the interior andesite-rhyolite assemblage, which formed in the early to middle Tertiary and thus is older than the Neogene diatom-rich sediments. However, volcanic units of this suite are present near several of the sedimentary basins, and they may have contributed sediments, silica, and nutrients to the lakes during erosion.

Climate, Flora, and Fauna

Global warming started in the late Oligocene, peaked between about 17 and 14 Ma, and then progressively cooled into the Pliocene (fig. 3; Zachos and others, 2001). The mid-Miocene warming in the Great Basin produced a temperate, moderate-rainfall climate, and the flora largely was similar to that found now in the temperate parts of western North America (Axelrod, 1956), with some variations due to latitude and elevation (Fields, 2002). Conifer forests and mixed oak-birch woodlands were common, marshes were present in lowlands (Starratt, 1987; Schorn and Erwin, 2002), and regional mammalian diversity soared during this period (Barnosky and Carrasco, 2002).

The cooling and drying trend into the Pliocene caused a gradual decrease in woodlands and an increase in grasslands and sagebrush, and eventually the formation of

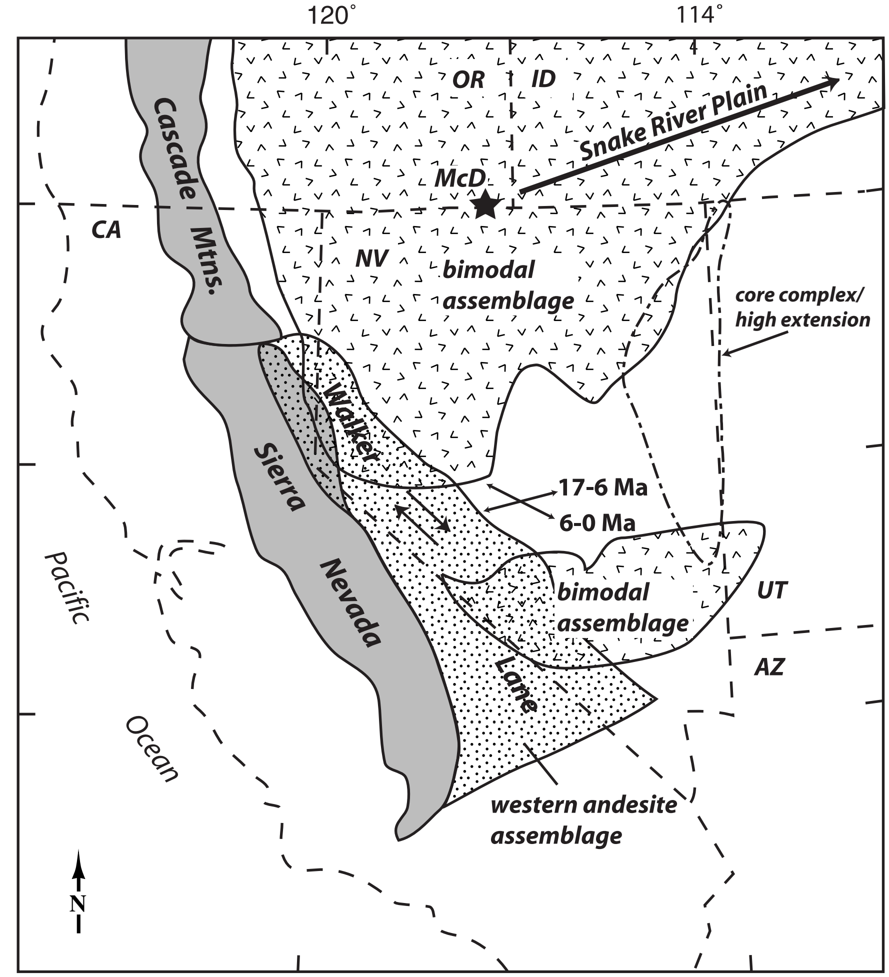

Figure 2. Regional geologic setting of the Great Basin region. The three volcanic assemblages include (1) the late Eocene to early Miocene interior andesite-rhyolite assemblage (represented by southwest-trending arrow), which covers much of central Nevada, (2) the early to late Miocene western andesite assemblage (light stipple), and (3) the middle Miocene to Holocene bimodal assemblage ('v' pattern). Arrow shows the northeast-trending trace of the Yellowstone hot spot along the Snake River Plain from its inception near McDermitt (star, McD). Different extensional directions and ages are shown by arrows for the central Great Basin; strike-slip arrows show dextral movement along the Walker Lane. Region of core complexes and high middle Miocene extension shown in dash-dot line. Modified from John and others (2000).

a desert scrub (sage-saltsage) and short grassland flora in the late Miocene and Pliocene (fig. 3; Retallack, 2001; Davis and Moutoux, 1998). The bare ground around the deep-rooted, widely spaced grasses enhanced runoff and nutrient transport (J. Repp, U.S. Nat. Res. Cons. Serv., written commun., 2003). Overall regional mammalian diversity decreased into the Pliocene (Barnosky, 2001; Davis, 2002).

Volcanism and tectonism had regional to local influences on the biota and their environments. Both formed dams across drainages or modified basins during sedimentation, and these geologic changes affected the ecosystems in those areas. Volcanism produced short- to long-term ecological conditions that, when seen in the geologic and fossil record, mimic global or regional climate changes (Harris and Van Couvering, 1995). For example, in the Succor Creek area of eastern Oregon (b, fig. 1), volcanic eruptions destroyed temperate-climate forests and produced a geologic record that falsely suggested cyclic arid to temperate climatic conditions (Taggart and Cross, 1990).

Episodic and different styles of tectonism in various parts of the region produced uplifts that affected both climate and the biota. Uplifts interfered with the east-flowing weather patterns, much as the Sierra Nevada has created a rain shadow on its eastern side since the Pliocene (Henry and Perkins, 2001). The uplifts also created elevation-related changes in precipitation, thereby locally increasing the amount of runoff and sediment transport into adjacent basins. The vegetation also responded to elevation changes (Taggart and Cross, 1990; Fields, 2002), with a corresponding vertical change in the types of soils and nutrients available for erosion.

Neogene Lacustrine Basins

The remnant Neogene sedimentary deposits in the Great Basin reflect lake-filled basins that were common and, at times, widespread in the region throughout the late Cenozoic. Some basins, such as the one now covered by the Great Salt Lake, episodically have contained lakes for the past 15 million years (Davis and Moutoux, 1998), but lakes in most basins had life spans of less than one to several million years. Clastic materials filled some basins, and lakes did not form except for only short periods of time. Some lacustrine basins, but certainly not all, contain diatom-rich sediments of various thicknesses and purities.

Ages and Distributions

Tephrochronology studies (Perkins and others, 1998; Perkins and Nash, 2002) show that Neogene basins and lakes in the Great Basin formed during several episodes. The earliest lakes began to develop at about 17 Ma, were more widespread by about 15 Ma (Stewart, 1992a; Perkins and others, 1998), and formed in shallow, broad basins during early regional extension. As shown on figure 1, basin-filling lakes formed in the White Basin-Overton Wash area in southern Nevada, the Stewart Valley and Middlegate basins in central Nevada, the Humboldt and Virgin Valley basins in northern Nevada, the Succor Creek basin in southeastern Oregon, and the Trapper Creek basin in southern Idaho. More localized lakes filled basins that were formed by coeval volcanic units or calderas, such as in the Whitehorse caldera in the Trout Creek area of southern Oregon (Barrow, 1983).

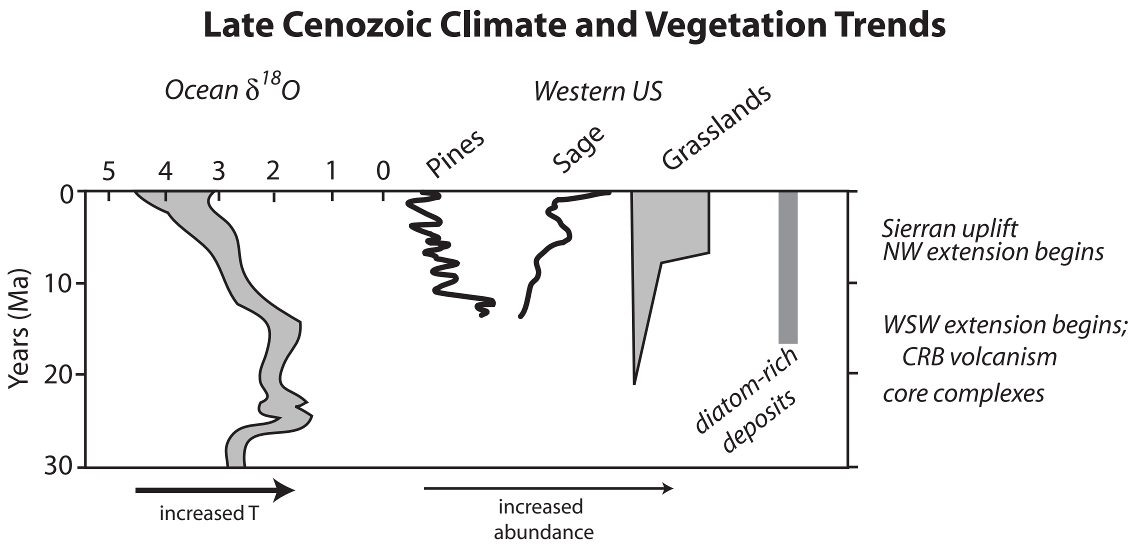

Figure 3. Global climate and regional vegetation changes in the Great Basin region. Oxygen isotope data show a thermal maximum at about 15 Ma, with a decrease in ocean and global climate temperatures to the present (from Zachos and others, 2001). Palynology studies indicate a decreasing abundance of pines and conifers and an increase in sage from about 12 Ma (jagged solid lines; Davis and Moutoux, 1998). Grasslands began to expand in the middle Miocene, with a large expansion at about 7–8 Ma (gray polygon; Retallack, 2001). The earliest freshwater diatomaceous deposits formed at about 16–17 Ma, and they continued to form into the Quaternary (vertical gray bar). Shown also are important tectonic events and the eruption of the Columbia River Basalt Group (CRB) between about 17 and 14 Ma.

A second period of basin formation began at about 13 Ma and lasted for a few million years. Lacustrine sediments deposited in these basins contain some of the larger diatom-rich deposits in the region, including those in western Nevada along the Walker Lane (fig. 1). These lake-filled basins include the Coal Valley and Esmeralda basins, as well as unnamed, possibly interconnected, basins between Hazen and the Brady area (Stewart, 1992a). Basins of similar age, such as the El Paso basin, were present in the Mojave region of southeastern California (fig. 1; Perkins and others, 1998).

The youngest lakes formed in the late Miocene and Pliocene in response to the formation of the modern topography. As shown on figure 1, these lacustrine sediments are present in the Panaca Formation of southeastern Nevada (Phoenix, 1948), the Verdi basin in western Nevada (Cashman and others, 1999; Trexler and others, 2000), the Thousand Springs Formation of northwestern Nevada (Greene, 1984), and the Chalk Hills and Glenns Ferry Formations of southwestern Idaho (Kimmel, 1982). Some of the late Pliocene and Pleistocene lakes that were extensive throughout the Great Basin (Reheis, 1999) filled basins that previously were occupied by Neogene lakes, and some basins, such as in the Great Salt Lake basin, may have contained lakes for more than 10 million years (Davis and Moutoux, 1998).

Basin Characteristics

Variations in Neogene tectonic environments, processes, and climates produced variable basin configurations and evolutions in the Great Basin region. In eastern Nevada, basins responded in different ways to middle Miocene detachment faulting and related uplift. Small orogenic basins, such as the Horse Camp basin and in the Sacramento Pass area in eastern Nevada (g, fig. 1), formed immediately adjacent to the detachment faults. Coarse clastic debris derived from the rapidly rising adjacent highlands was shed into the developing basins, disrupting the limited lacustrine environment (Horton and Schmitt, 1998; Miller and others, 1999; Martinez, 2001); diatom-rich sediments are not reported from these basins. Slightly more distal environments in the Humboldt Formation northeast of Wells (Mueller and others, 1999) and south of Elko (Smith and Ketner, 1976) received somewhat finer-grained orogenic sediments. These environments transitioned upward and outward into broad lacustrine basins between about 16 and 13 Ma, eventually forming extensive lacustrine sedimentary deposits of the Humboldt Formation throughout northeastern Nevada (f, fig. 1). The lacustrine sediments contain abundant airfall ash (10–100% of the basin-filling material; Sharp, 1939; Regnier, 1960; Wallace, 2003), and clastic materials are fine grained. In the Carlin sub-basin of the Humboldt Formation, south-flowing streams entered a lacustrine environment and introduced more clastic sediment to the northern lake sediments than to the southern sediments (A. Wallace, unpubl. data, 2003). Clastic sedimentation waned with time, and the lacustrine environment dominated the overall basin sedimentation. Diatom-rich sediments were deposited during this late, clastic-poor period of lacustrine sedimentation. Subsequent clastic sedimentation related to uplift eliminated the lacustrine environment.

In west-central and southwestern Nevada, broad, early-extensional basins formed in the middle Miocene (17 to 14 Ma) Stewart Valley and Middlegate areas along the Walker Lane (i, fig. 1) and in the Virgin Valley Formation near McDermitt (e, fig. 1). Stratigraphic sections in those locations contain modest to significant amounts of diatom-rich sediments (Starratt, 1987; Stewart, 1992a; Stewart and others, 1999; Greene, 1984). As extension continued and tectonic environments changed, various other basins along the Walker Lane began to form between about 13 and 7 Ma. At Coal Valley and Hazen, syn-sedimentation faulting changed the basin configuration during the life of the lake (Axelrod, 1956; Houseman, 2004). Most of the sediments in the Walker Lane basins are fine grained with significant air-fall ash, and coarser sediments are present only near the ancient shorelines (Axelrod, 1956; Stewart, 1992a). Tephrochronology studies show that several of the basins were active at the same time (Stewart and Perkins, 1999), but subsequent uplift and erosion has obscured any evidence of interbasin connections (Stewart, 1992a). In several areas, the lake environments eventually were succeeded by volcanic flow activity or coarse alluviation related to uplift of nearby horsts. Diatoms flourished in the lakes and formed diatom-rich sediments several tens to more than a hundred meters thick. These sediments are the main sources of diatomite in Nevada and are mined in the Lovelock (Trinity), Brady, Hazen, Clark, and Fernley areas.

Some lakes formed in response to middle Miocene volcanism. In eastern Oregon, middle Miocene rhyolite eruptions disrupted the drainage systems and formed locally extensive, diatom-bearing lakes (Barlock and Vander Meulen, 1991). In southern Oregon, a lake filled the moat of a caldera and produced significant diatomaceous deposits (Barrow, 1983). A broad lake formed between two northwest-trending zones of bimodal volcanism east of Paradise Valley, NV, between 16.1 and 15.2 Ma; diatomite has not been reported from this locale (Wallace, 1993; A. Wallace, unpubl. data, 2000–02).

Latest Miocene and Pliocene basins formed as the modern basin-and-range physiography began to develop at about 6 Ma. Near Panaca in southeastern Nevada, a depocenter formed behind a volcanic dam and produced the Panaca Formation (j, fig. 1). The unit largely is pedogenic but contains minor lacustrine and diatom-rich sediments near the center of the basin, and through-flowing drainage resumed when the dam was breached in the Pliocene (Phoenix, 1948; Pederson and others, 2000). The Muddy Creek Formation in southeasternmost Nevada formed at the same time (Bohannon, 1984). In southwestern Idaho, volcanic dams produced the late Miocene Glenns Ferry and Pliocene Chalk Hills Formations (c, fig. 1), which formed in successive lakes and produced thick diatom-rich sediments that have been mined for diatomite (Kimmel, 1982; Moyle, 1985). Other late Miocene and Pliocene basin sediments include the late Miocene Thousand Springs Formation in northwestern Nevada (d, fig. 1; Greene, 1984) and the Pliocene Hay Ranch Formation in northeastern Nevada (l, fig. 1; Gordon and Heller, 1993), as well as isolated to more widespread basins in eastern Oregon (the diatomite-bearing Otis basin near Vale) and western Idaho. In addition, Miocene and Pliocene sediments, including some lacustrine deposits, are concealed beneath extensive Quaternary alluvial fans in many major basins in the Great Basin.

Diatoms and Diatom-Rich Sediments

Various regional and local processes produced diatom-rich sediments, some of commercial quality and size, in some Neogene basins in the Great Basin over the last 17 million years. Given that these sediments comprise only a small percentage of the regional basin-filling sediments, their formation must have required specific local processes. Processes necessary to form commercial diatomite deposits were even more specific. The general geologic settings of many diatom-rich sedimentary sections and a few commercial diatomite deposits are known. However, detailed, published descriptions of diatom taxonomy or the geology of the diatomite deposits are very limited.

Figure 1 shows the locations of diatomite mines and prospects in the Great Basin region, regardless of size or economic value, based on U.S. Geological Survey mineral-deposit records. The majority of these diatomite deposits are small, with only minor exploration. Many other occurrences of diatom-rich sediments, some of them thick and extensive, are not included in those databases due to the lack of prospecting or development. All of these are located in areas shown as late Cenozoic sediments, although not all of these sediments contain diatom-rich sediments.

Diatom Taxonomy

Published descriptions of the taxonomy of Neogene lacustrine diatoms in the Great Basin are very limited. Diatoms have two basic forms—centric diatoms have a radial structural, and pennate diatoms have a bilateral symmetry—and both forms are present in Great Basin diatomaceous sediments and have different end uses. The published studies indicate that the most common genera are *Melosira*, *Fragileria*, and *Cymbella* (Krebs and Bradbury, 1984; Papke, 1992; Lenz and Morris, 1993), but that a variety of other diatom genera are present as well. Some species that previously were included in the *Melosira* genus now are assigned to the *Aulacoseira* genus (California Academy of Sciences, unpubl. data, 2003), but *Melosira* was used in Great Basin-related papers and thus is used in this report. *Melosira* and *Fragileria* are the dominant genera in the Trout Creek deposits in southeastern Oregon (d, fig. 1; Barrow, 1983), and *Navicula*, *Melosira*, and *Epithemia* are the main diatom genera in the late Miocene to Pliocene deposits in southwestern Idaho (Moyle, 1985). The middle Miocene genus *Actinocyclus*, although not particularly abundant, was areally widespread in the middle Miocene and thus provides a biochronological indicator (Krebs and others, 1987; Krebs and Bradbury, 1995; Bradbury and Krebs, 1995).

Characteristics of Diatom-rich Sediments

Lacustrine, diatomaceous sedimentary sections in the Great Basin vary considerably in thickness and lateral dimensions. Commercial diatomite deposits are less than ten to more than a hundred meters thick, whereas many non-commercial diatomaceous beds are considerably thinner or are diluted with non-diatomaceous sediments. Some diatomaceous sediments were deposited in narrow structural basins, and others were deposited from lakes that had large lateral extents. The two forms are superimposed in some places, such as at Hazen (Houseman, 2004).

The amounts of interbedded, nondiatomaceous material vary vertically and laterally through the diatom-rich deposits. Relatively uncontaminated diatom-rich sediments near the center of a basin may grade laterally into near-shore facies with increased amounts of clastic material. The locations of inflowing streams relative to centers of diatom sedimentation, as well as the topographic gradient of adjacent uplands, may have influenced the kinds and amounts of clastic interbeds in the basin sediments. Thin to thick clastic beds and/or volcanic flows separate diatom-rich zones in numerous basins, including those at Hazen and the Chalk Hills in western Nevada (h, fig. 1). The volcanic and coarser clastic interbeds indicate interruptions of and then a return to lower-energy conditions, in places in short, repeated cycles (see fig. 20F in Schwartz, 2001). The presence or absence of ash could have been due to (1) the location or size of eruptions that took place during diatom activity, and/or (2) the rate of diatomite formation relative to the recurrence rate and size of eruptions.

At several diatom-rich deposits, including the Trinity, Brady’s, and Hazen diatomite mines and prospects in western Nevada (h, fig. 1), the diatom-rich beds apparently are near the base of the Miocene section and are covered by either clastic sediments or volcanic rocks, suggesting that diatom deposition took place during early-extension basin development (Stewart, 1992a). Other diatom-rich deposits, such as Trout Creek (d, fig. 1; Barrow, 1983) and Chalk Hills (h, fig. 1; Schwartz, 2001), formed in basins between volcanic eruptions, although a million or more years may have separated volcanism and the deposition of the diatom-rich sediments. The Miocene-Pliocene, diatom-rich sediments of the Clover Creek diatomite deposit in southwestern Idaho (c, fig. 1; Moyle, 1985) were deposited on two suites of basalts shortly after each eruption.

Paleoecology and Formation

Water temperature, pH, chemistry, and nutrient concentration influence diatom activity, and those are influenced by a wide variety of processes. Very limited studies of Great Basin diatom-rich sediments indicate that the lake waters were warm and had neutral to slightly alkaline pHs (7 to 8 and perhaps greater), carbonate buffering, and low salinities and Na/K:Ca/Mg ratios, all of which favor diatom activity (Sheppard and Gude, 1983; Barrow, 1983; Lenz and Morris, 1993). Diatom-rich sediments in the Esmeralda Formation in Stewart Valley formed from alkaline, low-salinity lake waters, and the lake was rich in nutrients and was affected by seasonal thermal fluctuations (Starratt, 1987). In the Trout Creek diatom deposits in southern Oregon, diatom species indicate low water salinities and a continual balance between lake inflow and outflow (Barrow, 1993).

Pennate diatoms (such as *Fragileria*) and centric diatoms (such as *Melosira*) commonly occur in different parts of diatomite deposits, although some deposits contain a mixture of both types. The pennate:centric ratio has been used by some workers to show the level of eutrophy in a lake. Eutrophy indicates abundant nutrients (especially phosphorous and nitrogen) and high biotic productivity, which can be a function of season, position within a lake, or other ecologic factors (Wetzel, 2001). At Trout Creek (d, fig. 1), Barrow (1983) used alternating *Melosira*- and *Fragileria*-rich beds to infer seasonal changes in eutrophy. However, some pennate species prefer less-eutrophic water and some centric species favor eutrophic water (Hall and Smol, 1999; Bradbury, 1988). Additional factors contributing to the pennate:centric ratio include water depth (planktonic versus benthic environments) and stability of water conditions, such as open-water conditions, proximity to inflowing streams, near-shore turbulence, and wind activity. For example, at the Hazen diatomite mines, centric *Melosira* diatoms are present in basal sediments deposited in relatively deeper water, whereas pennate *Fragileria* diatoms are in the upper sediments that were deposited in shallower water (Krebs and Bradbury, 1984; Houseman, 2004).

Dissolved silica is required to form the siliceous diatom frustules (the preserved amorphous cell walls of diatoms). High diatom productivity can consume all available silica and limit diatom activity (Wetzel, 2001), although considerable numbers of frustules dissolve as they sink, thereby returning silica to the water. The abundant silica needed to form the large commercial diatomite deposits in the Great Basin required a large silica source. However, diatoms typically bloom only twice a year (spring and fall), so sufficient silica was needed only periodically for the thousands of years that it probably took to form a deposit. Dissolved silica derived from weathering in surrounding highlands was introduced into lakes through surface runoff and groundwater, and active tectonism and related erosion may have enhanced the weathering and transport processes. Particulate silica was derived from clastic sediments that washed into the lakes, and from ash and dust that fell on the lakes. In addition, grass washed in from surrounding highlands could provide considerable amounts of silica (Kidder and Gierlowski-Kordesch, 2002). However, too much volcanic ash might have limited diatom activity by smothering the lake, as shown in the ash-rich parts of the Humboldt Formation in northeastern Nevada. Geothermal systems also may have contributed silica where those systems were active beneath or adjacent to a lake.

Phosphorous (P) is the most important nutrient for diatom development, and studies of modern lakes indicate that diatom activity correlates directly with the amount of P, even in water with moderate to low amounts of dissolved silica (Hall and Smol, 1999; Wetzel, 2001). Phosphorous can be derived from many sources, and the P cycle and bioavailability within lakes are complex. In the Great Basin and much of the western United States, runoff from nearby highlands probably was the most likely local P source. Andesitic to basaltic volcanic rocks were common in the highlands near many of the diatom-rich sedimentary sequences in the Great Basin (fig. 4), as well as at numerous diatom locations in Idaho, Washington, and Oregon. Basalts and andesites usually contain far more P (1400–1600 ppm) than other igneous (170–700 ppm) and sedimentary (170–750 ppm) rocks (Krauskopf, 1979). Miocene basalts and andesites near the Chalk Hills and Hazen deposits contain as much as 15,000 ppm P (Schwartz, 2001; Houseman, 2004). Present surface runoff from Icelandic basalts is oversaturated with P derived entirely from interstitial glass in basalts (Arnrsson and others, 2002). Thus, in the Great Basin, enough P may have been released by seasonal runoff from the basalts and andesites to enhance diatom activity in many lakes. Runoff from these volcanic rocks also could have produced the low Na/K:Ca/Mg ratios that, as noted above, favor diatom activity. However, volcanic rocks of these compositions are scarce (or, if present, poorly exposed) in the vicinity of a few large deposits of diatom-rich sediments, such as those in the Trinity Range near Lovelock (h, fig. 1; Nash, 1995), so volcanic rock composition may not be the only factor in the source and availability of P and other elements. Both andesites and phosphorous-rich Permian sedimentary rocks were present in highlands surrounding the diatomite-bearing Carlin basin in northeastern Nevada (Evans and Ketner, 1971; Ketner, 1973), and each may have contributed P. Shales also are potential source for P, but these were relatively scarce in highlands surrounding Neogene lake-filled basins.

Lake paleoecologies are a dynamic interplay between seasonal and long-term hydrology, basin morphology and evolution, climate, and nutrient availability. Drought decreases lake size and inflow and increases evaporation, eutrophy (Webster and others, 1996), element concentrations, and possibly pH. Neogene, diatomaceous sediments that formed under these conditions were deposited in relatively restricted parts of the basin and contained diatom genera that favored those conditions. Conversely, periods of higher precipitation caused more water, clastics, and nutrients to enter the lakes. The lakes expanded, might have become connected with other lakes, and may have had more widespread littoral and marginal marsh environments, both of which increase eutrophy (Starratt, 1987; Wetzel, 2001). Neogene, diatom-rich sediments that formed during wet periods may have been more widespread laterally and contained genera that preferred those ecosystems. Each lake would have responded to the local prevailing conditions, and coeval lakes in the same region might, as a result, have produced slightly to very different diatom-rich sedimentary sections.

In structurally active areas, fault-related uplift and/or subsidence changed basin morphologies and surrounding topography. As a result, a broad, shallow basin, with its related paleoecology, could evolve through time into one or more sub-basins, each with somewhat different paleoecological conditions, diatom genera, and deposit configurations. In addition, continued uplift of adjacent areas would have increased the input of nutrients and clastic sediments, although too much clastic input could have ended robust diatom activity temporarily or permanently. Such changes have been documented along the Walker Lane (Stewart, 1992a; Stewart and Perkins, 1999) and in Miocene lakes in northernmost Nevada (Smith and Ketner, 1976; Wallace, 2003). Conversely, Houseman (2004) described the formation of early fault-related sub-basins at Hazen that filled and merged into a broad, shallow lake as fault activity waned.

Different diatom genera favored different ecological niches within the lakes or their margins. At Hazen, centric diatoms dominate in the early sediments, especially near shorelines, and pennate diatoms are widespread in the later, shallow-formed sediments (Houseman, 2004). With the regional increase in aridity (fig. 3) and probable related changes in lake habitats, chemistry, and source nutrients, the formation of diatom-rich sediments throughout the Neogene (fig. 3) suggests differences in diatom genera. Limited work by Bradbury and Krebs (1995) indicates changes in genera through the Neogene, with *Actinocyclus* in the middle Miocene and *Cyclotella* and *Stephanodiscus* in the Pliocene. They cite global species radiation as one reason for the change, but they also note that "paleoenvironmental changes and species competition" may have been causes.

Plant, mammal, and reptile fossils indicate that marshes and wetlands rimmed many of the lakes in the region, although the abundance and types of these organisms varied with increased aridity (Retallack, 2001; Davis and Moutoux, 1998). Throughout the Neogene, many of the lakes supported abundant fish (Smith and others, 1982; Brown, 1986; Smith, 1987), as well as algal (tufa) buildups that formed thin to thick, ostracod-bearing carbonate beds (Willden and Speed, 1974; Smith and Ketner, 1976). With increased aridity, the more widespread grasslands in nearby highlands (fig. 3) also may have contributed additional nutrients and silica to runoff (Kidder and Gierlowski-Kordesch, 2002).

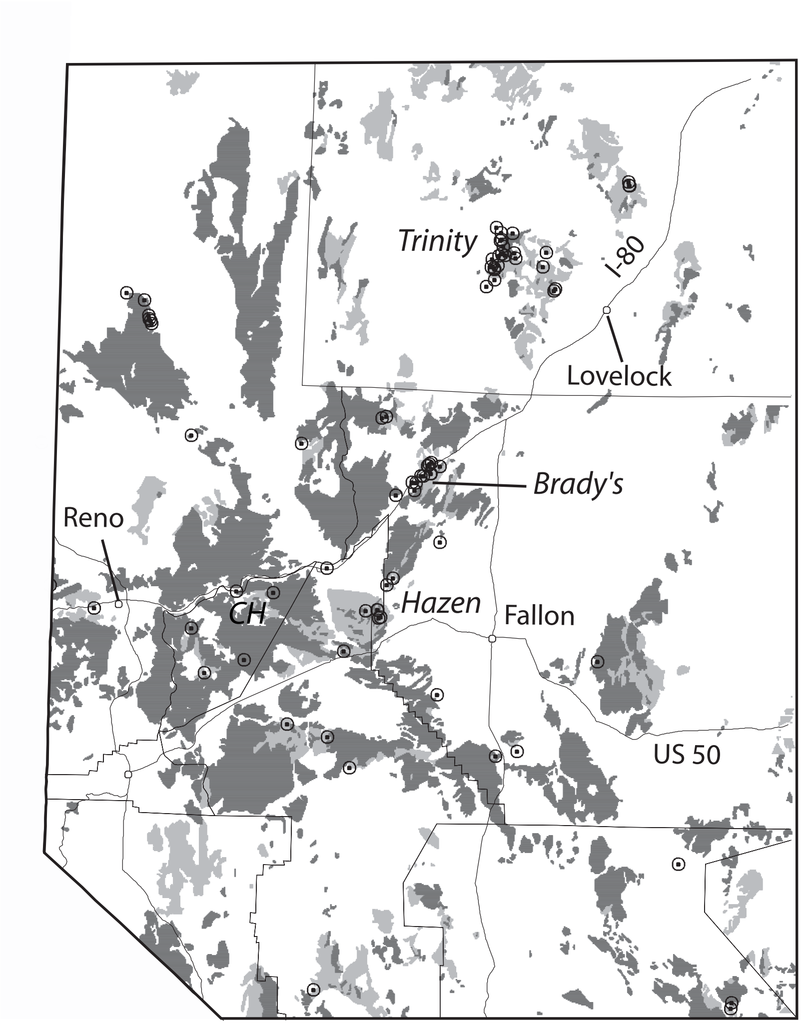

Figure 4. Map showing the distribution of late Cenozoic mafic to intermediate-composition volcanic rocks, sedimentary rocks, and diatomite deposits in west-central Nevada. Andesites and basalts have average phosphorous contents of 1400–1600 ppm, as compared to 170–700 ppm in felsic volcanics rocks Krauskopf (1979), which are common in the region as well. Phosphorous derived from andesites and basalts in the highlands surrounding late Cenozoic lakes may have enhanced diatom activity in the lakes. Diatomite and sedimentary rock locations as in figure 1; volcanic units from Stewart and Carlson (1978). Names of diatomite mine areas cited in text are shown; CH: Chalk Hills.

Duration of Formation of Diatom-rich Sequences

Many studies, both in marine and non-marine environments, have documented accumulation rates for diatoms in bottom sediments. For example, Clark (2001) estimated an annual diatom accumulation rate of about 1.3 mm/year in Miocene, shallow-marine diatomite deposits in south-central California. However, accumulation rates vary widely depending on the paleoecology, lake productivity, and climate, and changes in just the amount of phosphorous can have an enormous impact on diatom activity and accumulation rates (Hall and Smol, 1999). Also, depending on the water chemistry, significant amounts of diatom frustules (up to 90%) can be dissolved or consumed by other organisms during settling. Therefore, a direct comparison between thickness of diatom-rich sequences and the time needed for the sequence to form may not be realistic for the Neogene lakes of the Great Basin. Most of the occurrences of diatom-rich sediments in the region are small and thin and may have taken only a few thousand years to form.

Available geochronology provides general to specific ages for some diatom-rich sedimentary deposits (Perkins and others, 1998; Perkins and Nash, 2002), but at only two deposits do dates give clues regarding the duration of sedimentation. At the Brady's diatom-rich deposits in western Nevada (h, fig. 1), tephrochronology data suggest the diatom-rich part of the sequence took at least 600,000 years to form (Stewart and Perkins, 1999), and available geochronology at Hazen suggests a shorter time to form the entire diatom-rich sedimentary section (Stewart and others, 1994; Perkins and Nash, 2002; Houseman, 2004). However, the relative thicknesses of the two sections is unknown due to incomplete exposures.

Post-Depositional Events

Beginning with the end of diatom deposition, each basin was subjected to a variety of tectonic, volcanic, and alteration processes that, in many cases, modified or destroyed the diatom-rich sediments. In addition, later clastic sediments and volcanic units concealed many basinal sediments. Given the geologic evidence for relatively widespread Neogene lakes, the preserved and exposed diatom-rich sediments, including the commercial diatomite deposits, represent a subset of the original basins and possible diatomite deposits.

End of Diatomite Formation

Field evidence indicates that Great Basin diatom-rich sediments ceased to form when clastic or volcanic units effectively terminated the lake environment or when the lake drained or dried up. In the Trinity, Brady, and Chalk Hills areas (fig. 1), clastic sediments related to nearby uplift inundated the lakes and buried the diatom-rich sections (Nash, 1995; Stewart and Perkins, 1999; Schwartz, 2001). An ash-flow tuff was erupted across and eliminated a broad, shallow lake northeast of Winnemucca, NV (Wallace, 1993), and volcanic flows alternately covered and were covered by lake sediments in eastern Washington and southwestern Oregon. The capping basaltic andesite flows at Hazen, NV, are undated; if they are approximately the same age as the upper diatom-rich beds, they may have ended the lacustrine environment.

Some lakes, such as one near Panaca, NV, drained when the dam that created the lake was downcut and breached. In Pine Valley south of Carlin, the lake that produced the Hay Ranch Formation (1, fig. 1) may have drained as the developing Humboldt River drainage system expanded into Pine Valley (Reheis, 1999). Given the increased aridity through the Neogene, many of the smaller lakes likely just dried up (fig. 3).

Diagenesis and Alteration

Diagenetic alteration products are common in Great Basin lacustrine and diatom-rich sediments, and their presence usually reduces the commercial value of the diatomite deposits. The amount and type of alteration of the lacustrine sediments varied depending on permeability and porosity, pore- and groundwater composition, and the level of the ground water table during lithification. Alteration of volcanic ash in the sediments began almost immediately after sedimentation and produced various cements, chert phases, zeolites, and clay minerals that formed at the expense of the original sediments. Many of the recorded zeolite prospects in the central Great Basin are within and formed at the expense of ash-rich Neogene lacustrine sediments (fig. 5), some of which also contain relict diatom-rich sediments. However, alteration of diatoms to zeolites has not been documented in the Great Basin. In extensively altered sediments, such as northeast of Winnemucca, NV (Sheppard and Gude, 1983; Wallace, 1993), the original presence of diatom-rich beds may be difficult to determine. Diatoms themselves undergo a structural transformation almost immediately after deposition, with a subsequent change to more stable silica phases.

Miocene and younger hydrothermal systems formed around the many volcanic centers, and late Cenozoic high heat flow in the northern Great Basin has produced additional epithermal deposits and geothermal centers. Many of the volcanic and hydrothermal systems formed near coeval lakes or, in the case of young geothermal systems, within the sediments of long-extinct basins (fig. 5). Hydrothermal alteration generally is very localized, and it partially to completely produced chalcedony, opal, and clay minerals in lacustrine sediments in some areas (Ebert and others, 1996; Wallace, 2003). The effect, if any, on diatoms in the sediments has not been described. In addition, subaqueous fluid venting may have contributed silica to the lakes themselves, which may have affected bottom-water compositions and early diagenesis of diatom-rich and other lacustrine sediments.

Tectonic Activity and Erosion

Given the variation in tectonism and erosion through time and space in the Great Basin, the original lacustrine basins and deposits in some areas are intact, whereas a relict patchwork is all that remains in other areas. In western Nevada, field and tephrochronology studies (Stewart, 1992a; Perkins and others, 1998; Perkins and Nash, 2002) suggest the original presence of widespread lacustrine environments. However, Neogene uplift and related erosion has disrupted the original basins significantly (fig. 1; Stewart, 1992a), and alluvial sedimentation has concealed many of the lacustrine sediments. In this subregion, reconstruction of basin configurations and the diatom-rich sedimentary sequences in a basin-wide scenario from the isolated remnants would be extremely difficult (Stewart, 1992a; Bradbury, 1999). Some extension but relatively little uplift affected the western Snake River Plain of Idaho. As a result, the original basins and lacustrine deposits there remain fairly intact, although perhaps concealed by volcanic and relatively thin fluvial sedimentary deposits.

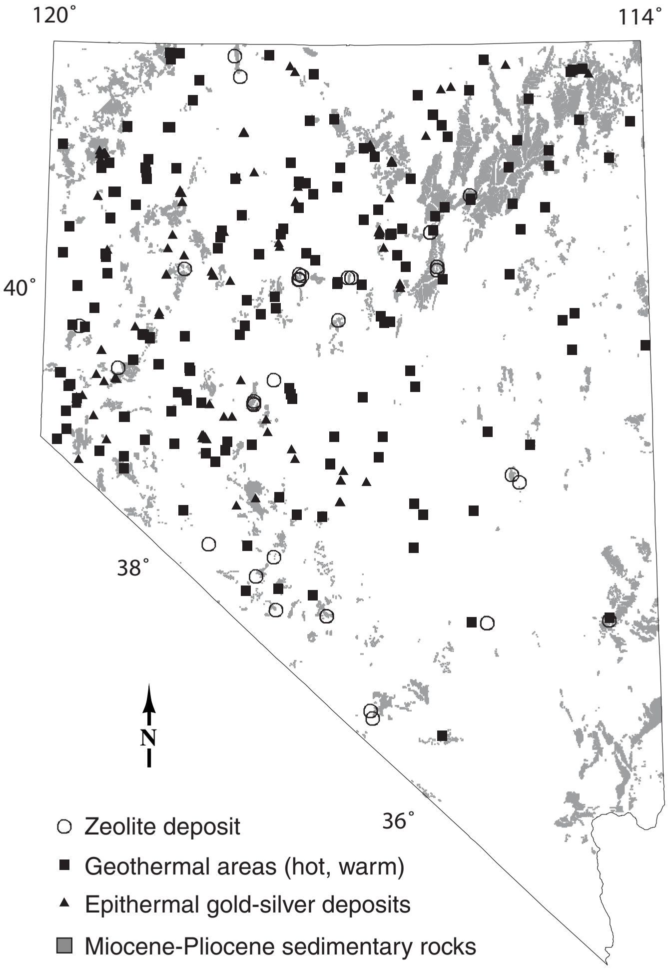

Figure 5. Map showing the locations of possible alteration of lacustrine sedimentary rocks and diatom-rich sediments. Diagenetic alteration formed zeolite deposits, and late Cenozoic epithermal gold-silver and geothermal systems silicified and altered lacustrine sediments. Miocene and Pliocene sedimentary rocks shown in gray. Geothermal locations from Garside (1994); epithermal and zeolite deposit locations from U.S. Geological Survey Mineral Resource Data System records; sedimentary rocks from Stewart and Carlson (1978).

The amount, style, and timing of uplift and erosion had a direct influence on the diatom-rich sediments and commercial diatomite deposits. As shown in the Coal Valley and Brady areas (Axelrod, 1956; Stewart and Perkins, 1999), uplift began during lacustrine sedimentation, sediments stripped from the highlands inundated the lake, and normal faulting began to modify and segment the basin. Uplift that takes place immediately after sedimentation might eliminate the lake and modify the groundwater table. This can be economically beneficial if it limits diagenetic alteration of the diatom-rich sediments and they retain the original diatom texture and purity. Furthermore, and perhaps most importantly for the diatomite industry, uplift of a diatomite deposit above the groundwater table can induce oxidative leaching of organic material, thereby increasing brightness, and contaminating trace elements such as As, S, and Fe. However, poorly cemented lacustrine sediments are more susceptible to erosion than more-resistant units, such as volcanic flows. These sedimentary deposits tend to form topographic lows that are closer to the water table or are more likely to be covered by later volcanic units or alluvial deposits. However, Nash (1995) noted that modest fault-related downdropping of diatom-rich sediments and concealment by relatively thin alluvial deposits combined to preserve the diatom-rich sediments in the Trinity area, where they are mined for diatomite. At the full extreme, extensive high-angle faulting and related erosion can completely eliminate a diatomaceous section or conceal it beneath extensive, thick alluvial deposits.

Application to Commercial Diatomite Deposits

Although this paper does not directly address the commercial diatomite deposits, the processes described here apply to those deposits and dictated the current distribution and characteristics of these deposits. Both size and purity of a diatomite deposit can be important, as can the diatom genera in the deposit, the amount of overburden that needs to be stripped, and the degree of secondary alteration (Dolley, 1999). Non-geologic factors, such as transportation distance, can affect the economic viability of a deposit, even one of high quality. The intended use of the diatomite often determines the economic viability of a deposit. Thus, depending on need, impure diatom-rich sediments or small, high-quality deposits of a specific genus can be as economic to mine as extensive or thick diatomite. Examples of the former deposits include deposits that, even with high calcium carbonate contamination, have a very high brightness and thus are suitable for paint and paper brightening. Very specific processes led to the formation and preservation of the latter deposits, and further work is needed to differentiate the processes that formed those deposits from those that formed the smaller deposits.

Conclusions

This paper summarizes many of the factors that led to the formation of diatom-rich sediments from Neogene lakes in the Great Basin region and to their subsequent destruction or preservation. Some of these factors are global to regional, such as climate and regional tectonics, whereas others are more local, such as volcanic flows and syn-sedimentary faulting. A favorable combination of these processes produced the presently exposed diatom-rich sedimentary rocks in various parts of the region, and less-optimum combinations elsewhere undoubtedly prevented the formation of diatom-rich sediments or destroyed or buried them after formation. These processes dictated the present distribution and characteristics of the diatom-rich sediments that are being mined for diatomite.

Several critical regional and local factors have received little or no research attention, and more information on some to all of these would provide a better understanding of lacustrine basins and diatom-rich sedimentary sequences in the region. Additional geochronology, both at local and regional scales, is needed to constrain the relation of diatom activity to volcanism and tectonism, both during and after the formation of the diatom-rich sediments, and to determine the duration and rates of deposition. Additional deposit-scale diatom taxonomic investigations, combined with studies on the original extents of the lakes, would provide important clues regarding basin-scale paleoecology. Chemical and isotopic studies on lake deposits and source-area rocks would help determine lake chemistry, paleoclimate, and the types and sources of various nutrients. The ultimate goals are to develop better regional exploration and assessment models for known and undiscovered commercial diatomite deposits, and to improve our understanding of the Neogene evolution of the Great Basin.

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Replenishment of Salt to the Bonneville Salt Flats: Results of the 5-Year Experimental Salt Laydown Project

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Abstract

From November 1997 to May 2002, Reilly Industries, Inc. (Reilly) and Bureau of Land Management (BLM) conducted a Salt Laydown Project in an attempt to increase the salt-crust thickness of Bonneville Salt Flats (BSF). The objective of the 5-year experimental project was to replenish approximately 1.5 million tons of salt and add a 0.4-inch thickness of new salt crust to the existing salt crust each year. The Salt Laydown Project demonstrated that sodium-chloride salt in brine removed from BSF for mineral extraction can be replenished.

During the 5-year period, 6.2 million tons of sodium-chloride salt was transported back to BSF. The average annual 1.2 million tons of salt exceeded an estimated annual salt loss of 0.85 million tons. Over the 5-year experiment, 4.2 million tons of salt removed for mineral extraction was replaced by 6.2 million tons of Laydown salt. The difference resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system. Before the Laydown Project, some of the brine removed from BSF was replaced by meteoric precipitation, which dissolved salt crust. During the Laydown Project, the removed shallow-aquifer brine was believed to be mostly replaced by Laydown brine, which generally approached halite saturation and consequently minimized salt-crust dissolution.

Satellite imagery shows a 5-square-mile increase in the salt crust from 1997 to 1999. Based on the new salt-crust area and its measured thickness of 0.25 to 1 inch, about 0.6 million tons of salt were added to the existing salt crust. The 2-inch increase to salt-crust thickness expected as a result of the project was not observed in measurements from recent test pits and auger holes excavated in BSF. However, geochemical modeling suggests that 17 to 25 million tons of additional salt could be assimilated into the shallow-brine aquifer beneath BSF. Therefore, excepting contribution to the new salt-crust area, most of the 6.2 million tons of salt transported to BSF was apparently incorporated into the underlying shallow-brine aquifer. This may contribute to additional salt-crust formation in the future.

Introduction

The Bonneville Salt Flats (BSF) are located in the western part of the Great Salt Lake Desert of northwestern Utah. BSF is part of a large playa that occupies one of several enclosed sub-basins that comprise the Great Salt Lake Desert (fig. 1). These sub-basins include the Bonneville Salt Flats, Pilot Valley, and the Newfoundland basin. BSF is roughly divided into a north and south half by the east-west trending Interstate Highway 80 (I-80) and the adjacent Western Pacific Railroad right-of-way. The Western Pacific (now Union Pacific) Railroad right-of-way is parallel to, and 1,400 feet south of I-80. BSF's north half includes sites of a historical circular race track and the 10- to 12-mile-long International Track, and is dominated by public land managed by U.S. Bureau of Land Management (BLM). Its south half is mainly private and dominated by commercial potash production. Twin cities of Wendover, UT and Wendover, NV are adjacent to I-80 and 4 miles west of BSF's western margin.

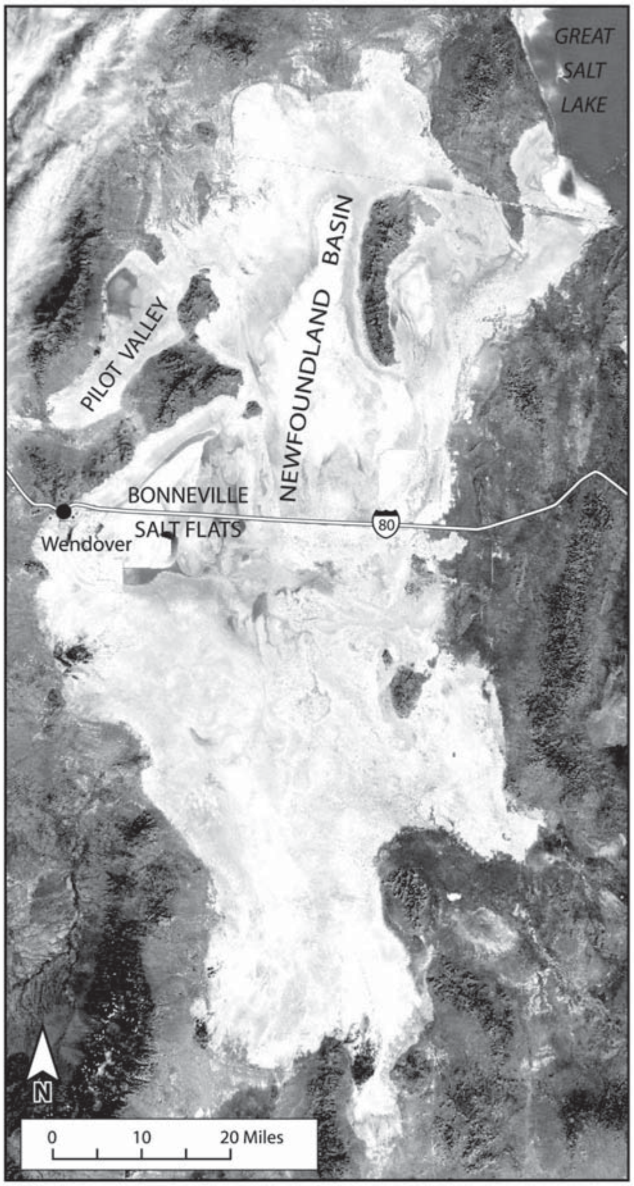


Figure 1. A portion of the Great Salt Lake Desert showing sub-basin locations (Bonneville Salt Flats, Pilot Valley, and Newfoundland basin).

Societal Need for the Salt-Laydown Project

Reported depletion of salt-crust thickness has been a concern to the public and land-managing agencies for at least 26 years (McMillan, 1974, p. 1; Lines, 1979, p. 4). This concern is based on changes in salt-crust area and volume reported between 1960 and 1988 that were measured north of the Western Pacific Railroad and I-80. McMillan (1974, p. 3) reported a 9 and 15% respective decrease in salt-crust area and volume during 1960–1974. Brooks (1991, p. 8) calculated 20 and 30.6% respective decreases in salt-crust area and volume during 1960–1988.

Because the BLM, Reilly Industries, Inc. (Reilly), and the racing community (represented by "Save the Salt" - STS) were concerned about the reported deterioration of BSF, they attempted to replenish salt to BSF through cooperative agreements. In 1991, Reilly and STS jointly funded a salt-replenishment feasibility study that resulted in a Salt-Laydown facility plan (Bingham, 1991). According to the plan, sodium chloride (NaCl) brine would be pumped out onto BSF at a rate of 6,000 gallons per minute, 24 hours per day, for 6 months (November–April) during each year of the program. This experimental program was scheduled to operate for 5 years. The Salt-Laydown facility plan suggested that up to 7.5 million tons of salt could be deposited during a 5-year period over a 28-square-mile area. According to Bingham (1991, p.2), the project could result in a 2-inch addition to the existing salt-crust thickness.

Based on the 1991 salt-replenishment feasibility study, BLM and Reilly entered into a Salt-Laydown Agreement in 1995. Under the Laydown Agreement, Reilly financed the installation and operation of a $1,000,000 Salt-Laydown facility, and BLM and Reilly initiated a cooperative monitoring agreement to measure the amount of salt delivered to BSF each year of the program. The Laydown Project began delivering brine to BSF on November 1, 1997, and completed the 5-year experiment on May 2, 2002. Reilly is currently continuing the Salt Laydown Project on a voluntary basis.

Previous Work

Published pre-1997 studies (i.e., pre-Salt Laydown Project) of the BSF range from investigations conducted from 1925 to 1993 and include work from the following: Nolan (1927), Turk (1969, 1978), Lindenburg (1974), McMillan (1974), Lines (1978, 1979), USGS Conservation Division (1981), Brooks (1991), Mason and others (1995), and Mason and Kipp (1998). Details of these studies and their conclusions are summarized in White (2003).

Objectives

This paper summarizes the results of the 5-year experimental Salt Laydown Project that was initiated on November 1, 1997, and completed on May 2, 2002. Also included is application of the TEQUIL geochemical model to predict possible changes in BSF salt-crust thickness as a result of halite dissolution from specified rainfall events.

This report's objectives are to: 1) describe components and operation of the Salt Laydown Facility, 2) explain and quantify results from 5 years of Laydown Project operation and compare project data with BSF baseline data, 3) compare pre- and post-Laydown salt-crust thicknesses and areal extent, and 4) evaluate effects of mixing Laydown brine with shallow-aquifer brine using the TEQUIL model, and provide explanation for the fate of the Laydown salt in the BSF solid-liquid system.

Laydown Facility Description

The Laydown facility (fig. 2) is composed of brackish-water supply wells, about 11 miles of transfer ditches and associated pumps, three evaporation ponds comprising about 1,300 acres of bedded salt deposits, and a brine-distribution manifold. Because the ditch system and brine-distribution manifold traverse a 13-mile distance over flat terrain, the biggest challenge is to move water from one end of this flat area to the other. The following description of the Laydown Facility shows how this water movement is accomplished.

Brackish water is obtained from seven alluvial-fan wells on the south flank of the Silver Island Range. Brackish water contains from 6.2 to 8 g/L TDS (total dissolved solids) (Mason and Kipp, 1998, p. 49), compared with the shallow-brine aquifer that averaged 244 to 297 g/L TDS during 1994–2002. Brackish water from the seven wells is pumped into a series of transfer ditches that move water south and under I-80, a distance of 4.5 miles. To keep the brackish water flowing, Brackish-water pump #1 (BW#1) was installed in the transfer ditch south of I-80. A second pump (Brackish-water pump #2 - BW#2) was installed 1.5 miles south of BW#1. With aid of BW#1 and BW#2, brackish water was delivered through a 24-inch-diameter discharge pipe into the northwest corner of Primary Pond #4 North (PP#4N) where the salt dissolution process began.

PP#4N is an old solar-evaporation pond that was used to precipitate NaCl (as the mineral halite) from potassium-bearing brine during the economic mineral-recovery process. The 921-acre halite deposit was estimated to be 3 to 4 feet thick, and to contain about 8 million tons of NaCl. During its residence time in PP#4N (about 15 to 30 days), the brackish water dissolved as much as 2 pounds of salt per gallon, and the density of the resulting brine approached 1.2 g/mL (NaCl saturation). In the first three years of the project, PP#4N supplied 4.6 million tons of salt to the Laydown Project.

At the beginning of the project's fourth year, the efficiency of salt recovery from PP#4N began to decrease and brine quality dropped below acceptable limits. To resolve this problem, the brackish-water flow was re-routed through existing transfer ditches, and pump BW#2 was moved from PP#4N to the North Ripening Pond. North and South Ripening Ponds (NRP and SRP) then became the primary sources of Laydown salt. Salt-crust thickness measurements obtained from 26 auger holes drilled in NRP and SRP during 2002 averaged slightly more than 4 feet. Based on these measurements, salt tonnage present in NRP and SRP was estimated to be about 4 million tons. Because

NRP and SRP combined acreage was about 400 acres (less than half of PP#4N's 921 acres), less surface area was available for salt dissolution. To ensure a sufficient supply of brine for the project, as brine in NRP and SRP reached a grade of 14% NaCl (or brine density of about 1.12 g/mL) it was transferred from these ponds and stored in PP#4N. This brine transfer allowed for faster cycling of brackish water through NRP and SRP, provided more storage room for the developing brine, and enabled the 14% brine to dissolve additional salt from PP#4N and increase its grade to a more acceptable level (about 18–20% NaCl, or brine density of about 1.16 g/mL). During the last 2 years of the project, the NRP-SRP-PP#4N pond system supplied nearly 1.6 million tons of Laydown salt to the project.

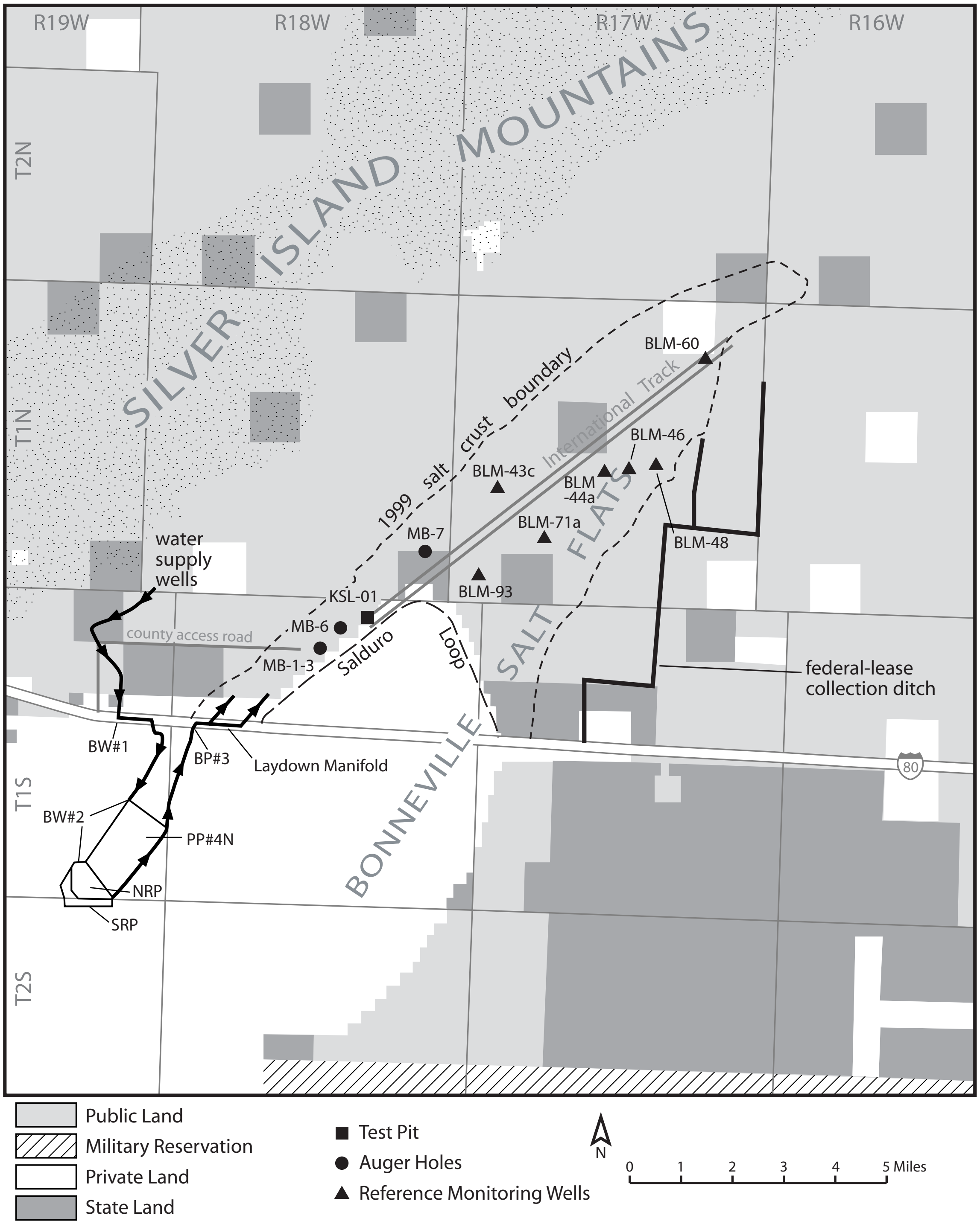


Figure 2. **Index map of reference monitoring wells, auger holes, and Reilly Laydown facilities in relation to Interstate 80, and Bonneville Salt Flat features (e.g., Salduro Loop, International Track, and county access road), Arrows on transfer ditches show water-flow direction.**

Linking NRP and SRP to PP#4N also allowed for continued use of the original brine discharge head gate in the southeast corner of PP#4N. From the southeast corner of PP#4N, brine flows through a north-trending, 3.3-mile transfer ditch that terminates at Brine pump site #3 (BP#3 - fig. 3). Brine is lifted approximately 11 vertical feet above the transfer ditch by the active pump and discharged into a concrete vault. Pumping the brine into the concrete vault provides sufficient hydraulic head for the brine to flow north for a distance of about 0.4 miles through a 24-inch-diameter discharge pipe. The north-trending discharge pipe passes under I-80 and discharges brine into the west end of a brine-laydown manifold. The laydown manifold is an east-west trending, 1.5-mile-long, 30-foot-wide area between westbound I-80 and a parallel frontage road. Brine flows north from the manifold and onto BSF through twelve culverts that are uniformly spaced along the manifold's length.

Methods

Methods used to compile data presented in this paper are described by White (2002a, p. 436–444), which summarized the first 3 years of the 5-year experimental Salt Laydown Project. Because this paper summarizes the completed 5-year project, data generated during the last 2 years of the project have been added to an appendix derived from White (2002a) and published on BLM's website (White, 2003).

Results and Discussion

Laydown brine was delivered to BSF for 5 years with the objective of adding salt to the salt crust. The Laydown brine was discharged to the salt crust from November through April where it mixed with the winter transient pond described by Mason and Kipp (1998, p. 33) and White (2002a, p. 444). Because of its source and location (mainly on the salt crust), the transient pond is hydrologically connected with the shallow-brine aquifer.

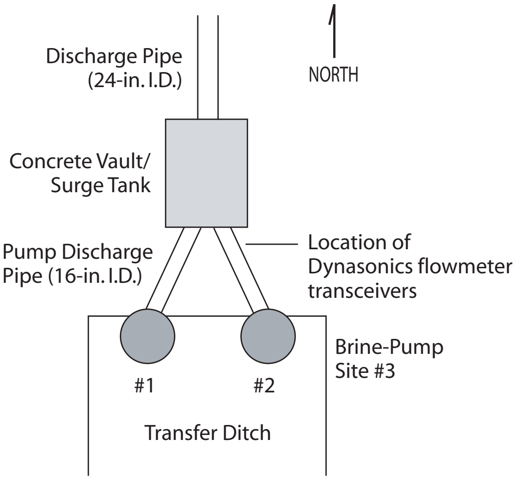


Figure 3. Plan view of Brine-pump site #3; pump #2 is active, and pump #1 is standby.

In the 1991 salt-replacement feasibility study, Bingham (1991, p. 2) estimated that a 0.4-inch thickness of NaCl salt could be added to the total salt-crust thickness each year. However, the effects of adding Laydown brine to the transient pond, and consequently to the shallow-brine aquifer, were unknown. Results focus on the following questions regarding the influence of adding Laydown brine to the transient pond:

- How much dissolved salt was delivered to BSF by the Laydown Project?
- How much salt was added to the salt crust?
- Does shallow-aquifer brine chemistry vary historically, and how does it compare with Laydown brine chemistry?
- How does composition of salt precipitated as a result of the Laydown Project compare with that of pre-Laydown salt crust?
- How much dissolved Laydown salt may be assimilated into the shallow-brine aquifer?
- Has the composition of minerals precipitated from the shallow-brine aquifer changed as a result of the Laydown Project?

Progress of Salt-Crust Restoration

The Laydown experiment was conducted during six-month periods (November through April of the following year) for five successive years. To simplify yearly data reporting in the following tables, fiscal year terminology is used unless otherwise indicated. A fiscal year is defined as the period from October 1 through September 30 of the following year, and is identified with the FY prefix.

Tons of salt delivered to BSF

Over 5 years of operation, the Laydown project delivered to BSF 6.3 billion gallons of brine containing 6.2 million tons of NaCl (table 1), about 83% of the possible salt mass estimated (Bingham, 1991, p. 2). Annual salt delivered averaged 1.2 million tons, and ranged from 0.76 to 1.96 million tons.

The average mass delivered exceeded the estimated salt loss of 0.85 million tons (Mason and Kipp 1998, p. 93). Densities for the delivered brine typically ranged from 1.15 to 1.19 g/mL (table 2). Minimum annual densities usually occurred in January or February, and maximum values usually occurred in November. The mass delivered and the brine densities were low in FY98 because of start-up problems (White 2002a, p. 444). The largest masses of salt delivered and highest brine densities occurred in FY99 and FY00 due to improvements to the Laydown Facility during 1998 (White 2002a, p. 445). Brine density decreased in January and February 2000. In March 2000, the salt-crust surface of PP#4N was ripped by a bulldozer to improve salt dissolution and, in response, the brine density increased (table 2).

At the beginning of FY01, efficiency of salt recovery from PP#4N began to decrease and brine quality dropped below acceptable levels. To resolve the problem, brackish-water flow was re-routed from PP#4N to North and South Ripening Ponds (NRP and SRP), which became the primary sources of Laydown salt for the last 2 years of the 5-year experimental project (see fig. 2). Because of difficulties encountered while making the transfer from PP#4N to NRP and SRP, and the reduced surface area available in the two new ponds, the mass of Laydown salt delivered was reduced.

Two strategies were successfully used to increase salt dissolution into the Laydown brine: 1) brackish-water was pumped for 15 to 20 days per month, rather than the entire month, to allow a specified volume of brackish water greater residence time in NRP and SRP and enhance salt dissolution; 2) brine was transferred from NRP and SRP to PP#4N for storage and additional salt dissolution (PP#4N still contained about 0.5 million tons of salt as of January 2002). Although FY01 and FY02 Laydown tonnages were similar (table 1), the efficacy of using PP#4N as a storage pond to help upgrade the brine from 14 to 18–20% NaCl content (or a brine density of 1.12 to 1.16 g/mL, respectively) may be reflected in slightly improved FY02 brine densities, as compared with those of FY01 (table 2).

Table 1. FY98-02 totals of Laydown NaCl tonnage, acre-feet, gallons, and pump hours.

Totals	NaCl, million tons (dry)	Pumped Brine		Hours Pumped Per Year (Nov-Apr)		
		acre-feet	million gallons	Maximum Possible	Actually Pumped	% of Possible
FY98	0.825	3,161	1,030	4,344	2,567	59.1
FY99	1.965	5,335	1,738	4,344	4,332	99.7
FY00	1.833	5,345	1,741	4,368	4,340	99.4
FY01[1]	0.764	2,571	884	4,344	2,205	50.8
FY02[2]	0.836	2,780	906	4,344	2,413	55.5
FY98-02	6.229	19,192	6,300	21,744	15,857	72.9

[1] Includes 7 days of pumping from May 1 to 7, 2001.
[2] Includes 2 days of pumping from May 1 to 2, 2002

Table 2. Average monthly Laydown-brine-density values (expressed in g/mL) for November through April during FY98-02.[1]

Month	Nov	Dec	Jan	Feb	Mar	Apr
FY98	1.161	1.080	1.074	1.178	1.148	1.133
FY99	1.194	1.192	1.183	1.187	1.186	1.189
FY00	1.187	1.178	1.152	1.145	1.178	1.202
FY01[2]	1.164	1.155	1.119	1.148	NP	1.148
FY02[3]	1.132	1.158	1.162	1.144	1.157	1.161

NP – No production
[1] Density values based on daily brine-sample measurements conducted in Reilly's Wendover laboratory.
[2] Average brine density for 7 days of pumping from May 1–7, 2001 was 1.127.
[3] Average brine density for 2 days of pumping from May 1–2, 2002 was 1.166.

Yearly production data from the Salt Laydown Project has demonstrated that NaCl salt in brine removed from BSF for mineral extraction can be replenished. During the 5-year experimental project, 6.2 million tons of NaCl salt was transferred to BSF. Using USGS-estimated annual salt loss of 0.85 million tons per year (Mason and Kipp 1998, p. 106), about 4.2 million tons of salt may have been removed from the shallow-brine aquifer via the federal lease-collection ditches north of I-80 during the same 5-year period. This resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system.

Volume of Laydown brine added to the shallow-brine aquifer

Mason and Kipp (1998, p. 92) modeled fluid and salt inflow and outflow to the shallow-brine aquifer and demonstrated a volumetric balance between annual recharge and discharge that was within 5%. However, the yearly addition of Laydown brine would skew this annual volumetric balance towards additional recharge. Laydown brine volumes during the 5-year experiment ranged from 2,570 to 5,340 acre-feet (values rounded from table 1) and were initially added to the transient winter pond volume. A portion of these annual Laydown volumes contributed to recharge of the shallow brine aquifer during the winter months, while any remaining volume contributed precipitated salt to the salt crust as the residual transient pond evaporated during the spring and summer months.

An obvious question is how this additional volume of Laydown fluid could be accommodated within the system while maintaining the recharge-discharge balance. Several options are possible: 1) the average amount of annual meteoric precipitation decreased (reducing water levels in the shallow-brine aquifer), 2) the area covered by the transient pond increased, or 3) a combination of the previous two conditions occurred. Review of available weather data and recent field observations suggest a combination of the listed conditions. For example, average meteoric precipitation for BSF and vicinity was less during the 1997–2002 Laydown project compared to historical records. Specifically, the sum of monthly average meteoric precipitation for November–April and May–October periods recorded at the Wendover airport weather station was about 30% less than that of its 1934–2002 period of record (table 3).

Table 3. Meteoric precipitation data from Wendover, UT Airport weather station: 1997–2002 sum of monthly averages for Nov-Apr and May-Oct periods are compared with those of the station's 1934–2002 period of record (Western Regional Climate Center 2003).

Calendar year	Nov-Apr Avg.	May-Oct Avg.
1997	0.52	2.04
1998	1.76	5.68
1999	0.92	1.35
2000	1.71	0.76
2001	1.89	0.78
2002	1.09	0.86
1997–2002 Avg (n = 6)	1.32	1.91
1934–2002 Avg (n = 69)	2.03	2.70
Percent difference	35	29

Decrease in meteoric precipitation over the 5-year period would result in less recharge, consequently increasing storage in the shallow-brine aquifer. Additional available storage is also suggested by October 2000 and 2001 field observations (White 2002b). In October 2000, the shallow-brine aquifer water level was at the surface of the salt crust. During October 2001, sparse water level data from measurements of auger holes drilled in the center of the salt crust along a 2-mile stretch of the International Track recorded shallow-brine aquifer static water levels that averaged about 1.3 feet below ground level. Assuming that this depth to the shallow-brine aquifer applied to the 31 square miles of salt crust existing in the fall of 1999, and porosity was 45%, a volume of approximately 11,600 acre-feet of additional storage would become available, which would easily accommodate the yearly Laydown brine volume.

Evidence of increase in transient pond area coverage was also observed during an October 2001 field examination; 1-inch thick salt crust extended from the east margin of the 1999 salt-crust boundary and thinned to a feathered edge at the lease-collection ditch system shown in figure 2 (White 2002b). Presence of this thin salt crust shows that the 2000–2001 transient winter pond extended beyond the 1999 salt-crust boundary.

Based on the forgoing, the added Laydown volume can be assimilated into the shallow-brine aquifer, and has potential to help maintain salt-crust mass balance. Specifically, before the Laydown Project, some of the brine discharged from BSF through the lease collection ditch was replaced by meteoric precipitation, which dissolved salt crust (Mason and Kipp, 1998, p. 45). During the Laydown Project, the shallow-aquifer brine discharged through the lease collection ditch was believed to be mostly replaced by Laydown brine that approached halite saturation and consequently minimized salt-crust dissolution.

Amount of salt added to the salt crust

Area measurements—Using measurements from Landsat 5 imagery, White (2002a, p. 445–447) estimated that the salt crust area increased by about 5 square miles during a 2-year period (September 1997 to October 1999). BSF salt-crust areas measured from fall 1997, 1998, and 1999 Landsat 5 scenes were approximately 26, 29, and 31 square miles, respectively (fig. 4). The new 5-square-mile area was added to the eastern margin of the salt crust (as it existed in the fall of 1997), and the following measurements apply to the 5-square-mile addition. Based on salt-crust density (110 lbs/ft^3 - rounded from Mason and Kipp, 1998, p. 54) and thickness measurements (0.25 to 1.0 inches), the 5-square-mile increase may represent about 0.16 to 0.64 million tons of salt, which could represent about 23% of the 2.8 million tons of NaCl salt delivered by the Laydown Project during FY98 and FY99. Salt-crust thickness studies and geochemical modeling of the effects of mixing Laydown brine with the shallow-aquifer brine (described in the following sections) suggest that most of the Laydown salt tonnage not included in the 5-square-mile area was probably assimilated into the shallow-brine aquifer.

Salt-crust thickness measurements—The salt-replenishment feasibility study (Bingham, 1991, p. 2) estimated that the Laydown Project could add 0.4 inches of additional salt per year to the surface of the salt crust. In an attempt to verify this predicted increase of salt-crust thickness, BLM measured salt-crust thicknesses during the life of the Laydown Project and compared these measurements with two different types of historical salt-crust measurements: 1) total salt-crust thickness (i.e., from the surface of the salt-crust to its interface with underlying carbonate mud), and 2) thicknesses of individual halite and gypsum strata that make up the total salt crust.

Total salt-crust thickness—Historical measurements of total salt-crust thickness were made by the Utah State Department of Highways (UDOT) in 1960 and 1974, and by BLM in 1988 (McMillan 1974; Brooks 1991). UDOT and BLM each augered more than 100 holes in the salt crust during their respective studies. Because the 1988 BLM auger-holes locations were surveyed (Brooks 1991, p. 4) and their salt-crust thicknesses were the most recent historical record available, the 1988 measurements were compared with BLM total salt-crust measurements made during the Laydown Project so that any measurable changes could be documented.

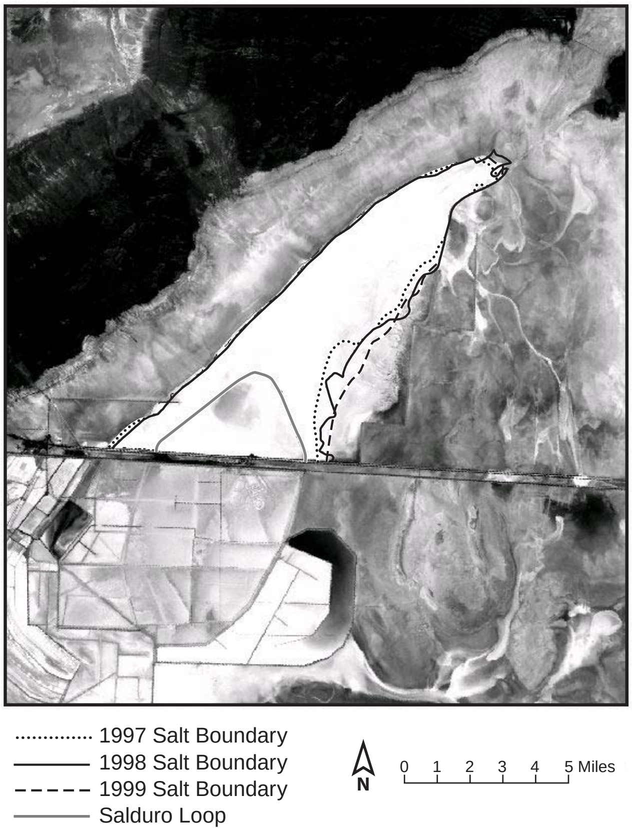


Figure 4. 1999 Landsat 5 image showing progressive increase in salt-crust area from September 1997 through October 1999.

From 1998 through 2002, BLM measured total salt-crust thicknesses at 13 selected BSF monitoring locations (see fig. 2 and table 4). The 1988 thickness values for these 13 locations were extrapolated from BLM's 1988 data (Brooks 1991; White 2002a, p. 443). Comparisons were made between the 1988 thickness measurements and 20 recent measurements made from 16 auger holes and 4 test pits distributed among the same 13 locations during the 1998–2002 period. Total salt-crust thickness values from the 20 measurements averaged 27 inches, and ranged from 12 inches at MB-2 to 42 inches at BLM-93. Extrapolated 1988 total salt-crust thickness values for the 13 locations also averaged 27 inches, and ranged from 12.2 inches at MB-2 to 46.8 inches at BLM-93.

When 1998–2002 total salt-crust thickness measurements were compared with their correlative 1998 thickness measurements, nine locations exhibited thickness decreases (from 0.2 to 5.2 inches), while four locations showed thickness increases (from 0.5 to 3.2 inches). However, when 1998–2002 measurements were compared among themselves, locations where multiple total salt-crust measurements were taken either exhibited the same thickness from year to year (i.e., BLM-46, BLM-60, and BLM-93), or showed substantial thickness increases (i.e., 4+ inches for BLM-43C and BLM-44A). Generally, greater variability of total salt-crust thickness was observed between 1988 and 1998–2002 measurements, rather than among those of 1998–2002.

This range of change in total salt-crust thickness between the 1988 and 1998–2002 measurements may be due not only to seasonal and spatial variation in the salt-crust thickness (see "Salt crust strata thickness"), but may also be a function of historical weather events and difficulty with replicating salt-crust thickness measurements.

For example, Mason and Kipp (1998, p. 55) estimated 10 to 14 million tons of salt were dissolved from the salt crust just north of I-80 during the winter of 1993. This transfer of solid-phase salt from the salt crust to the shallow-brine aquifer was due to greater than normal precipitation in January, and unseasonably cool temperatures in January and February. Mason has suggested that this 1993 winter flooding was a significant event that had potential to markedly affect salt-crust thickness, and may be one of several important mechanisms responsible for the variation observed in total salt crust thickness between 1988 and 1998–2002 (J.L. Mason, Hydrologist, USGS, written commun., October 3, 2003).

Table 4. Total salt-crust thickness measurements taken at 13 locations during 1998–2002, compared with correlative 1988 thicknesses (thickness and change expressed in inches).

Location[1]	1988[2]	1998[3]	2000[3]	2001[3]	2002[4]	Change[5]
MB-1	14.8	12.5				-2.3
MB-2	12.2	12.0				-0.2
MB-3	20.8	19.0				-1.8
MB-6	22.7	22.0				-0.7
MB-7	33.4	36.0				+2.6
BLM-43C	34.7		31.8	36.0		+1.3
BLM-44A	30.7			26.4	31.2	+0.5
BLM-46	26.2		24.0	24.0		-2.2
BLM-48	18.4			13.2		-5.2
BLM-60	20.2		19.5	19.5	19.2	-1.0
BLM-71A	35.8			32.4		-3.4
BLM-93	46.8		42.0	42.0	42.0	-4.8
KSL-01	32.8				36.0	+3.2

[1] Auger holes MB-1-MB-7 drilled along the International Track; auger holes and test pits associated with BLM-43C, etc. placed adjacent to these reference wells; test pit KSL-01 near International Track near mile-post 3 (see figure 2).

[2] Values extrapolated from Brooks (1991) using Radian CPS/PC v. 4.2.

[3] Auger holes (n = 16).

[4] Test pits (n = 4).

[5] Change between 1988 and 1998, 2001, or 2002 measurements.

Difficulties replicating total salt-crust measurements were reported by Kohler (1994–95). Brooks (1991, p. 3) measured 1988 total salt-crust thicknesses from each auger hole using a method similar to that used by UDOT (see White 2002a, p. 449) and reported difficulty in replicating measurements within the same hole. Kohler (1994–1995) also attempted to replicate total salt-crust thickness measurements within the same hole and among multiple, closely spaced holes using the UDOT method. He drilled three holes along a 27-foot line that was located approximately 125 feet northwest of monitoring well BLM-93. The holes were located at both ends and in the center of the line, and the center hole was spaced about equidistant (13 and 14 feet) from each end. Kohler reported that three independent measurements of total salt-crust thickness within the same hole varied by ±1.2 inches (or ±0.1 foot), and measurements among the three holes varied by as much as 6 inches over a 27-foot lateral distance. This reported variation could easily mask the reported change in total salt-crust thickness summarized in table 4. Additionally, variability of total salt-crust thickness measurements within individual holes and among closely spaced holes, along with the imprecise UDOT measurement method suggest that using the 1988 total thickness values as an absolute baseline for comparison with recent thickness measurements to determine gain or loss of salt crust may introduce significant error. These comparisons are probably qualitative at best.

This preliminary comparison with 1988 thickness measurements is based on a small population of data from 16 auger-hole and 4 test-pit locations collected from 1998 through 2002. To more accurately assess effects of the Laydown Project on total salt-crust thickness, thickness measurements from a larger population of drill holes need to be collected on a yearly schedule (White 2002a, p. 449).

Salt crust strata thickness—Pre-Laydown Project thickness measurements of individual halite and gypsum strata were made from 10 test pits excavated in the salt crust by BLM during 1994–1997. These test pits were located adjacent to six reference-monitoring wells whose locations were surveyed (BLM-42A, BLM-43C, BLM-46, BLM-60, BLM-71A, and BLM-93 - see fig. 2). Based on halite and gypsum strata thickness measurements from these test pits, it was determined that at least five distinct strata comprised the salt crust (White 2002, p. 447). These five strata were consistent in sequence and composition among the 10 test-pit locations (table 5). The 1994–1997 salt-crust strata thickness measurements were used as baseline thickness values for comparison with later salt-crust strata measurements performed during the Laydown Project.

Because Bingham (1991, p. 2) predicted that the 5-year Laydown experiment could add up to 2 inches of thickness to the existing salt crust, it was originally thought that annual measurements of the salt-crust strata during the Laydown Project would show a gradual thickness increase in the surface stratum (dense-cemented halite). Therefore, multiple-year thickness measurements of the salt-crust strata sequence were made from seven test pits and ten auger holes excavated adjacent to six monitoring-well locations during 1998-2002 (BLM-43C, BLM-44A, BLM-46, BLM-60, BLM-71A, and BLM-93-five of these six locations were also used for the baseline 1994–1997 measurements). The datum selected as a horizon from which to reference all thickness measurements was the top surface of the first uncemented gypsum stratum beneath the surface salt-crust stratum (see table 5). This gypsum stratum was consistently present as the next stratum beneath the surface salt-crust stratum (dense-cemented halite).

Twenty-two dense-cemented-halite stratum thickness measurements were made from these six monitoring-well locations. The 22 measurements averaged 2.3 inches with a standard deviation of 0.6 inches. Of the 22 measurements, 18 were within the thickness range of 1.7 to 2.9 inches, and 4 were outside this range (4.2, 3.5, 1.5, and 1.5 inches). BLM-44A (adjacent to the International Track and thickest portion of the salt crust) exhibited maximum thicknesses of 3.5 and 4.2 inches, while BLM-60 (which lies at the extreme northeast margin of the salt crust) had minimum thicknesses of 1.5 inches.

Although 1994 and 1998–2002 thickness measurements from these reference locations were compared, none of these locations showed the predicted 2-inch thickness increase in dense-cemented halite stratum thickness at the end of the 5-year experiment (table 6). In fact, between 1994 and 2001, dense-cemented halite stratum thicknesses actually decreased at BLM-46, BLM-43C, and BLM-60 by 0.2, 0.5, and 0.8 inches, respectively, and only increased at BLM-93 and BLM-71A by 0.7 inches each. Thickness decreases at three locations and additions of less than 1 inch at two locations were despite an addition of 6.2 million tons of NaCl salt to BSF during the Laydown Project.

Several factors may have contributed to the measured decreases and variability in dense-cemented halite stratum thickness:

- Annual and/or seasonal variations in weather.
- Laydown salt contributions to other salt-crust strata.
- Laydown salt contributions to the shallow-brine aquifer.

Depending upon the amount of halite dissolved from the surface stratum, an apparent thinning (or thickening) of the dense-cemented halite stratum could occur during unseasonably wet (or dry) years in spite of increased salt tonnage added to BSF by the Laydown Project (White 2002a, p. 448). A possible example of seasonal weather variation influencing salt-crust thickness is illustrated in Table 6. The 2002 thickness measurements of dense-cemented halite stratum were taken in March, and without exception were all less than the fall 2001 measurements. Comparing spring 2002 thickness measurements with those of fall 2001, BLM-43C and BLM-44A had 0.6 and 0.7-inch decreases, BLM-46, BLM-60, and BLM-71A each showed 0.5-inch decreases, and BLM-93 had a 0.2-inch decrease. Empirical data and TEQUIL modeling suggest that a 1-inch rain event would dissolve about 0.14 inches from a 1-inch thickness of dense-cemented halite stratum (see "Prediction of BSF Salt-Crust Dissolution from One-Inch Rainfall Event"). It would take a single rainfall event equivalent to 4.8 inches to dissolve between 0.6 and 0.7 inches of salt-crust thickness. The average annual precipitation recorded at the Wendover, UT airport during the period 1924–2001 was 4.8 inches, and the average precipitation for March during the same period of record was 0.4 inches (Western Regional Climate Center, 2003 - Note, March was the month 2002 thicknesses were measured). Based on the aforementioned meteorological data, it seems unlikely that the observed thickness differences are due solely to rainfall, especially since a year's worth of rainfall would be required to achieve the observed decrease in 2002 thicknesses.

Table 5. Salt-crust stratum sequence and thickness ranges from 10 BLM test pits (Kohler, 1994–95, and Kohler and White, 1997). See White (2003, Appendix A6) for detailed descriptions of each stratum.

Stratum	Thickness, inches
Dense-cemented halite (surface stratum of the salt crust)	1.3 to 2.9
First uncemented gypsum mixed with carbonate clay	0.5 to 1.2
Cemented-coarse-porous halite	1.4 to 7.7
Secnd uncemented gypsum mixed with carbonate clay	0.4 to 1.8
Uncemented-coarse halite	18.0 to 24.0[1]
Carbonate clay	ND

[1] Thickness range is based on one test pit that was excavated to the salt/mud interface.

ND Not determined.

Table 6. 1994–2002 thickness comparisons of the dense-cemented halite stratum from test-pit and auger-hole locations placed adjacent to BSF reference monitoring wells during the year listed. Measurements taken in late summer-autumn unless otherwise indicated (thickness expressed in inches).

Location	1994	1998	2000[1]	2001[1]	2002[2]	Thickness change between 1994 and 2001[3]
BLM-44A	ND	ND	ND	4.2	3.5	ND
BLM-46	2.8	ND	2.2	2.6	2.1	-0.2
BLM-93	1.8	2.4	2.3	2.5	2.3	+0.7
BLM-71A	1.7	ND	ND	2.4	1.9	+0.7
BLM-43C	2.9	ND	2.0	2.4	1.8	-0.5
BLM-60	2.8	ND	1.5	2.0	1.5	-0.8

[1] Auger holes

[2] Spring measurements

[3] Maximum thickness measured during Laydown Project

ND Not determined

With regard to contributions to other salt-crust strata, examination of table 7 reveals thickness variation not only of dense-cemented halite, but also of cemented-coarse-porous halite and uncemented-coarse halite strata in seven closely spaced test pits at BLM-93.

However, when respective thicknesses of these three halite strata were added together for each of the last three consecutive years (2000–2002), the average sum was 39.1 inches, and range of summed halite thickness was relatively narrow (i.e., from 37.3 to 40.5 inches). This suggests a possible interrelationship between the three different halite strata in the salt-crust stratigraphic sequence. The shallow-brine aquifer, which maintains the salt crust and governs its strata morphology, is in contact continuously with the uncemented-coarse halite stratum, and seasonally with cemented-coarse-porous and dense-cemented halite strata as the level of the shallow-brine aquifer fluctuates seasonally. These fluctuations in the water table combined with seasonal changes in brine concentration may help facilitate mass transfer of salt from one stratum to another. Furthermore, this mass transfer may be reflected by the undulating top and bottom surfaces observed in the dense-cemented halite and cemented-coarse-porous halite strata. This observed undulation resulted in significant salt-crust strata thickness differences within a short lateral distance (i.e., 2 feet or less). For example, yearly dense-cemented halite thicknesses measured from 18-inch-wide by 24-inch-long test pits excavated at BLM-93 from 2000 to 2002 varied by as much as 0.5 to 1.5 inches over a 24-inch distance. Coarse-porous halite thicknesses measured from the same test pits at BLM-93 varied more dramatically by 1 to 2.5 inches over the same lateral distance (White 2002b). Perhaps the most critical observation is that reported lateral variation of dense-cemented halite stratum thickness measurements exceeds reported thickness changes measured from the same stratum during the Laydown Project (see table 6).

Table 7. Salt-crust stratum sequence and thickness measurements from seven BLM test pits excavated adjacent to monitoring well BLM-93 (one test pit was excavated at the site during each year listed).

	Stratum Thickness, inches						
Stratum	1994[1]	1995[1]	1997	1998	2000	2001	2002[2]
Dense-cemented halite	1.8	1.9	1.9	2.4	2.3	2.5	2.3
First uncemented gypsum mixed with carbonate clay	1.0	0.7	0.6	1.1	1.0	0.5	0.6
Cemented-coarse-porous halite	2.9	2.4	2.8	1.6	6.0	3.5	2.3
Second uncemented gypsum mixed with carbonate clay	0.6	0.6	0.6	1.5	0.5	1.0	ND
Uncemented-coarse halite	ND	ND	ND	ND	29.0[3]	34.5[3]	34.8[3]

ND Not determined

[1] Kohler, 1994–1995 unpublished field notes.

[2] Pit excavated in spring; previous pits (1994–2001) excavated in late summer or early fall.

[3] Total thickness of uncemented-coarse halite (depth to salt-carbonate mud interface measured).

Lack of progressive salt-crust thickness increases in the surface stratum at reference monitoring-well locations (see table 6) strongly suggest that 1) most of the Laydown salt is initially incorporated into the shallow-brine aquifer, while 2) some is distributed to increased salt-crust area and other subsurface salt-crust strata (e.g., cemented-coarse-porous halite). Additional TEQUIL modeling calculations indicate that between 17 and 25 million tons of Laydown-brine NaCl could be assimilated into the shallow brine aquifer (see “Fate of Laydown-brine NaCl...”). Whereas this salt would eventually be incorporated into the salt crust as halite, there may be a lag time between the period of Laydown-brine delivery and this incorporation. Consequently the effects of this salt addition would not be measured until some time in the future.

In summary, the seasonal and spatial variation of surface stratum and underlying halite strata thicknesses not only make individual salt-crust strata thickness measurements difficult, but also help mask any progressive increases in salt crust thickness that may be contributed by the Laydown Project.

Brine Composition

Comparison of 1994–2002 shallow-aquifer brine samples with historical data

Seven years of recent BLM samples of shallow-aquifer brine were compared with 186 USGS samples collected from 1976 to 1993 (table 8), and 18 samples of shallow-aquifer brine collected by USGS in 1925 (Nolan 1927, Plate 3; see White, 2003, Appendix A1). Sodium and chloride ions dominated both groups of samples. Sodium made up about 91% of cation content, and chloride made up 97% of anion content in both BLM and USGS samples. Magnesium and potassium jointly made up about 8% of cation content in both sample groups, with magnesium and potassium averaging 3 and 5%, respectively. The 1925 potassium and magnesium concentrations (0.131 and 0.126 moles/L) were nearly identical to the average concentrations of the 1976–2002 samples (0.131 and 0.129 moles/L). TDS ranged from 244 to 297 g/L between 1976 and 2002, but peaked to 309 g/L in FY92.

A closer examination of table 8 shows that the data can be separated into two groups based on comparison of ion concentrations (i.e., 1976–1996 and 1997–2002). Molar concentrations of sodium, magnesium, and chloride in the 1976–1996 group are generally high relative to the same species in the 1997–2002 group. For example, the sodium ranges for 1976–1996 versus 1997–2002 are 4.11–4.51 and 3.74–3.95 moles/L respectively. Assuming no errors were introduced during the 1997–2002 sample collection and analyses, and recognizing the sparseness of the data (i.e., multiple-year gaps between sampling periods of record), mechanisms causing the sodium, magnesium, and chloride concentration differences between 1976–1996 and 1997–2002 sample groups are currently unknown.

By contrast, potassium, calcium, and sulfate are relatively unchanged in 1997–2002 compared to 1976–1996 concentrations, and this consistency may be due to buffering by associated solids (i.e., aqueous calcium and sulfate in equilibrium with gypsum in near-surface sediments, and aqueous potassium by adsorption and desorption on clays in the subsurface - B.F. Jones, Research Geochemist, USGS, written commun., July 31, 2003).

However, the FY81-B, K, and L members of the 1976-1996 group are an exception, in that they exhibit potassium concentrations (0.085, 0.095, and 0.114 moles/L) that are markedly below the average potassium concentrations for both 1976–1996 and 1997–2002 groups (0.151 and 0.133 moles/L, respectively). Magnesium concentrations (0.120-0.141 moles/L) for FY81-B, K, and L are also below the 1976–1996 group's average concentration (0.161 moles/L). These samples were collected in the spring (May) rather than in late summer (time of peak evaporation). Consequently, any spring storm precipitation would dissolve salt crust and maintain sodium and chloride concentrations at a constant level in the shallow-brine aquifer (see FY81 sodium and chloride values in table 8). The lower potassium and magnesium concentrations are more difficult to explain, although they could have been affected by spring storm dilution; however: 1) potassium concentrations are inconsistent with conservative levels achieved by solids buffering mentioned above, and 2) reduced magnesium concentrations may be due to incorporation of aqueous magnesium and silica in the formation of magnesium-silicate interstratifications in fine clay minerals (Jones and Spencer 1999, p. 297).

Comparison of Laydown brine with shallow-aquifer brine

During the 5-year project, overall composition of the Laydown brine was generally similar to that of the BSF shallow-aquifer brine in that sodium and chloride were the dominant ions in both brines. On average sodium, made up 97% of the cation content in the Laydown brine and 90% of that in the shallow-aquifer brine. Chloride made up nearly 98% of the anions in both brines. Four additional ions (magnesium, potassium, calcium, and sulfate) were also present in both brines, although present as traces in the Laydown brine.

Due to initial startup problems, the FY98 Laydown brine contained about 15 to 64% less salt (as indicated by solution density) than the FY00 BSF shallow-aquifer brine. Improvements to the Laydown facility resulted in FY99 and FY00 Laydown-brine concentrations that exceeded those of the shallow-aquifer brine (table 9). Specifically, concentrations of sodium and chloride in the FY00 Laydown brine were 16 and 8% higher than those in the FY00 shallow-aquifer brine, and TDS were 7% higher. The slightly elevated values are not unexpected because NaCl (halite) was the main salt present in Primary Pond #4N. However, sodium and chloride concentrations in the FY01 and FY02 Laydown brines were less than their respective shallow-aquifer brine concentrations. Sodium was nearly 9 and 2% less, chloride was 12 and 6% less, and TDS were 14 and 8% less for FY01 and FY02, respectively. The cause of this decrease in concentration during FY01-02 was depletion of the easily recoverable salt supply in PP#4N, and the subsequent necessity of having to move to two smaller evaporation ponds (NRP and SRP).

Table 8. Comparison of recent (BLM) samples with historical (USGS) samples of the BSF shallow-aquifer brine (samples usually collected during August and September unless otherwise indicated).

			Average Major Ion Concentrations, moles/L								
Sample Suite	n	Density	Na	Mg	K	Ca	Cl	SO_4	TDS	Avg Mole Balance[1]
BLM:										
FY02	19	1.180	3.91	0.119	0.136	0.031	4.30	0.056	257	0.003766
FY01	20	1.172	3.89	0.107	0.130	0.030	4.24	0.050	254	0.003476
FY00	10	1.173	3.74	0.102	0.110	0.033	4.09	0.051	244	0.003183
FY97	20	1.185	3.95	0.109	0.134	0.028	4.24	0.058	256	0.001462
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051	282	0.003822
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052	286	0.010115
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055	297	0.002707
USGS:										
FY93	20	1.181	4.31	0.154	0.139	0.028	4.37	0.060	297	0.013832
FY92	26	1.185	4.44	0.162	0.170	0.028	4.50	0.070	309	0.014853
FY81- B[2]	34	1.185	4.22	0.120	0.095	0.031	4.70	0.053	276	0.007897
FY81- K[2,3]	17	1.188	4.37	0.141	0.085	0.032	4.77	0.055	283	0.003655
FY81- L[2]	18	1.189	4.23	0.134	0.114	0.030	4.80	0.053	281	0.009904
FY76-78- K[3]	10	1.167	3.88	0.114	0.120	0.030	4.23	0.055	253	0.002155
FY76-78-USGS[4]	43	1.189	4.51	0.148	0.159	0.031	4.86	0.056	293	0.002053
1925	18	ND	ND	0.126	0.131	ND	ND	ND	ND	ND

TDS Total dissolved solids, g/L

ND Not determined

[1] Acceptable limits are ± 0.0055 moles (calculated using method of Sturm and others 1980, p. 175).

[2] Samples collected by Conservation Division in May; "B" and "L" well numbers were 10-foot-deep auger holes.

[3] "K" monitoring wells were hand-augered to depths of 19 to 23 feet by Turk (1969, p. 64–65) and subsequently sampled by Lines (1978) and Conservation Division (1981).

[4] "USGS" represent monitoring wells 25 feet deep or less, sampled by Lines (1978).

Compared to sodium and chloride, magnesium, potassium, calcium and sulfate were present in relatively low concentrations in both shallow-aquifer and Laydown brines. Potassium and magnesium made up 5 and 3 to 4%, respectively, of the average cation content for the FY94-02 shallow-aquifer brines.

However, potassium and magnesium concentrations in the FY98-FY02 Laydown brines were as much as an order of magnitude less than those in the shallow-aquifer brine. Calcium concentrations in the Laydown and shallow-aquifer brines were similar, while sulfate concentrations in the Laydown brine were about 30 to 50% of those in the shallow-aquifer brine.

Traces of potassium and magnesium in the Laydown brine may have been contributed from microscopic volumes of shallow-aquifer brine entrapped as fluid inclusions in the precipitated halite in PP#4N, and possibly entrained in the pore spaces between halite crystals (recent microscopic examination of similar halite salt-crust samples from the Newfoundland basin revealed presence of fluid inclusions - B.F. Jones, Research Geochemist, USGS, personal commun., September 5, 2000). This mechanism may account for elevated potassium and magnesium concentrations observed in FY01 and FY02 Laydown brines that were 5 to 6 times that of FY98-FY00 Laydown brines. The elevated concentrations are probably due to contribution from precipitated halite in NRP and SRP, which were the sources of Laydown brine during FY01-FY02. NRP and SRP are used during the summer months to concentrate production brine from about 4 to 7.5% KCl as part of the potash-production process. Some of this enriched brine remains entrapped in newly precipitated halite crystals and in intergranular pore spaces within the 4-foot thick-bedded halite floors of these ponds. Brackish water used to dissolve bedded salt for the Laydown brine accumulates traces of potassium and magnesium from any fluid inclusions in the new salt it dissolves and from any mixing with residual process brine (table 9).

Predicted Mineral Precipitation from Transient-Pond Brine

The BSF transient pond currently receives input from the shallow-brine aquifer, meteoric precipitation and the Laydown Project. To identify which minerals could precipitate from the transient-pond brine, its chemistry was simulated using a range of compositions as input for TEQUIL modeling. The compositions used were those of 1) pre-Laydown shallow-aquifer brine, 2) mixtures of pre-Laydown shallow-aquifer brine and Laydown brine, and 3) post Laydown shallow-aquifer brine. Effects of a simulated rainfall event on the dissolution of salt crust were also examined.

Simulation of mixing Laydown brine with the transient pond

The shallow-aquifer brine and the Laydown brine represent the two compositional extremes possible for mixtures used to simulate effects of mixing Laydown brine with the transient pond. Simulated transient pond compositions were based solely on contributions from shallow-aquifer and Laydown brines (input from rainfall was ignored). Two different mixtures of the two compositional extremes were simulated for modeling purposes. They include a 90% + 10% and a 50% + 50% mixture of shallow-aquifer and Laydown brines. The 90% + 10% mixture simulates a condition in

Table 9. Seven years of shallow-aquifer brine analyses from selected BSF monitoring wells (MW) compared with 5 years of Laydown-brine analyses; samples collected by BLM and Reilly.

			Average Major Ion Concentrations, moles/L							
Sample Suite	n	Density	Na	Mg	K	Ca	Cl	SO_4	TDS	Avg Mole Balance[1]
BSF MW Brine:[2]										
FY02	19	1.180	3.91	0.119	0.136	0.031	4.30	0.056	257	0.003766
FY01	20	1.172	3.89	0.107	0.130	0.030	4.24	0.050	254	0.003476
FY00	10	1.173	3.74	0.102	0.110	0.033	4.09	0.051	244	0.003183
FY97	20	1.185	3.95	0.109	0.134	0.028	4.24	0.058	256	0.001462
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051	282	0.003822
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052	286	0.010115
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055	297	0.002707
Laydown Brine:[3]										
FY02[4]	112	1.154	3.81	0.069	0.056	0.015	4.04	0.015	237	0.000013
FY01[4]	99	1.144	3.55	0.059	0.033	0.015	3.73	0.015	219	0.000013
FY00	30	1.164	4.33	0.012	0.014	0.033	4.43	0.031	262	0.004198
FY99	27	1.185	4.29	0.013	0.009	0.034	4.45	0.031	261	0.004801
FY98A	9	1.058	1.34	0.005	0.005	0.016	1.32	0.016	80	0.001891
FY98B	8	1.130	3.16	0.008	0.008	0.025	3.33	0.026	195	0.006570

TDS Total Dissolved Solids, g/L

[1] Calculated using method of Sturm and others, 1980, p. 175; acceptable limits are ± 0.0055 moles.

[2] Samples collected in August and/or September from selected BSF monitoring wells in a 27-well suite.

[3] With exception of FY98A and B and FY01-02,average sampling frequency was two times per month (Nov through April); FY98A and B were collected in January and March-April 1998, respectively.

[4] Daily samples collected and analyzed by Reilly.

which the transient pond interacts with the shallow brine aquifer as a well-mixed system. The 50% + 50% mixing ratio simulates a condition in which the transient-pond volume does not mix with the shallow brine aquifer, and only the transient-pond volume is considered. Although it is known that the transient pond and shallow brine aquifer are hydrologically connected, this simulation provides a case in which the Laydown-brine component is larger than in the previous case. Details of and rationale for these two simulations are reported in White (2002a, p. 452–453).

Chemical analyses from FY94 and FY97 samples of the shallow-brine aquifer were selected as the end members that represent the compositional range for the shallow-brine aquifer. Pre-Laydown transient pond composition was assumed to be similar to that of the shallow-brine aquifer. To simulate mixing the Laydown brine with the transient pond, the two end members were combined with the FY00 Laydown-brine composition (highest of annual Laydown concentrations) to make two different brine mixtures (i.e., FY94 shallow-aquifer + FY00 Laydown brine, and FY97 shallow-aquifer + FY00 Laydown brine). Each of the two brine mixtures was subdivided into a 90% + 10% and a 50% + 50% mixing ratio to make four different mixing combinations. To calculate new cation and anion molar concentrations for the four mixing combinations, the FY94 and FY97 shallow-aquifer and FY00 Laydown brine analyses were run through the mixing function of AquaChem v. 3.7 software (Waterloo Hydrogeologic, Inc., 1998). Calculated molar concentrations from these four mixing combinations and an excess amount of halite were used as inputs to the TEQUIL 25°C version. Ten moles of halite were input to 1) simulate placing each brine mixture on the surface of halite-dominated salt crust, and 2) determine capacity of the four different brine mixing combinations to assimilate additional salt.

TEQUIL modeling

Description—TEQUIL is based on Pitzer electrolyte equations and calculates liquid-solid-gas equilibria in complex brine systems (Moller and others, 1997). The TEQUIL 25°C version for the Na-K-Ca-Mg-H-Cl-OH-SO_4-HCO_3-CO_2-H_2O system (Harvie and others, 1984) was selected for use in this study.

Parameters and Output—To simulate brine evaporation in a closed system, TEQUIL was constrained to reduce the original water mass of the brine by 10% in the first evaporation step, and then reduce the resulting new water mass by 10% in the second evaporation step, and so on. After 45 evaporation steps, more than 99% of the original water mass was depleted (the simulation evaporated the brine to dryness without replenishment from an outside source such as rainfall). The original water mass was 1000 g or 55.508 moles.

Output from the model lists the new brine volume and resulting composition from each evaporation step, and identifies the mineral species that precipitate at each step. Brine composition (i.e., water, major ions, and precipitated mineral species) from each evaporation step is expressed in moles. TEQUIL uses the brine composition from the previous evaporation step as input to calculate the brine composition for the next evaporation step. This step-wise process continues until brine compositions have been calculated for all 45 evaporation steps. New molar concentrations of the brine at any step in the simulated evaporation sequence can be obtained for additional modeling simulations (see "Prediction of BSF Salt-Crust Dissolution from One-Inch Rainfall Event").

TEQUIL-generated plots for simulations presented in this paper are reported as mineral mass precipitated versus percent water remaining as evaporation progresses. Because halite mole values far exceed those of all other predicted mineral precipitates, halite is plotted on the primary Y axis, and the other predicted mineral precipitates are plotted on the secondary Y axis.

Mineral precipitation from pre-Laydown transient pond

TEQUIL modeling was used to predict mineral precipitation from the transient pond. Because chemical composition of the transient pond was assumed to be similar to that of the BSF shallow-brine aquifer, pre-Laydown shallow-brine aquifer composition was represented by annual chemical analyses of monitoring-well samples collected during a 6-year period (FY92–FY97) (table 10). Average molar concentrations (of six major ions) from each year of the 6-year sample period were the input to TEQUIL, which then produced six modeled simulations of precipitated mineral suites.

The minerals predicted to precipitate from the FY92-93 and FY96-97 brine compositions were nearly identical, while the FY94 and FY95 results were slightly different. Predicted mineral-species plots for FY92, FY94, and FY97 are shown in figures 5–7, and plots for FY93, FY95, and FY96 are in White (2003, Appendix A8).

Table 10. Pre-Laydown average molar concentrations of the shallow-brine aquifer from four years of BLM monitoring-well samples and two years of USGS monitoring-well samples

Sample	n	Density	Na	Mg	K	Ca	Cl	SO_4
BLM Samples:								
FY97	20	1.185	3.95	0.109	0.134	0.028	4.24	0.058
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055
USGS Samples:								
FY93[1]	9	1.186	4.38	0.160	0.163	0.029	4.65	0.063
FY92[1]	9	1.194	4.44	0.195	0.193	0.028	4.67	0.068

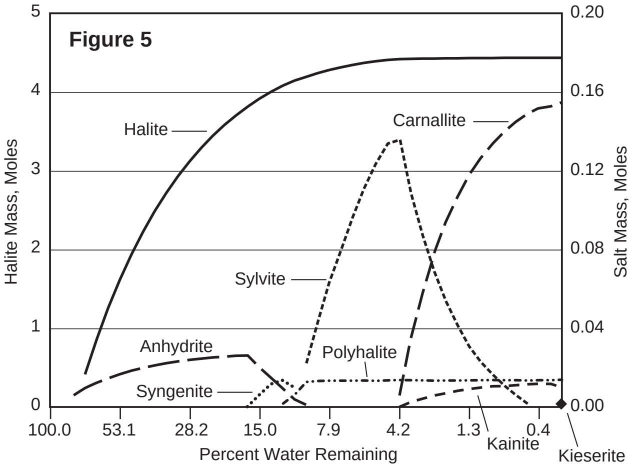
[1] These 9 samples are from 9 of 26 BSF monitoring wells sampled by Mason and others (1995, p. 50, table 4) in 1992–93; these same 9 wells were also sampled by BLM during 1994–97 (see White, 2003, Appendix A1, tables A1.9-A1.10).

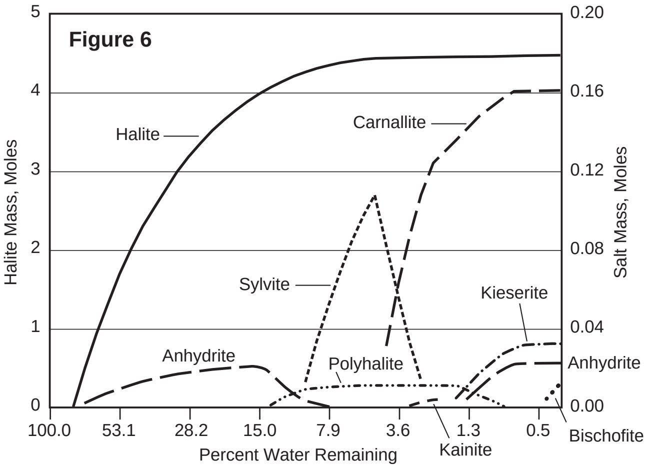
The order of mineral precipitation for the various years was as follows (See White 2003, Appendix A9 for mineral species chemical formulas and their respective gram-molecular weights):

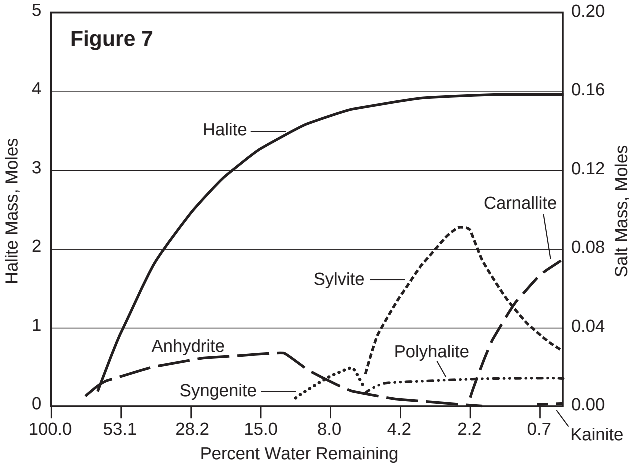
- FY92–93 and FY96–97: anhydrite-halite-syngenite-sylvite-polyhalite-carnallite-kainite.
- FY94: anhydrite-halite-polyhalite-sylvite-carnallite-kainite-kieserite-bischofite.
- FY95: anhydrite-halite-polyhalite-sylvite-carnallite-kieserite.

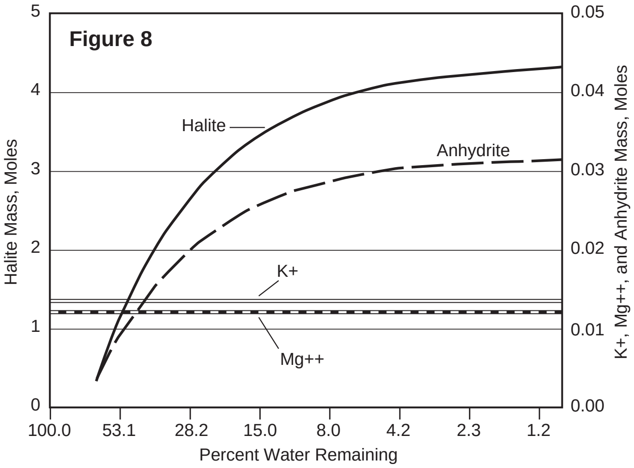
The predicted potassium and magnesium mineral precipitates only occurred after 85 to 90% of the water was evaporated and about 90% of the halite was precipitated. One should also note that as evaporation progressed, new salt species were precipitated at the expense of some previously precipitated salts, which were simultaneously resorbed into solution. This resorption was in response to reaction of the solid-phase salt with residual brine to form another salt. For example, anhydrite began to resorb as polyhalite and sylvite precipitated; subsequently, carnallite formed at the expense of sylvite, and polyhalite resorbed as kainite and kieserite began to precipitate (see figs. 6 and 7; B.F. Jones, Research Geochemist, USGS, written commun., July 31, 2003).

To simplify modeling of mixing the transient pond with Laydown brine, FY94 and FY97 monitoring-well sample analyses were chosen to represent the compositional range of the transient pond. FY94 was selected because its predicted mineral precipitates differed the most from the 6









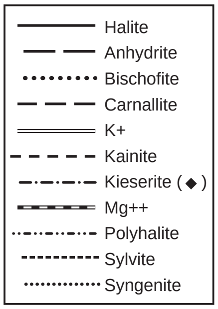


Figure 5. TEQUIL-predicted mineral precipitation plots from average analyses of USGS FY92 monitoring-well samples (n=9).

Figure 6. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY94 monitoring-well samples (n=19).

Figure 7. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY97 monitoring-well samples (n=20).

Figure 8. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY00 Laydown-brine samples (n=30).

years of monitoring-well samples examined. FY97 was selected because its average chemical composition was closest to shallow-brine aquifer and subsequent transient pond composition just prior to the first delivery of Laydown brine to BSF on November 1, 1997.

Mineral precipitation from Laydown brine

In contrast with the seven or eight minerals predicted to precipitate from the two transient-pond end members, only anhydrite and halite were predicted to precipitate from the FY99 and FY00 Laydown brines. Because of their very low concentrations, all potassium and magnesium contained in these brines remained in solution after 99% of the water was removed (fig. 8).

Mineral precipitation from mixtures of transient pond and Laydown brines

The TEQUIL-predicted mineral precipitations from the four brine-mixing combinations were essentially the same as those predicted for their end-member components (i.e., FY94 and FY97 monitoring-well brines—see figs. 6 and 7). However, as the mixing ratios were changed from 90% + 10% to 50% + 50%, the first appearances of individual mineral precipitates were delayed by a period of five evaporation steps, and corresponding mineral masses precipitated were reduced proportionately depending upon the mixing ratio.

Although both sets of mixing ratios approached halite saturation, they were able to dissolve additional halite (halite saturation is equivalent to a brine density of 1.2 g/mL; average densities for FY94 and FY97 monitoring-well samples and FY00 Laydown samples were 1.192, 1.185 and 1.164 g/mL, respectively.). TEQUIL output for both mixing ratios showed that from 1.2 to 1.9 moles (or 12 to 19 %) of halite from the 10 moles used to simulate contact with the halite-dominated salt crust were dissolved during the first evaporation step (figs. 9–12). The model predicted that the portion of the 10 moles dissolved in the first evaporation step would be reprecipitated by the fourth or fifth evaporation step. After reprecipitation restored the halite 10-mole mass, halite in excess of 10 moles was contributed by Na+ and Cl- originally contained in the 90% + 10% and 50% + 50% mixing combinations prior to their contact with 10 moles of halite.

As was previously mentioned, the FY00 Laydown brine was enriched in sodium and chloride, and depleted in potassium and magnesium. TEQUIL output at evaporation step #1 showed that mixing Laydown brine with the two transient-pond end members resulted in increased concentrations of NaCl (see “Fate of Laydown—Brine NaCl...”), and a dilution of potassium and magnesium concentrations. Consequently, a larger reduction of original water mass was required to initiate precipitation of carnallite and sylvite. For example, the first occurrence of sylvite in the FY94 monitoring-well plot (fig. 6) coincided with a 90% reduction in original water mass; however, the first occurrence of sylvite in the FY94 monitoring-well + FY00 Laydown plot (50% + 50% mixing ratio) coincided with a 95% reduction in water mass (fig. 10).

In summary, TEQUIL simulation of mineral precipitation from the four brine-mixing combinations showed the following:

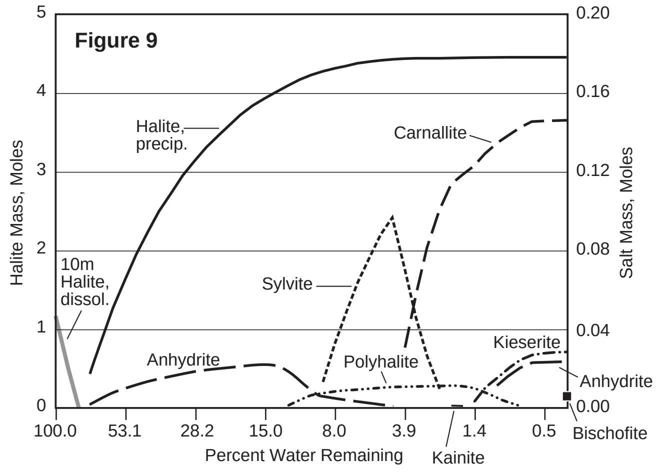
- No new mineral precipitate species were introduced as a result of mixing Laydown brine with transient-pond brine, and subsequently evaporating the brine mixture.
- Anhydrite and halite were the first mineral species to precipitate and were the only minerals present until the original water mass was reduced by 87 and 93%, respectively (figs. 9–12).
- Potassium and magnesium mineral precipitates (sylvite and carnallite) did not appear until the original water mass was reduced by 91 to 97%, and 96 to 98% of the halite was precipitated.
- When compared with the two transient-pond end members (FY94 and FY97), the 90% + 10% and 50% + 50% mixing ratios usually had first occurrences of their mineral precipitates shifted to later evaporation steps, and the maximum predicted mass of precipitated carnallite and sylvite decreased by about 10 to 70% depending upon the mixing ratio (compare figs. 6 and 7 with figs. 9–12).

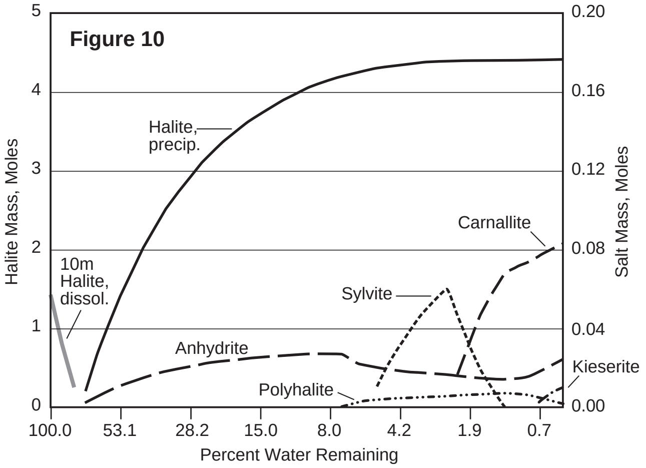
Mineral precipitation from shallow-brine aquifer: pre- and post-Laydown

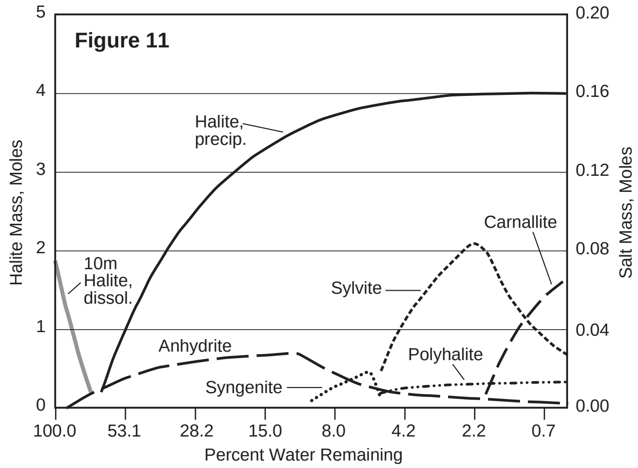
TEQUIL model simulations were also used to compare predicted mineral precipitation between pre- and post-Laydown samples from the BSF shallow-brine aquifer. FY97 monitoring-well samples collected one month prior to the start of Laydown brine delivery were selected for comparison with FY00 and FY02 monitoring-well samples. FY00 and FY02 samples were collected about one month prior to the start of the 3rd and 5th year of Laydown brine delivery to BSF. Predicted mineral-precipitate plots for FY97, FY00, and FY02 monitoring-well samples were nearly identical (figs. 7, 13, and 14):

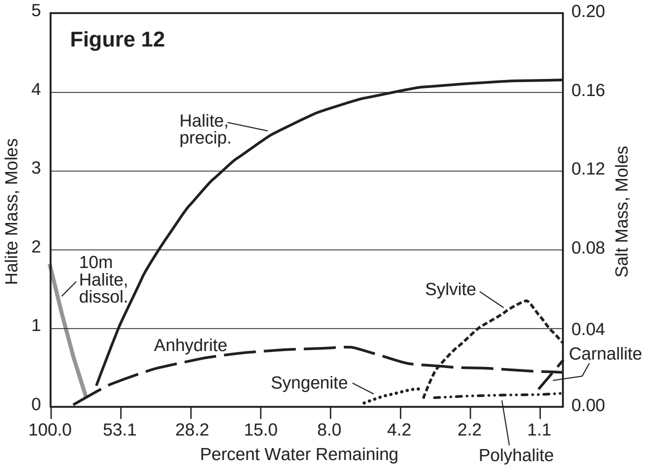
- Predicted mineral precipitates were the same for all three monitoring-well samples; halite and gypsum were first minerals to precipitate and were the only minerals present until 90% of the original water mass was evaporated.
- Relative positions of first occurrences of precipitated sylvite and carnallite were the same for the three samples; sylvite and carnallite first appeared when evaporation reduced the original water mass by 94 and 98%, respectively, and 96% of the halite precipitated.
- Maximum predicted masses for carnallite were identical for FY97, FY00, and FY02 (0.075 moles).
- Maximum predicted masses for sylvite were nearly the same for FY97 and FY02 (0.091 and 0.093 moles) and slightly less for FY00 (0.079 moles).

These results are not unexpected for several reasons: 1) ionic species comprising both shallow-aquifer and Laydown brines were identical and relative concentrations of their dominant species were similar (see table 9), so one would reasonably expect a similar mineral species assemblage upon evaporation of a mixture of the two brines; 2) contribution of Laydown-salt tonnage to dissolved salts contained in the shallow-aquifer brine is a small percentage of the total resource present, so a massive change to the shallow-aquifer brine chemistry would be unlikely. Using parameters of Mason and Kipp (1998, p. 54) about 60 and 175 million tons of salt were estimated to be present in portions of shallow-brine aquifer covered by respective 28- and 80-square-mile areas of BSF salt crust and adjacent mudflat. These areas were selected because the 28-square-mile area was expected to be affected by the Laydown project (Bingham 1991), and the 80-square-mile area of BSF playa north of I-80 was where the shallow-aquifer brine was identified as being most concentrated (Mason and Kipp 1998, p. 54). The 6.2 million tons of Laydown salt transferred to BSF during the 5-year experiment represents 10 and 4%, respectively, of the brine resource estimated to be contained within these two areas.









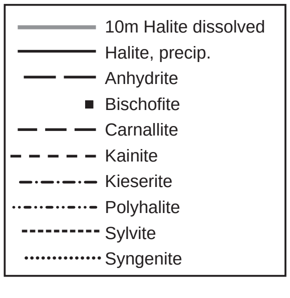


Figure 9. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY00 Laydown brines (90% + 10% mixing ratio).

Figure 10. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY00 Laydown brines (50% + 50% mixing ratio).

Figure 11. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY00 Laydown brines (90% + 10% mixing ratio).

Figure 12. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY00 Laydown brines (50% + 50% mixing ratio).

Fate of Laydown-Brine NaCl when Mixed with The Shallow-Brine Aquifer

During 5 years of Laydown Project, 6.2 million tons of NaCl were delivered to BSF. However, tons of Laydown NaCl precipitated as salt crust and tons of NaCl that remained in solution in the shallow-brine aquifer were unknown. TEQUIL outputs from previously described simulations were examined to see if fate of Laydown NaCl could be quantitatively described.

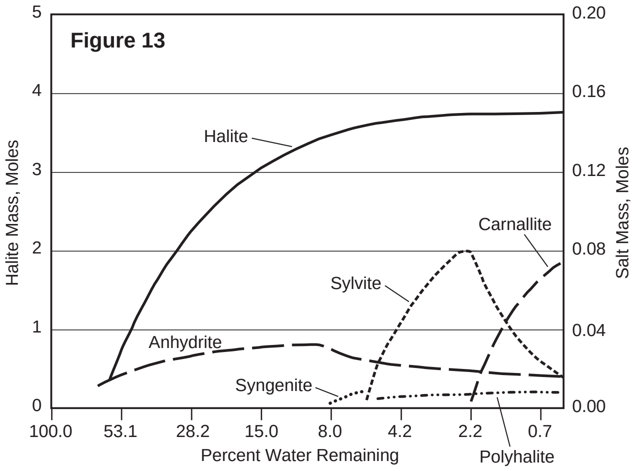
TEQUIL output from 90% + 10% and 50% + 50% mixing ratios that were contacted with an excess of halite (10 moles) showed that the simulated solutions could dissolve additional NaCl. Based on this output, TEQUIL was used to determine how much of the 6.2 million tons could be assimilated by the shallow-brine aquifer within the 28 square-mile area of BSF affected by the Laydown Project. Model output from each of the following brines and brine-mixture simulations was examined: 1) pre-Laydown transient pond end members (FY94 and FY97 MW samples), 2) Laydown brine (FY00 LD), and 3) 90% + 10% and 50% + 50% mixing ratios of the FY94 MW + FY00 LD and FY97 MW + FY00 LD simulations. TEQUIL-calculated moles of sodium from the first evaporation step of these simulations were converted to pounds and tons of NaCl dissolved per gallon (table 11).

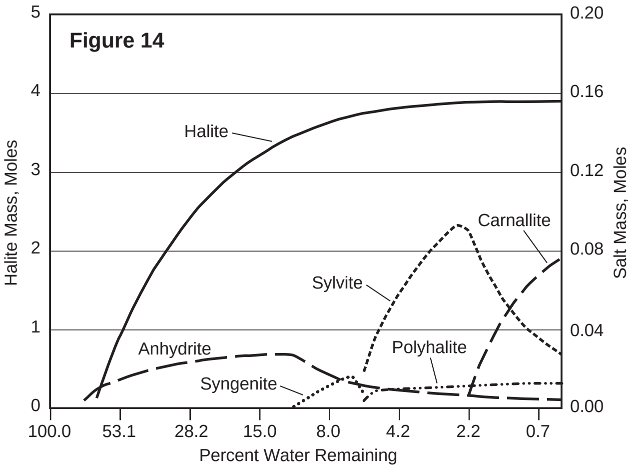
Based on the TEQUIL output at the first evaporation step (table 11), the transient-pond end members (FY94 MW and FY97 MW) contained 2.179 lbs/gal (pounds/gallon) and 1.926 lbs/gal of dissolved NaCl. When FY94 MW and FY97 MW were compared to their corresponding 50-50 mixtures, the dissolved NaCl weight increased to 2.842 lbs/gal and 2.896 lbs/gal, respectively. Subtracting the weight of dissolved NaCl in the 50-50 mix from the weight of dissolved NaCl in the transient-pond end member results in an increased capacity of 0.663 lbs/gal and 0.97 lbs/gal for FY94 MW and FY97 MW. When the increased capacity is multiplied by the 52.5 billion-gallon volume of the shallow-brine aquifer within the 28-square-mile area affected by the Laydown Project, the FY94 MW and FY97 MW end members could accommodate 17 and 25 million tons of additional NaCl. This is about three to four times the 6.2 million tons delivered to BSF by the Laydown Project.These calculations suggest that the 6.2 million tons could initially be assimilated into the shallow-brine aquifer as NaCl in solution. The capability of the shallow-brine aquifer to accept additional NaCl is significant, because it is the shallow-brine aquifer that regulates the distribution of NaCl mass to the BSF salt crust. If the Laydown NaCl mass is assimilated by the shallow-brine aquifer, then: 1) one would anticipate an increase of NaCl concentration in the affected area of the shallow-brine aquifer, and 2) it would not be unreasonable to expect that more halite mass would be added to the existing salt crust as a result of this increased NaCl concentration.

Table 11. TEQUIL-calculated moles of Na at the first evaporation step converted to pounds and tons of NaCl dissolved per gallon of brine.

Sample	Na moles	NaCl lbs/gal	NaCl tons/gal (*10^{-3})
FY94 MW (n=19)	4.473	2.179	1.089
FY97 MW (n=20)	3.954	1.926	0.963
FY00 LD (n=30)	4.328	2.108	1.054
90% + 10% 94 + 2K[1]	5.666	2.760	1.380
50% + 50% 94 + 2K[1]	5.835	2.842	1.421
90% + 10% 97 + 2K[1]	5.866	2.857	1.428
50% + 50% 97 + 2K[1]	5.947	2.896	1.448

[1] Includes 10 moles of halite to simulate contact with salt crust.





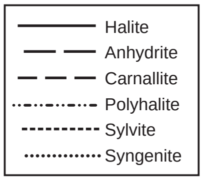


Figure 13. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY00 monitoring-well samples (n=10).

Figure 14. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY02 monitoring-well samples (n=19).

Based on salt-crust monitoring using Landsat 5 imagery, thickness measurements, and geochemical modeling, new halite deposition from five years of brine delivery by the Laydown Project is probably distributed into:

- New salt-crust area (5-square-mile increase since 1997);
- Shallow-brine aquifer (with NaCl assimilation capacity of 17 to 25 million tons); and
- Halite strata (i.e., dense-cemented halite, cemented-coarse-porous halite, and uncemented-coarse halite strata) that comprise the 26-square-mile area of salt crust existing as of 1997.

Prediction of BSF salt-crust dissolution from one-inch rainfall event

As was previously mentioned, annual and seasonal variations in weather have potential to cause changes in salt-crust stratum thickness. To help quantify this possibility, TEQUIL was used to model a 1-inch rainfall event on BSF to determine how much salt-crust mass would be dissolved and consequently, how much thickness would be removed. The 1-inch rainfall was selected because it exceeds the average monthly rainfall measured at Wendover, UT airport during the 1924–2001 period of record (Western Regional Climate Center, 2003). It should be noted that rainfall is not evenly distributed between Wendover airport and BSF during any single event (e.g., compared with average March precipitation of 0.4 inches at Wendover airport, Reilly recorded 0.2 inches during March 2003 at its potash-producing facility, which is 4 miles east of the airport - R. Draper, Mill Superintendent, Reilly Industries, Inc., written communication, March 30, 2003). Therefore, a single event 1-inch rainfall covering BSF would be a significant occurrence.

A 50% + 50% mixture of transient pond and rainwater was used in the modeled simulation. The 50% + 50% mixture simulates a condition where a 1-inch rain event falls on a 1-inch deep transient pond that covers BSF. Complete mixing of rainwater with the transient pond was assumed, resulting in a new composition for the 1-inch deep pond (pond expands its area from mixing with rain).

Because they are hydrologically connected, the transient-pond composition was assumed to be the same as shallow-aquifer brine composition. The shallow-aquifer brine composition was represented by average chemical analyses of the FY97 monitoring-well brine, and rainwater composition was taken from Hem (1989). The mixing function of AquaChem v.3.7 (Waterloo Hydrogeologic, Inc., 1998) was used to calculate new cation and anion molar concentrations from mixing transient pond with rainwater (table 12). The resulting 50% transient pond (TP) + 50% rainwater (RW) mixture plus 10 moles of halite were input to TEQUIL to simulate contact of the new pond composition with the BSF salt crust.

TEQUIL-calculated moles of sodium (3.996 moles) from the first evaporation step of this simulation were converted to pounds NaCl dissolved per cubic foot of brine (15.9 lbs/ft3). To calculate the thickness of salt crust removed, the following assumptions were made:

- 1 cubic foot of salt crust has a density of 110 lbs/ft^3 (after Mason and Kipp 1998; rounded from 109.8 lbs/ft^3).
- Salt crust mass per inch of crust in the cubic foot is 110 lbs/12 in. = 9.17 lbs/in.
- Salt mass dissolved into 1 inch of water is 15.7 lbs NaCl/ft^3/(12) = 1.31 lbs.
- Depth of salt crust dissolved by a 1-inch rain event is 1.31 lbs/(9.17lbs/in.) = 0.143 in.

The natural spatial variability in the thickness of dense-cemented halite stratum was ±0.6 inches for 82% of 22 measurements (see table 6). Therefore, the salt-crust dissolution predicted as a result of a 1-inch rainfall event (a significant event on BSF) cannot solely account for this natural variability in the dense-cemented halite stratum thickness. Other factors must also be operative.

Table 12. Molar concentrations used as input for TEQUIL simulations of transient pond mixed with rainwater.

Sample	Na	Mg	K	Ca	Cl	SO_4	Density
Transient Pond[1]	3.954	0.109	0.134	0.028	4.239	0.058	1.185
Rainwater[2]	$2.4x10^{-5}$	$6.0x10^{-6}$	$3.0x10^{-6}$	$1.6x10^{-5}$	$1.6x10^{-5}$	$2.3x10^{-5}$	1.000
50% TP + 50% RW	1.977	0.054	0.067	0.014	2.119	0.029	1.092

[1] FY97 monitoring-well average (n = 20); FY97 was selected because it was pre-Laydown Project.

[2] From Hem, 1989, p. 36, Table 6, item #2; 7.0 x 10^{-6} moles of bicarbonate were added to achieve charge balance required by TEQUIL

Conclusions

The Salt Laydown-Project demonstrated that sodium-chloride salt in brine removed from BSF for mineral extraction can be replenished. The average annual 1.2 million tons of salt exceeded an estimated annual salt loss of 0.85 million tons:

- Salt-mass balance during the 5-year experiment was maintained in quasi-steady state because the 4.2 million tons of salt removed was replaced by 6.2 million tons of Laydown salt.
- The difference between 6.2 and 4.2 million tons resulted in a net addition of about 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system.
- Before the Laydown Project, some of the brine removed from BSF was thought to be replaced by meteoric precipitation, which dissolved salt crust.
- During the Laydown Project, the removed shallow-aquifer brine was believed to be mostly replaced by Laydown brine that approached halite saturation and consequently minimized salt-crust dissolution.
- The salt addition appears to be distributed between the shallow-brine aquifer, new salt-crust area, and various salt-crust strata.

Monitoring during the project produced the following conclusions regarding changes in salt crust thickness, areal extent and mass:

- Five different strata comprise the salt-crust; thickness measurements of the dense-cemented halite stratum (surface stratum of the salt crust) and underlying cemented-coarse-porous halite stratum showed substantial variation in thickness from 1994 to 2002, while in comparison, minimal change in total salt-crust thickness was observed at 13 monitoring locations from 1988 to 2002.
- None of the monitoring sites where multiple-year thickness measurements were taken showed the expected +2-inch increase in dense-cemented halite stratum thickness at the end of the 5-year experiment (i.e., from 1997 to 2002).
- An unusually wet (or dry) year could measurably decrease (or increase) the thickness of the dense-cemented halite stratum from year to year despite increased salt tonnage added to BSF by the Laydown Project.
- Although the yearly Laydown tonnage would maintain or increase the current mass of NaCl in the salt-crust deposit and shallow-brine aquifer, observed annual and spatial variation in dense-cemented halite stratum masked the annual 0.4-inch increase in salt-crust thickness predicted by the Laydown feasibility study.
- An estimated 5-square-mile increase in salt-crust areal extent was observed between September 1997 and October 1999. This added area represents an estimated 0.2 to 0.6 millions tons of salt that may have been contributed by the Laydown Project.

Geochemical (TEQUIL) modeling of brine compositions determined during the project produced the following conclusions regarding salt addition to the shallow-brine aquifer:

- The model showed that the shallow-brine aquifer within the 28-square-mile Laydown area has the capacity to accept 17 to 25 million tons of NaCl; this tonnage is three to four times the 6.2 million tons of Laydown salt delivered to BSF during the five years of the Laydown Project.
- The ability of the shallow-brine aquifer to assimilate additional salt suggests that most of the 6.2 million tons of Laydown-delivered salt currently resides in the shallow-brine aquifer; furthermore, only 0.6 million tons of Laydown salt could be accounted for in the 5 square miles of new salt crust, and the expected +2 inches of thickness addition to the salt crust was not observed at any of the monitoring locations upon conclusion of the 5-year experiment.
- The Laydown NaCl mass assimilated into the shallow-brine aquifer is eventually redistributed in the salt crust as part of new surface and additional subsurface halite crystal growth.
- The addition of Laydown brine to the shallow-brine aquifer does not change the salt-crust mineral assemblages; anhydrite and halite were the only minerals predicted to precipitate from two different mixing ratios of Laydown brine and shallow-aquifer brine in an open system such as BSF.
- The model predicted a 1-inch rainfall event would dissolve no more than a 0.14-inch thickness of salt crust; however, recorded natural spatial variability in thickness was ±0.6 inches from a 2.3-inch mean thickness obtained with 22 measurements of dense-cemented halite stratum; consequently, salt-crust dissolution predicted as a result of a 1-inch rainfall event cannot solely account for this natural variability in the dense-cemented halite stratum thickness. Other factors must also be operative.

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Hunting an Elusive Quarry: Geology and Early Stone Architecture in Ohio

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Abstract

The early pioneers recognized that certain Ohio sandstones, limestones, and dolomites have desirable building-stone characteristics. Several important historical structures in Ohio were constructed of locally quarried stone as early as 1797, six years before Ohio statehood. The first quarries of significant size were located in Ross County and produced building stone from the Mississippian-age Berea Sandstone. The Berea Sandstone was used in the construction of Ohio's first state house at Chillicothe, completed in 1801, and in the building of Thomas Worthington's magnificent estate, Adena, finished in 1807.

Another early center of quarrying activity in Ohio is in Scioto County, where Mississippian-age Buena Vista sandstone was quarried as early as 1815 and used primarily in the rapidly growing Cincinnati area. Pennsylvanian-age sandstones were quarried beginning in 1803 near Zanesville in Muskingum County to build homes and public buildings. The small town of Centerville in Montgomery County has the largest collection of early stone houses still intact in Ohio. Several homes were constructed prior to 1820 using Silurian-age Dayton Limestone quarried nearby.

The Berea Sandstone, Buena Vista sandstone, and Pennsylvanian-age sandstones remain important sources of building stone in Ohio today. Even though the oldest quarries have long been abandoned and the lively stories of the early stone masons forgotten, their craftsmanship and the durability of Ohio building stones are evident in the buildings that remain more than two centuries later.

Introduction

Ohio is fortunate to have an abundance of high-quality geologic construction materials: clay and shale for brick; sand and gravel for foundations and roads; high-calcium limestone for cement; gypsum for wall board; and sandstone, limestone, and dolomite for building stone. A building stone is any naturally occurring stone, generally of superior quality, that is quarried and used in masonry construction. Sandstone and limestone are the primary building stones quarried in Ohio. Dimension stone is building stone that has been sawn to size and used for exterior facing and trim on large buildings or as cut and dressed stone in residential construction. Building stone can also be used in landscaping (flagstone, curbstone, and retaining walls) or in heavy construction such as bridge abutments and piers. Durability (resistance to chemical and physical weathering) is the most important quality of a building stone. Strength, density, color, access to markets, and ease of quarrying and carving are also important characteristics of desirable building stones. Architectural effect is a more subjective quality: can the stone be used in a way that is aesthetically pleasing? Many Ohio sandstones, limestones, and dolomites have one or more of these characteristics and have been used to build many important historical structures in Ohio.

A Brief History of the Building Stone Industry in Ohio

Native Americans and the early explorers in the Ohio portion of the Northwest Territories used loose stone found along streams and hillsides to construct a variety of structures such as walls, foundations and enclosures. A Native American mound constructed north of Athens contained approximately 1,850 short tons (1,678 metric tons) of stone and an ancient Native American stone fort northwest of Somerset in Perry County enclosed an area of 40 acres (16.2 hectares; Howe, 1851).

The earliest settlers in Ohio used locally-derived stone to help provide three of the basic requirements of civilization: food (stone for grindstones to produce meal and flour), shelter (stone for buildings) and a means to honor the dead (gravestones). The first permanent settlement in Ohio was founded in 1788 at Marietta in Washington County. The majority of the early dwellings and fortifications were constructed with earth and logs; however, it was not long before the abundant and high-quality Pennsylvanian and Permian-age sandstones in the area were being used for foundations, gravestones, and grindstones (See table 1).

Locally quarried sandstone was used extensively throughout Ohio from 1804 to 1916 in the iron-making industry because it is moderately refractory, thus making it suitable for furnace linings. In addition, Ohio sandstone is resistant to abrasion and slag acidity, and becomes impervious to gas penetration as the heat of the iron furnace transforms quartz sand grains into the mineral tridymite (Stout, 1946; table 1).

The construction of the Ohio & Erie canal in eastern Ohio and the Miami & Erie canal in western Ohio from 1825 to 1847 was a major boon to the state's stone industry. Tremendous amounts of locally derived building stone were used in the extensive lock and dam system. The canal itself made long-distance transport of stone much easier (Hannibal, 1998).

The impressive Greek Doric architecture of the Ohio State House in Columbus was made possible by availability of large blocks of locally quarried Devonian-age Columbus Limestone (fig. 1). The State House cornerstone was laid July 4, 1839 and the building was completed in 1861 (Melvin and

TABLE 1. Selected stone structures in Ohio constructed prior to 1820

County	Township	Name	Date completed	Geology	Source	Comments
Adams	Liberty	Thomas Kirker house	1805	Silurian	Adams County Historical Society	Built by Thomas Metcalfe; private residence
Butler	City of Hamilton	First Courthouse and jail	1810	Cincinnati Group (Ordovician)	Western Biographical Company, 1882	33 ft. x 52 ft. two-story stone building
Columbiana	Yellow Creek	Hopewell Furnace	1804	Lower Freeport sandstone (Pennsylvanian)	Stout, 1946	First iron furnace in Ohio
Columbiana	Elk Run	The Ohio Paper Mill	1807	Lower Freeport sandstone (Pennsylavanian)	Herdendorf, 2000	First paper mill in the Northwest Territories
Franklin	City of Columbus	Penitentiary	1815	Columbus Limestone (Devonian)	Kilbourne, 1819	High-quality “freestone”
Greene	Miami	Clifton Mill	1802	Silurian	Herdendorf, 2000	One of largest grist mills in U.S.
Hamilton	City of Cincinnati	Ziegler farm	1797	Cincinnati Group (Ordovician)	Howe, 1851	
Hamilton	City of Cincinnati	Steam Mill	Circa 1818	Buena Vista Sandstone? (Mississippian)	Kilbourn, 1819	87 ft X 62 ft, nine-story building
Hamilton	City of Cincinnati	Water-works	1819	Cincinnati Group (Ordovician)	Cist, 1841	8-ft thick walls
Muskingum	Falls	Headley Inn	1802	Pottsville Group (Pennsylvanian)	Frary 1936	Private residence
Muskingum	Wayne	Water Works	1817	Allegheny Group (Pennsylvanian)	Carskadden, 1986	Stone reservoir
Pike	Benton	Eager Inn	Circa 1797	Buena Vista Sandstone (Mississippian)	*Waverly Watchman,* Nov. 26, 1974	Stone Inn on Zanes Trace; abandoned
Ross	Scioto	“Paint Hill” house	1807	Berea Sandstone (Mississippian)	Newcomb, 1950	Private residence
Ross	Scioto	Governor Tiffin house	Circa 1805	Berea Sandstone (Mississippian)	Ohio Federal Writers Project, 1938	Outstanding gardens
Scioto	Niles	Joseph Moore house	1814	Buena Vista Sandstone (Mississippian)	Bownocker, 1915	
Washington	Waterford	Wolf Creek Mills	1790	Pennsylvanian	Herdendorf, 2000	First industry in Ohio

McKenzie, 1992). The potential of the Columbus Limestone to be used for building purposes was recognized early by the local residents as indicated by the establishment of the quarries northwest of Columbus prior to 1815 (table 1).

The development of the huge quarries in the Mississippian-age Berea Sandstone (fig. 1) in northern Ohio marked the beginning of the "golden age" for the Ohio building stone industry. Grindstones had been made from the Berea Sandstone at Berea in Cuyahoga County since 1828, but it was the quarries opened by the Cleveland Stone Company and its predecessors at South Amherst in Lorain County in 1869 which made the Berea the dominant building stone by value in the United States by the late 1800's. In 1880, the value of Ohio building stone production was ranked first in the country (Orton, 1884).

The Pennsylvanian-age Massillon sandstone (fig. 1) was quarried as early as 1857 in Holmes County and was considered Ohio's most important source of brownstone. Markets extended from New York, south to Birmingham, Alabama, and west to St. Louis (Bownocker, 1915, p. 143).

Intense competition from domestic and imported stone, the extensive use of concrete substitutes, as well as increased steel construction, had a negative impact on the Ohio building stone industry in the early 1900s. Dimension stone production in Ohio continued to decline throughout the 20th century, decreasing from 193,643 short tons (175,634 metric

Generalized Column of Bedrock Units in Ohio

Time Stratigraphic Unit		Rock Unit	
System	Group	Formation, Significant Members or Beds	
Permian	Dunkard	Greene Fm	
		Washington Fm	
Pennsylvanian	Monongahala		Pittsburgh (No. 8) coal
	Conemaugh	Casselman fm	
		Glenshaw fm	Ames ls
	Allegheny		Upper Freeport (No. 7) coal Lower Freeport ss * Brookville (No. 4) coal
	Pottsville		Homewood ss * Massillon ss * # Sharon ss/congl
Mississippian			Maxville ls
		Cuyahoga Fm	Black Hand Ss Mbr * Buena Vista Ss Mbr * #
			Berea Ss * #
Devonian			Ohio Sh Columbus Ls *
Silurian	Salina		Tymochtee Dol # Lockport Dol
		Bisher & Lilly Fm Dayton Fm* Brassfield Fm #	
Ordovician	Cincinnati (informal) Black River	Fairview Fm * Point Pleasant Fm*	
Cambrian		Knox Dol	

* - Historical building-stone production
\# - 2001 building-stone production

Figure 1. Generalized stratigraphic column for Ohio, emphasizing rock units which produce building stone. Modified from Larsen (1998).

tons) in 1950 (Klein, 1951) to 85,231 short tons (77,305 metric tons) in 1970 (May, 1971). In 2001, six companies produced 60,550 short tons (54,919 metric tons) of building stone in Ohio, primarily for rough construction and landscaping (Wolfe, 2002; fig. 2).

Historical Stone Buildings in Ohio

The Old Stone Fort, an enigmatic 14-foot by 14-foot (4.3-m by 4.3-m) structure, built of hand hewn sandstone (Pennsylvanian-age Allegheny Group) and located near the Tuscarawas River in Coshocton County, has 22-inch (56-cm) thick sandstone walls and narrow vertical openings for gun ports on three sides that apparently provided a stout defense against enemies (Pollack, 1985). It is uncertain whether the Old Stone Fort was erected by French explorers in the late 1600s or by early settlers around 1803.

A very early, well-documented use of Ohio stone for building purposes occurred in 1800 when construction began on the first state house at Chillicothe in Ross County. The two-story stone building is believed to be the first public stone edifice erected in the Northwest Territories. The masonry work on the square, hipped-roof and cupola-style building was done by Major William Rutledge, a soldier in the Revolutionary War (Newcomb, 1950). Ohio's first constitution was written there in 1802, and the building served as the state's capital from 1803 to 1810 and from 1812 to 1816. Unfortunately, the historical building was razed in 1852 to make way for the Ross County Courthouse. In 1940, the Chillicothe Gazette built a replica of the first statehouse as the headquarters for its newspaper operations.

Ohio's first state house was constructed of Mississippian-age Berea Sandstone that was quarried to the immediate southwest of Chillicothe at Cemetery Hill (Hyde, 1921). Old

Figure 2. Map of Ohio showing the locations of the most significant historical (pre-1820) building-stone quarries in the state. The locations of Ohio building-stone quarries active in 2001 are also shown.

quarries extended continuously for several hundred yards along the southern and eastern face of this hill. All stone used in the early history of Chillicothe for building, foundations, and curbing came from these quarries. The Berea Sandstone in this area is usually 25 to 35 feet (8 to 11 m) thick, though only the top 10 to 15 feet (3 to 5 m) was suitable for building purposes. The Berea is a fine-grained, light-gray sandstone that weathers light brown. Bedding is generally 6 to 12 inches (15 to 30 cm) thick. Beds greater than 12 inches (30 cm) thick are rare, but 6-inch (15 cm) thick material is abundant. Thicker sandstone layers are sometimes found in the Berea and were used to construct larger objects such as watering troughs (Hyde, 1921).

Thomas Worthington's wonderful estate, Adena, was built in 1807 on a hill overlooking Chillicothe and the Scioto River Valley (fig. 3). Thomas Worthington is considered the Father of Ohio Statehood, he served as the state's first U.S. Senator and the sixth governor of Ohio. Adena was designed by Benjamin Latrobe, the first professional architect in the United States, and is one of only two Latrobe-designed homes still standing in the U.S. The stonemasons were brothers John and Presley Morris of whom little else is known (Ware, 2002). The Berea Sandstone used to build the estate was quarried onsite. A stratigraphic section at Adena (Hyde, 1921) reveals the sandstone in the upper portion of the Berea to be thicker bedded at Adena than at Cemetery Hill.

Dr. Increase Matthews built a single-story sandstone house in 1804 at Putnam (now part of Zanesville) in Muskingum County. The Stone Academy at Putnam was constructed in 1809 to be used as the new statehouse, but a competing brick building in nearby Zanesville was chosen instead. The building stone for both the Stone Academy and the Matthews house was produced from a quarry located northwest of what is now the intersection of Woodlawn Avenue and Pershing Street in Zanesville and was originally owned by Increase Matthews (Carskadden, 1986). A Pennsylvanian-age Pottsville Group sandstone, informally known as the "Homewood" (Stout, 1918; fig. 1), was quarried. The "Homewood" sandstone is light brown, medium to coarse grained, micaceous in part, and thick bedded to massive. The "Homewood" is approximately 27-feet (8 m) thick at the former Matthews quarry.

The Philip Moore Jr. stone house (fig. 4) at West Portsmouth in Scioto County is believed to be the oldest standing sandstone home in Ohio. Philip was a Revolutionary War veteran and started building the house in 1797 of Berea Sandstone quarried from the hillside approximately 300 feet (90 m) south of the home.

Scioto County became an important quarrying center in the early 1800s. Initially, large quantities of the Mississippian-age Buena Vista sandstone (fig. 1) were recovered from blocks that had become detached from hillside outcrops in Scioto County. Soon, extensive quarries, railroad sidings, and stone-cutting facilities were constructed (fig. 2). Local residences such as the Joseph Moore house at Rockville (table 1) and public buildings in Portsmouth were built using the Buena Vista, but the majority of the sandstone was rafted down the Ohio River to Cincinnati for building purposes in that burgeoning city (Bownocker,

Figure 3. View of the front of Thomas Worthington's magnificent estate, *Adena*, constructed in 1807 overlooking the Scioto River Valley and Chillicothe in Ross County, Ohio. The Mississippian-age Berea Sandstone used to build the estate was quarried onsite.

1915). The Buena Vista sandstone is blue-gray to light-brown, fine grained, medium bedded, and typically 25 feet (8 m) thick, including interbedded shales (Mather, 1838).

In 1805, Cincinnati only had four stone houses (Roe, 1895), but by the early 1820s four stone-cutting factories employing 18 men, and a steam mill, capable of sawing 120,000 feet (37 km) of stone a year, were operating in Cincinnati (Drake and Mansfield, 1827). A survey taken in 1826 lists 18 stone buildings in Cincinnati including the U.S. Banking House of the Branch Bank and the Methodist Society building that were most likely constructed of Buena Vista sandstone from Scioto County (Drake and Mansfield, 1827; Mather, 1838).

Ordovician-age Cincinnati group limestones (fig. 1) quarried locally were also used for early construction in the Cincinnati area (table 1). Cincinnati group limestones were not competitive with other Ohio building stones, however, because of thin bedding, interbedded shale layers, and pyrite inclusions.

The Old Stone House in Lisbon, Columbiana County, which today houses the Lisbon Historical Society, was built by Louis Kinney in 1805 of Pennsylvanian-age Lower Freeport sandstone quarried nearby (Stout and Lamborn, 1924). (Note: Columbiana County had the largest population by county in Ohio according to the 1810 and 1820 census).

The First Presbyterian Church of West Union, also known as "The Church of the Governors" was built in 1810. Thomas Kirker, Ohio's second governor, was instrumental in raising the funds to build this Adams County church. Stone mason Thomas Metcalfe, called the "Old Stonehammer" by many (Howe, 1851, p .27), was awarded the contract to build the church walls. The building stone used was quarried adjacent to the church and is dolomite from the Silurian-age Bisher and Lilly Formations (Schumacher, personal commun.).

Centerville, 8 miles (13 km) south of Dayton in Montgomery County, has the largest collection of early stone houses still intact in Ohio. Approximately 15 homes were constructed of locally-quarried Silurian-age Dayton Limestone (fig. 1) prior to 1820 (Houser, 1977). Ashahel Wright, the great uncle of the famous Wright brothers, Orville and Wilbur, occupied a stone home built in 1806. The trapezoid stone lintels above the doors and windows of the Wright house are unique to the area (Houser, 1977, p. 41). The amazing craftsmanship of Jonathan Munger, an early stonemason of Centerville, can be seen at the well-preserved Benjamin Wallingsford house (fig. 5) that was built prior to 1810. Joseph Tice, also a well-known stonecutter in the area, shaped and cut limestone for many of the early Centerville buildings. Much of the early building stone in Centerville came from the Garard quarry southwest of Centerville (Houser, 1977, p. 144). The Dayton Limestone, also called "Dayton marble," would become the dominant building stone in southwest Ohio in the mid to late 1800s (Orton, 1884). It was desirable because of its durability, attractive light gray color, and crystalline texture. An excellent update on the Dayton Limestone, including probable locations of historical quarries, can be found in Sandy (1992).

Figure 4. Front and side view of the Philip Moore Jr. home at West Portsmouth in Scioto County, Ohio. Philip was a Revolutionary War veteran and is believed to have started building the house in 1797. The house is constructed of Mississippian-age Berea Sandstone quarried from the hillside approximately 300 feet (90 m) to the south.

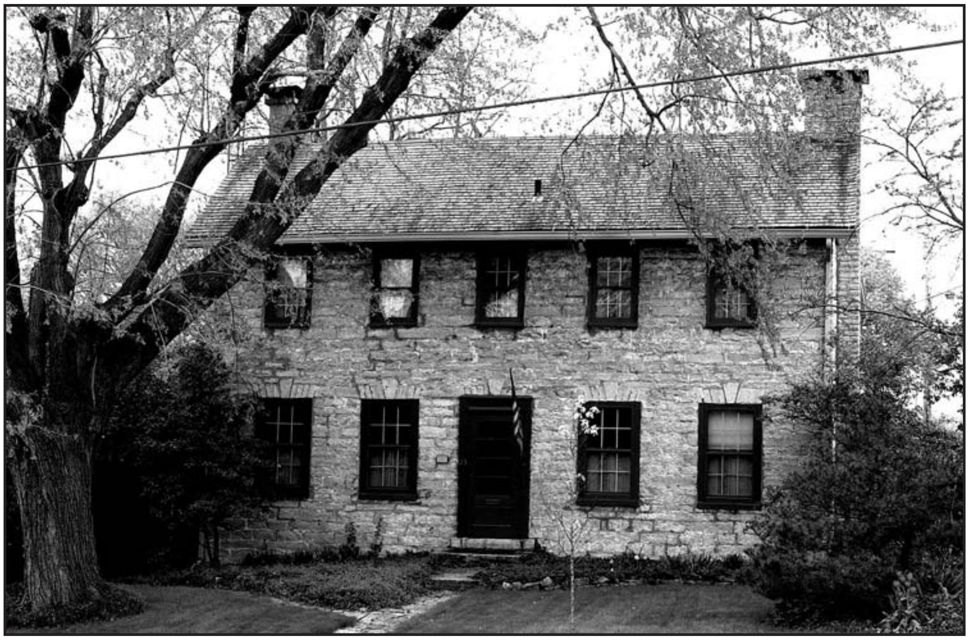

Figure 5. View of the front of the well-preserved Benjamin Wallingsford house at Centerville in Montgomery County, Ohio. The home was built prior to 1810 and was constructed using Silurian-age Dayton Limestone quarried to the immediate southwest.

Summary

The variety and quality of Ohio building stone was readily apparent to the early inhabitants of the state. Skilled masons, quarry owners, and architects were attracted to Ohio very early in its settlement to design and construct the stately homes and splendid government buildings that signified the emerging prominence of the state in national affairs. The geology of Ohio strongly influenced the type of architecture and the longevity of the buildings that its citizens built. The ingenuity, innovation, and diligent labor of the early quarrymen and stone masons can be admired in the centuries-old stone structures found throughout Ohio today.

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Hydrogeology of Clayton Valley Brine Deposits, Esmeralda County, Nevada

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Abstract

This paper seeks to define the geology and character of the aquifers in the Clayton Valley brine field, Esmeralda County, Nevada. Six aquifers are recognized in this closed basin playa in west-central Nevada. These are the sources of the lithium reserves and resources of Chemetall Foote Corporation, Silver Peak Operations, Nevada. Lithium-rich brine resides in confined to semi-confined hydrologic units within the playa region.

Several hundred exploration borings as deep as 2,000 feet have been drilled since 1964 seeking brine for production purposes. Approximately 200 production wells over the years have supplied brine to an extensive pond system for the purpose of concentrating the brine by solar evaporation.

Clayton Valley is a graben structure that has enhanced the accumulation of pluvial and interpluvial sediments, the precipitation of evaporites, and accumulation of lithium bearing brine. Extensive faulting has created hydrologic barriers as demonstrated by brine and water samples taken from boreholes on either side of these faults. Basin depth has been determined from geophysical surveys to be several thousand feet.

Seismic and gravity surveys reveal numerous horst and graben features in a gently synclinal, deepening basin to the east-southeast. In the southern and western sections of the playa, downdrop and thickening of the basin-filling sediments is not as pronounced as in the northeast. Each of these areas has its own unique characteristics and is tapped for production.

Introduction

Lithium brine is extracted from aquifers within the closed basin of Clayton Valley, located in the west central region of Nevada, approximately 50 miles east of the Sierra Nevada, within the Basin and Range province (fig. 1). Interest in potassium minerals led Leprechaun Mining and Chemical Inc., to many playas of the western United States. Chemical analysis of Clayton Valley sediments revealed abnormally high lithium, potassium, and sodium chloride concentrations. In 1964, Foote Mineral Company acquired the mining rights and began in earnest the development of the playa system for the express purpose of producing lithium carbonate from brine. Production from the carbonate plant began in 1966. Initially, only a few production wells were constructed in the west central region of the playa. Target production was from a marker aquifer soon to be known as the Main Ash Aquifer. This aquifer, which occurs throughout the playa, has been the largest and most productive horizon.

Production wells currently tap six aquifer systems that yield brine to various evaporation ponds. Upgrading of brine salinity occurs over a 12 to 18 month period. Twenty active evaporation ponds make up 4,150 acres of surface area and hold up to several billion gallons of brine (figs. 2 and 3). Annual brine evaporation is 35 inches compared to freshwater evaporation of 56 inches with an average rainfall of 4 to 5 inches and a temperature range from 2 to 108ºF. Currently, 50 wells are producing brine from all of the aquifers at rates from 30 to 325 gallons per minute (gpm). Depths of production wells vary from 230 feet to 1,160 feet with future plans to complete wells to 1,650 feet.

The playa represents an area of approximately 25 square miles at an elevation of about 4,270 feet above the level of the sea. The surface sediments are characterized by salts, clays, and silts, changing to sands and gravels and boulders towards the periphery of the playa.

Regional Hydrogeologic Setting

Basin and Range topography is represented in this western Nevada valley as a basin that is closed topographically and does not exhibit typical northeast-southwest linear horst and graben valleys seen in much of the rest of the state. The Angel Island and Paymaster Canyon high angle, normal faults act as hydrologic barriers along the southeastern playa edge near Angel Island. The Angel Island fault intersects the Cross Central normal fault (fig. 1).

Stratigraphic impediments occur around much of the rest of the playa, isolating it from significant freshwater recharge and dilution. Groundwater flow barriers have created the ideal environment for the accumulation of the brine reserves being mined today. Basin sediments accumulated in a low energy lacustrine environment where evaporation and precipitation ratios controlled the deposition of either significant amounts of saline minerals or of detrital sediments. Increases in TDS (total dissolved solids) generally correlate to increase in lithium values. Hydrologic recharge in the form of underflow into the basin is occurring from the northwest, where physiographic highs surrounding the basin are at their lowest, and minor dilution troughs are known to exist. Recharge may also be entering through Paymaster Canyon. Recharge to the confined and leaky confined aquifers that comprise this valley may be partially sustained by percolation along range-front faults, growth faults, fault creep zones, and associated paths of deep percolation. Brine temperatures typically do not exceed 80ºF. Basin deepening in the northeastern playa sector is illustrated in numerous borings through marker beds, particularly the Main Ash Aquifer, which strikes along a northeast-southwest trend and dips approximately 30º to the southeast (fig. 4).

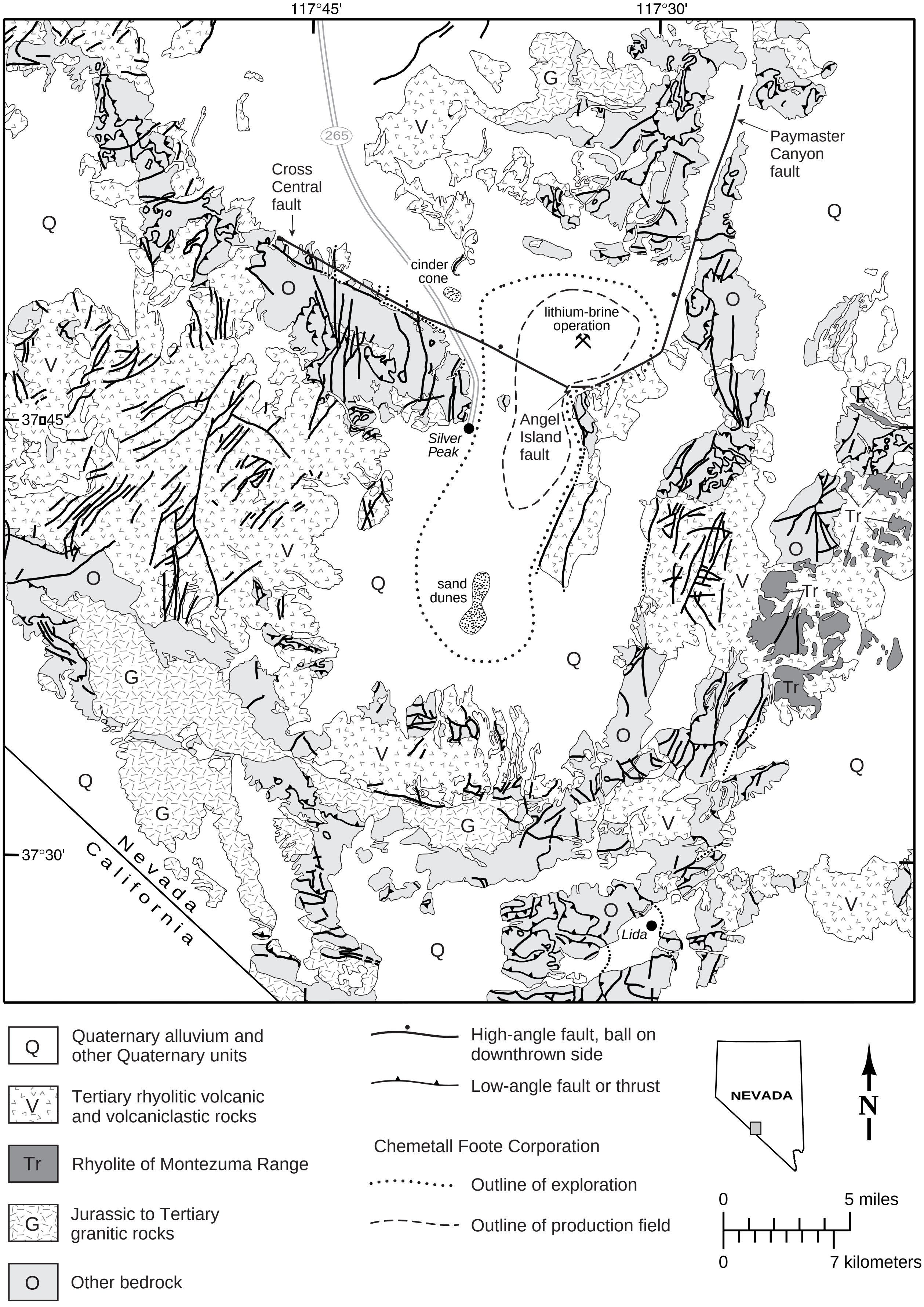

Figure 1. Generalized geology in the Clayton Valley area (modified from Price and others, 2000, and Albers and Stewart, 1972).

Figure 2. Aerial photograph of evaporation ponds at Silver Peak in Clayton Valley. The nearly square pond just north of center is about 1 mile square.

Figure 3. Chemetall Foote pond with salt and carbonate precipitates. Quaternary cinder cone in distance along State Route 265 (photo by J.G. Price, 1995).

Two aquifers, the Main Ash and Lower Aquifer System, are largely composed of air-fall and reworked volcanic ash, which serve as reservoirs for the brine but not as the primary source of lithium. Lithium supply source is probably from lithium-rich rhyolitic tuff on the eastern margin of the basin (fig. 1; Kunasz, 1974; Price and others, 2000) and possibly from deep-seated geothermal water flow that may have conducted lithium-rich water from the magma chamber source for the tuff. Basin filling sediments are largely illite, smectite, and kaolinite clays in order of predominance (Kunasz, 1970), with lenses of silt, sand, and gravel deposited during pluvial and interpluvial events. Ash beds of varying continuity are interlayered with these detrital sediments (fig. 4) as well as chemical sediments such as gypsum, calcium carbonate, and halite. In addition to the two ash aquifers, other aquifers are in beds dominated by tufa, gravel, salt, and silt grading to sand and gravel.

Aquifers

The presence of six aquifers is revealed by data accumulated over the past 39 years from exploration holes, production wells, geochemical analysis, pumping tests, and seismic, gravity, and magnetic surveys (fig. 4):

- Lower Gravel Aquifer (fig. 5)
- Lower Aquifer System (figs. 5 and 6)
- Main Ash Aquifer (figs. 5, 6, and 7)
- Marginal Gravel Aquifer (fig. 5)
- Tufa Aquifer (fig. 5)
- Salt Aquifer System (fig. 5)

Pumping tests and records from continuous production pumping have shown evidence for conductivity between certain aquifer systems. Brine salinity in production wells varies from 40,000 to 170,000 mg/L TDS with corresponding specific gravity varying from 1.025 to 1.21. Lithium values well in excess of 400 ppm have been pumped from the basin (Papke, 1976; Vine, 1980). Kunasz (1970) and Davis and others (1986) report economic grades in the range of 230 to 300 ppm. Recharge to the aquifers is at a lesser rate than depletion by approximately a one-to-two margin. Declines in lithium values are caused by fresh water recharge and can be correlated to specific pathways of dilution by frequent brine analysis over the entire well field. The magnesium/lithium ratio is relatively low, facilitating the economic separation of the magnesium before final processing.

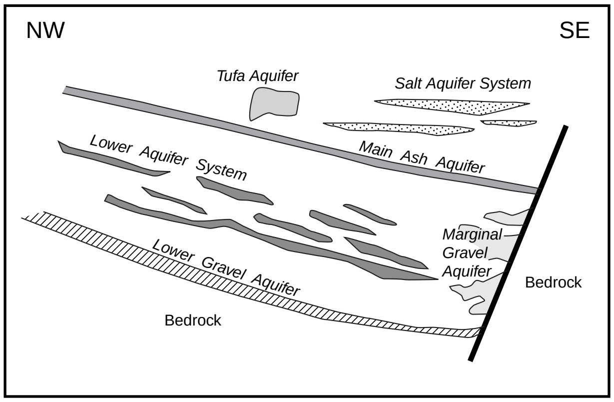

Figure 4. Schematic cross section of aquifers in Clayton Valley along the dip of the basin.

Seismic surveys (figs. 8 and 9) indicate that basin downdrop is on the order of 4,000 feet, creating a structural depression for the accumulation of infilling sediments and brine. Confined to semi-confined aquifers are defined by their artesian characteristics, with levels rising from tens of feet to approximately 200 feet above the top of aquifers. Static brine levels range from 70 to 400 feet below the surface of the playa. The unsaturated zone consists largely of clay, silt, and sand with local halite and gypsum interbeds. Vertical fluid migration within the playa is generally considered to be negligible due to the thickness of the clay sediments of very low hydraulic conductivity. However, geophysical surveys suggest interbasin faults may exist, creating potential pathways for limited vertical migration of fluids. Aquifers are discussed below in order of formation during the evolution of the basin as is currently known.

Geophysical work and exploratory borings have defined the bedrock and lacustrine sediment contact as well as aquifer locations in the Clayton Valley. Drill-hole data have identified the Lower Gravel Aquifer (LGA), which consists of gravel with sand and silt matrix interlayered with local clean gravel. Gravel clasts are of limestone, dolomite, marble, pumice fragments, siltstone, and sandstone. The LGA has high transmissivity estimated from airlift volumes and production rates and has lithium concentrations sufficient to enhance ore reserves significantly if developed further. Currently, one partially penetrating well is producing from the LGA at a rate of 300 gallons per minute. The LGA is shown to thicken to the north-northeast, the deepest part of the basin (fig. 5). Known thickness varies from 25 to over 350 feet. Brine migration down dip may yield higher specific gravity fluids deeper in the basin due to brine density differential. The LGA has not been drilled in the deepest area of the basin.

Above the LGA are the Lower Aquifer System (LAS) ash beds, which are moderately continuous throughout the playa north of the Cross Central fault (figs. 1 and 5). Individual ash beds occur in localized to areally extensive units. Brine from this system is typically high in lithium concentration and contains about 160,000 TDS. The LAS ranges from approximately 350 to 1,100 feet below ground surface, and is below the Main Ash Aquifer marker bed (figs. 4 and 6). Permeability is limited due to narrow lenses of ash of lesser depositional continuity. An inferred origin for some of the thinner lenses of the LAS may be as pluvial events carrying reworked ash, possibly from peripheral highland areas into the lake environment. Alluviation of ash from a single event of ash deposition in the highlands over the extended time suggested by the thick host sequence is unlikely. Therefore, the ash beds probably represent multiple eruptions. Basin subsidence coincided with pluvial deposition over several hundred vertical feet north of the

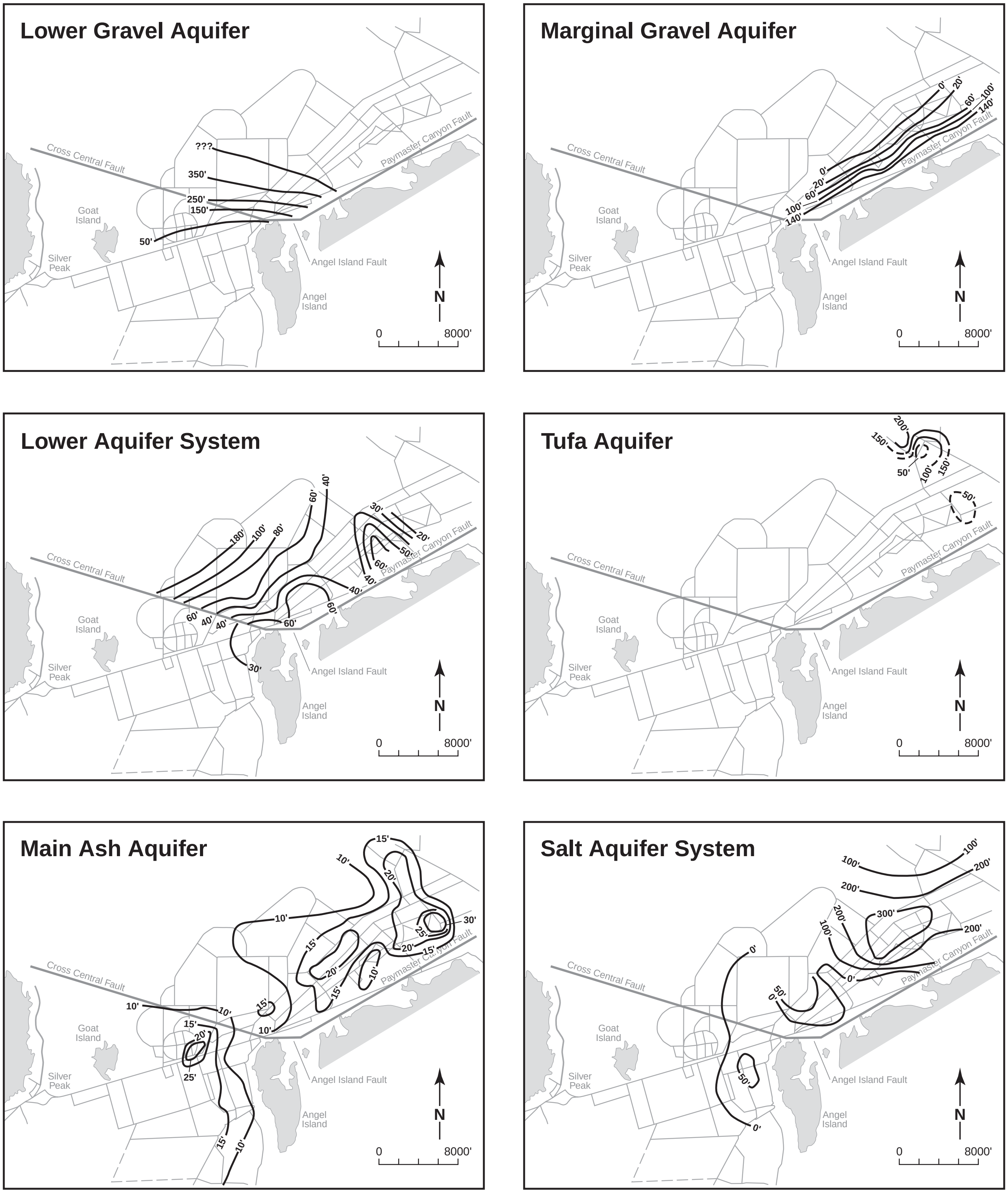

Figure 5. Isopachs of the Lower Gravel Aquifer, Lower Aquifer System, Main Ash Aquifer, Marginal Gravel Aquifer, Tufa Aquifer, and Salt Aquifer System (thickness in feet, superimposed on outlines of brine ponds and pertinent fault systems).

Cross Central fault. With the exception of a small area near Angel Island (fig. 5), the LAS is not present south of this fault, indicating non deposition or subsequent erosion there, and relatively rapid sedimentation north of the fault. Isolithium values in this aquifer system (fig. 10) suggest that the intersection of the Cross Central and Angel Island faults somehow controlled lithium concentration in the aquifer.

Production began in 1966 from the Main Ash Aquifer (MAA), which varies in thickness from 5 to 30 feet (fig. 5). Thicker sequences of ash coincide reasonably well with interbasin depressions also indicated by the overlying Salt Aquifer System (SAS) (fig. 5). Particles in the ash range in size from submicroscopic to welded fragments of several inches or more. Depth to the MAA ranges from 200 feet in the southwest to over 750 feet in the northeastern playa, where downdropping of the hanging wall, or bedrock, has exceeded that of the southwestern playa. Sedimentation in the east likely exceeded that to the west as indicated by the thickening of clay units eastward as detected by gravity and seismic geophysical analysis. Continuity of the MAA throughout the northeastern area of the Clayton Valley playa makes it an excellent marker bed. This aquifer is

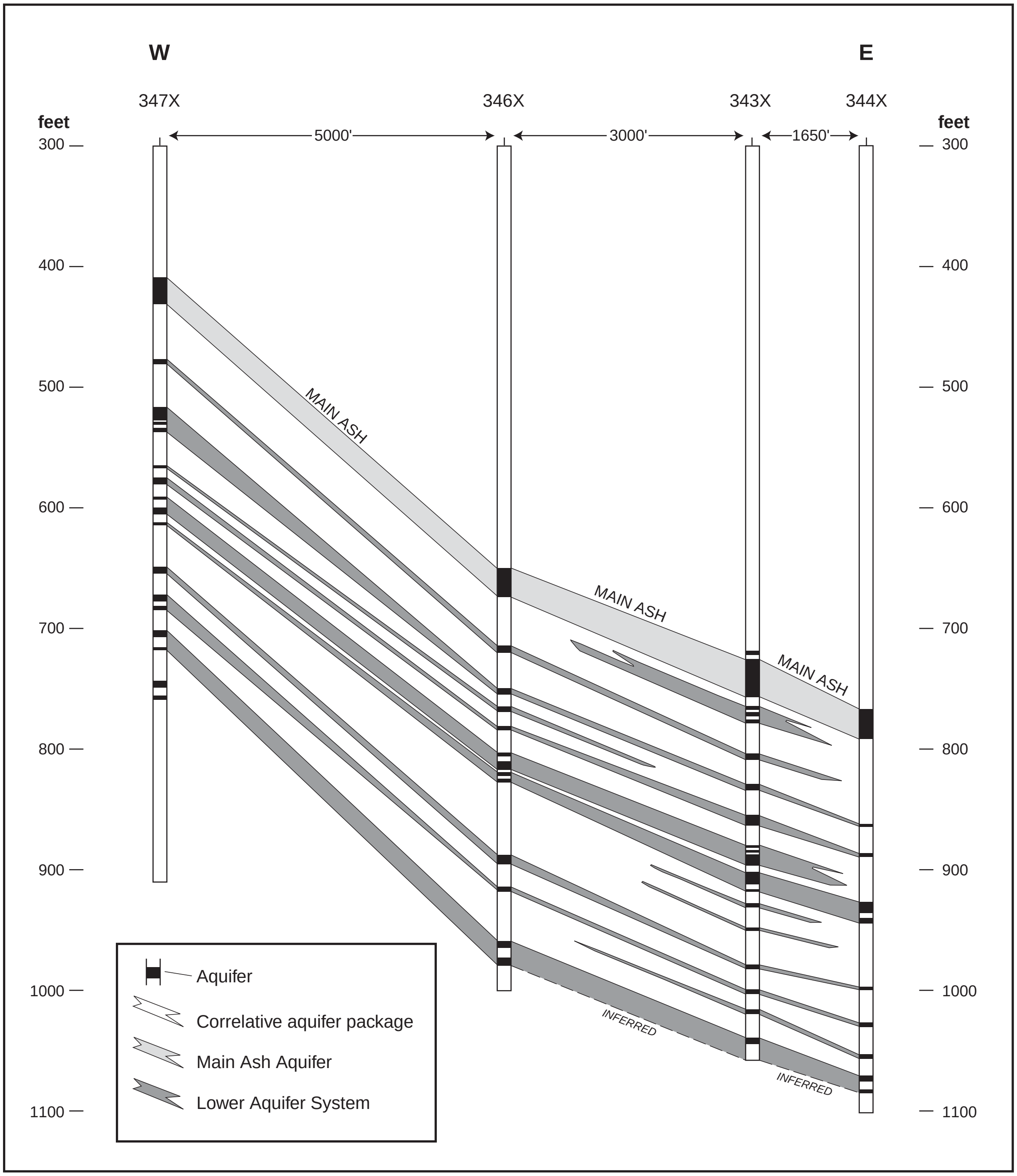

Figure 6. Generalized cross section of the Main Ash and Lower Aquifer System, looking north (depths in feet below the playa surface, modified from a figure drafted by M.W. Hardy, 1993).

characterized by moderate transmissivity and yields. Salinity currently ranges from 80,000 to 95,000 TDS.

The Long Valley caldera eruption and ash coverage from the Bishop Tuff 760,000 years before present is well documented (fig. 11). No other Quaternary eruption of great volume is known to have occurred nearby. Smaller events at Lassen Peak/Brokeoff Mountain 400,000 years before present and Mt. Mazama (Crater Lake) approximately 6,800 years before present are less likely to have deposited as much ash in Clayton Valley; however, the possibility remains. Assuming that the Bishop Tuff is the most plausible source of the MAA, sedimentation in the western playa is estimated at 0.003 inches per year. Thicknesses in the eastern playa suggest a sedimentation rate of as much as 0.012 inches per year.

Marginal Gravel Aquifer (MGA) wells have been exploited over the past 22 years to supplement production with high volume, low salinity brine (40,000 TDS) from the silt, sand and gravel of the linear growth-fault system bordering the playa known as the Angel Island and Paymaster Canyon Fault system (fig. 5). It is along this east-northeast-trending fault system that the majority of basin drop and displacement has occurred. The gravels were presumably eroded from the bedrock in the footwall of the fault and shed down onto the hanging-wall. This growth-fault material and contained brine along the playa side of the fault system is partly constrained by the gravel-playa clay interface. Drill holes to the southeast of this fault zone and up slope contain large volumes of fresh water. Therefore, it is believed that this fault system serves as a major hydrologic barrier that effectively preserves the integrity of the brine field from dilution.

The Tufa Aquifer (TA) is in the northwest sector of the playa. Limited production and exploration holes suggest a ring-like tufa or travertine formation that thickens towards its outside edges (fig. 5). Whether submarine vents seeping fluid into the ancient lake or surficial hot spring terraces composed of $CaCO_3$ formed these features has yet to be determined with certainty. The TA has a moderate to high yield potential. Production from this small, localized aquifer is at moderate rates, with relatively low salinity (40,000 TDS). Historical values have been on the order of 100,000 TDS, suggesting that brine extraction is enhancing fresh water migration into the region from the north-northwest and possibly from Paymaster Canyon to the northeast. Pumping tests and production data have shown hydraulic connection with the Main Ash Aquifer.

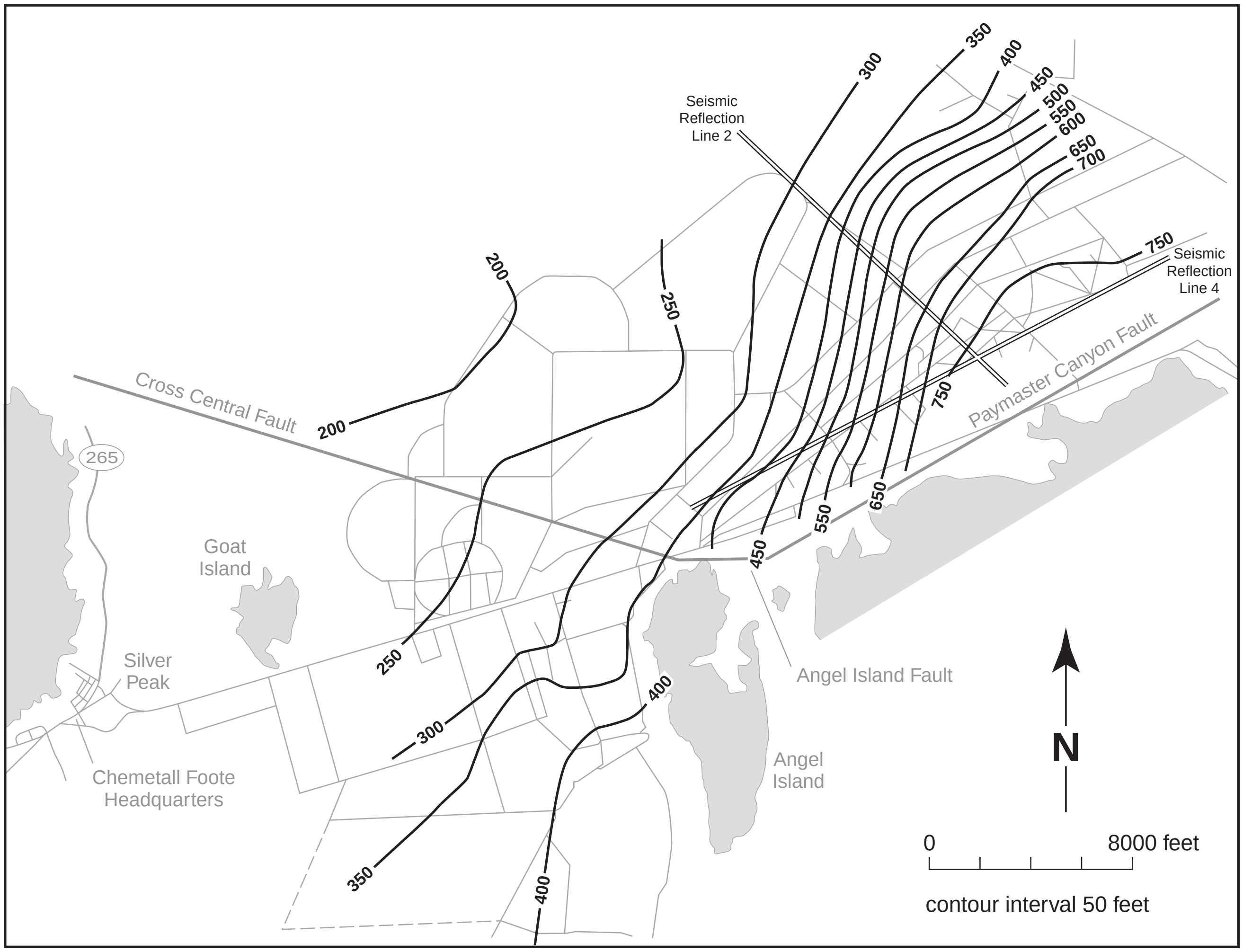

Figure 7. Structural contours of the top of the Main Ash Aquifer (depth in feet below the playa surface).

In the northeast playa, the aerial extent of the Salt Aquifer System (SAS) is somewhat continuous in its occurrence (fig. 5). Vertically, lenses of salt vary from fractions of an inch to approximately 70 feet in thickness with interbeds dominantly of clay, some silt and sand, and minor amounts of gypsum, ash, and organic matter. In addition they contain some caverns. Salt was likely precipitated in lowland standing water by the concentration of minerals through evaporation during contemporaneous subsidence of the basin. Typically less than 600 feet in depth, the SAS provides moderate to high-grade lithium brine at moderate yield rates. Transmissivity varies with depth; deeper salt beds are more compact and less yielding than upper lenses. The moderate pumping levels and the relatively high lithium concentrations make this a viable, economic, and intriguing aquifer.

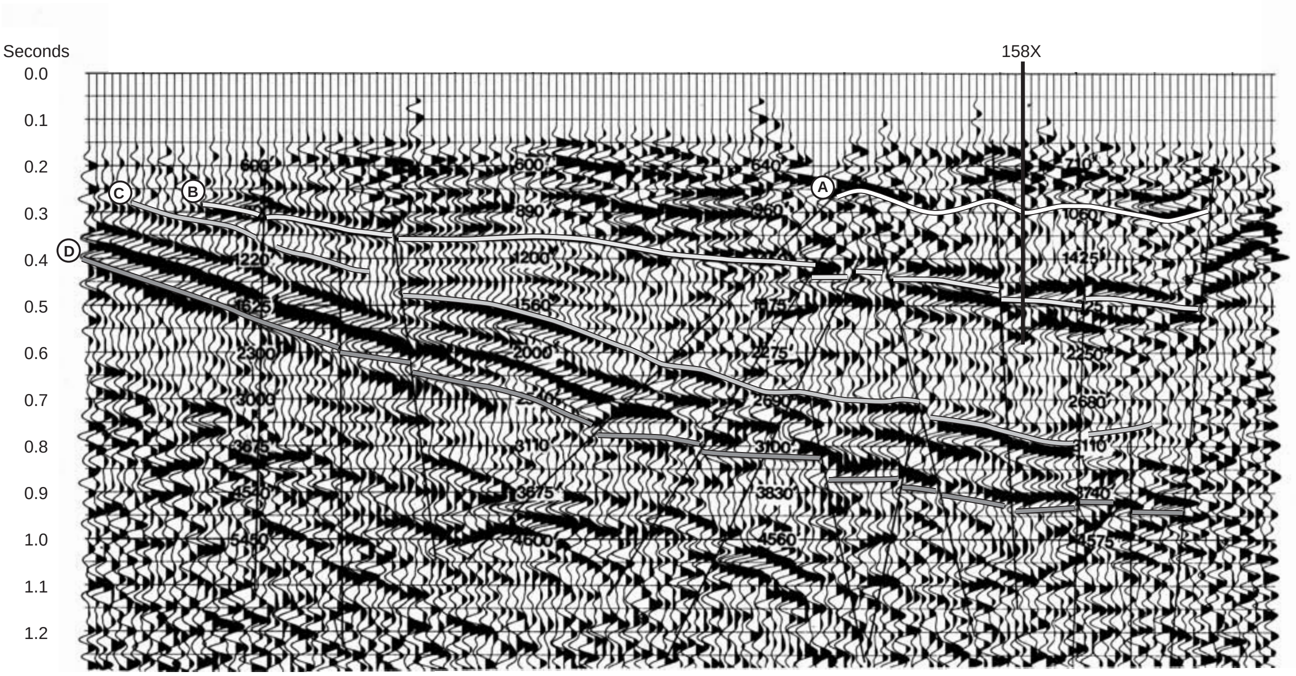

Figure 8. Seismic line 2, looking northeast, potentially identifies aquifers in cross section along basin dip (interpreted depths in feet).

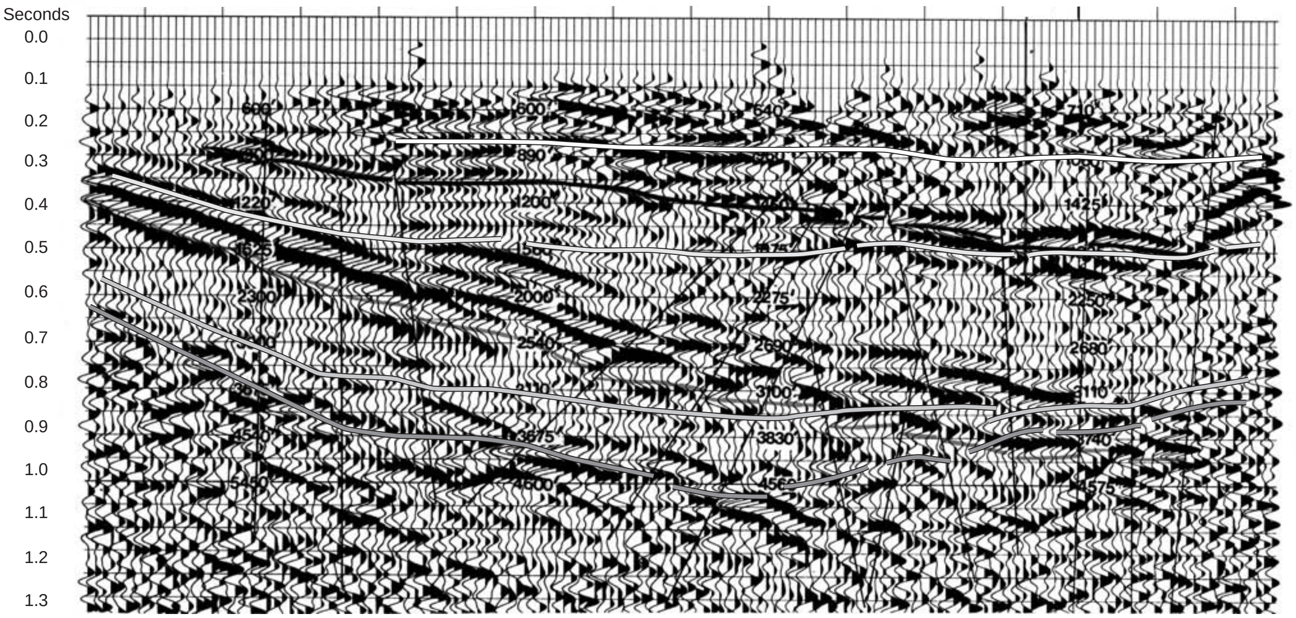

Figure 9. Seismic line 4, looking northwest, potentially identifies aquifers along the general strike of the basin lithology, and suggests a gently asymmetrical character. Interpreted depths in feet.

Summary

Lithium brine at Clayton Valley resides within six economic yet potentially interconnected aquifer systems. The aquifers were created through structural and stratigraphic controls, which were significant in both isolating higher grade brine and in the creation of aquitards within individual and collective aquifer systems. Some aquifers, such as the LAS, are relatively isolated, with production wells showing no interference on neighboring wells drilled into adjoining aquifers. In other systems, such as the TA and MAA, pumping data that indicate interference suggest a connection. In a low-energy lacustrine environment, few sedimentary layers may be sufficiently porous for use as aquifers; however, Clayton Valley has numerous ash layers or lenses that act as ore-bearing aquifers (MAA and LAS) along with chemical sediments (SAS and TA).

Production from all six of the aquifers continues on a regular, full-time basis. Shallow aquifers (SAS) have a high-grade, moderate production rate with a low cost per pound ratio. Deeper aquifers such as the LGA or the peripheral MGA are of lesser grade and cost more to produce, but their high volumes help to sustain production from the pond system. Depletion of the aquifers through production exceeds recharge by a factor of 2. Specific dilution pathways cause a progressive decline in lithium concentration. Proper management of the well field demands close attention to changes due to pumping from such a complex system.

Acknowledgments

I would like to thank Clifford B. Loundagin, General Manager of Chemetall Foote Corporation for his insights, discussions, and perspectives contained in this paper, which would not have been possible without his assistance. I thank Mike Hardy for his earlier work, Ihor Kunasz for exhaustive research and advice, and other past employees of Chemetall Foote for filling the files with so much useful information. I thank Steve Castor, Nevada Bureau of Mines and Geology (NBMG), for technical and editorial suggestions that improved this manuscript, and Alan Coyner, Joe Potseega, Chris Ross, Dennis Gaddy II, and Melissa Jennings for their assistance. I thank Ron Hess, Susan Tingley, and Richard Meeuwig for their scanning, drafting, and editing at NBMG. And thank you, Walt Lombardo, for urging me to write this paper. I am sincerely grateful to Jon Price (NBMG) for the

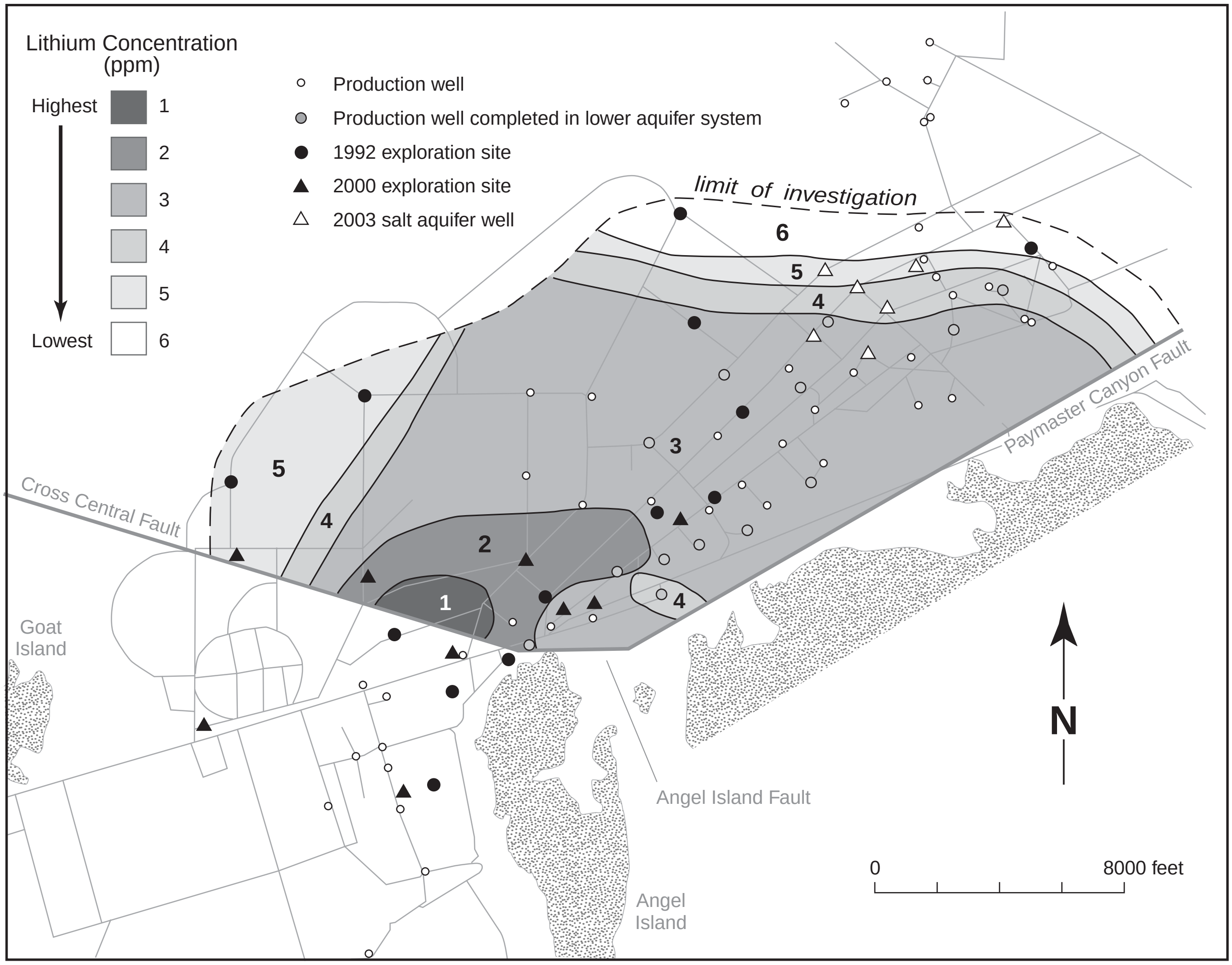

Figure 10. Isolithium map of the Lower Aquifer System (modified from a figure drafted by M.W. Hardy, 1993).

structure, layout, ideas, and discussion. Most of all, I thank my children for their patience and my wife, Susan Renee, for her encouragement and support.

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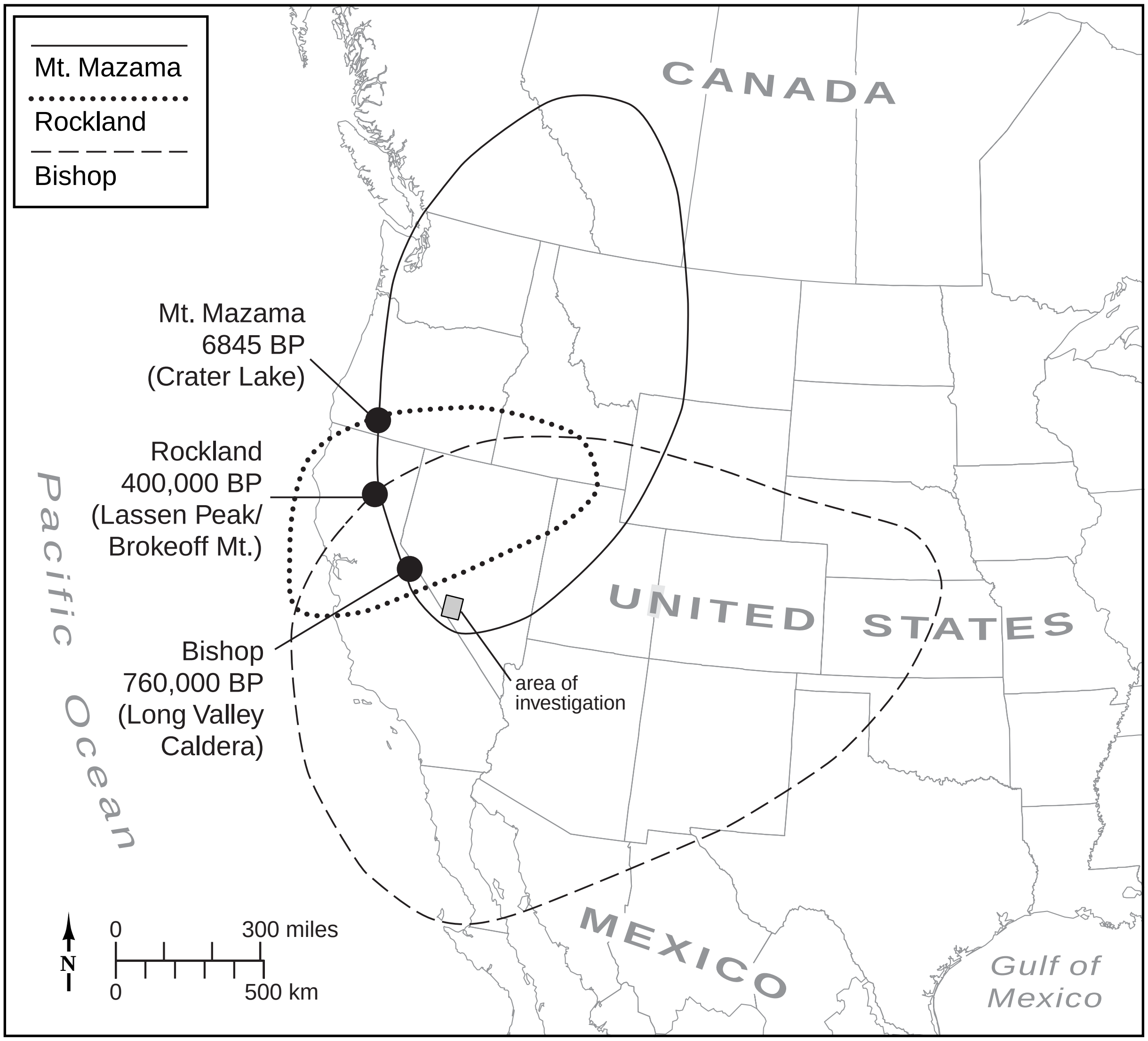

Figure 11. Possible sources of ash aquifer materials comprising the Main Ash Aquifer and Lower Aquifer System.

Abstracts of Other Presentations

(posters and talks for which no papers were submitted)

Carrara Marble and Cement Company Deposits, Southern Nye County, Nevada [Poster]

D.M. Anderson, Anderson Resource Associates, Inc.

Marble in Carrara Canyon on the southwestern flank of Bare Mountain resembles marble from Carrara, Italy. Quarrying of this deposit began in 1904. In 1911 the American Carrara Marble Company established a town and installed ore haulage rails from the town to the quarries. The first shipment was to Los Angeles in 1914, using the Las Vegas and Tonopah Railway that paralleled modern Highway 95. The operation ceased during World War I. Another attempt at production was made in 1921, but abandonment of the railroad and power lines doomed this operation.

In the quarry area, Bare Mountain is primarily Cambrian carbonate and clastic metasedimentary beds that have been uplifted, tilted, and faulted. The marble resource is in the Carrara Formation, which contains interbedded limestone, siltstone, and micaceous shale. The marble is 400 to 1,000 feet thick and is white to black, with tan, green, and other colors present. Exposed white marble is 80 to 150 feet thick near the head of Carrara Canyon where quarrying took place. Black dolomitic marble, which overlies the white marble with a distinct contact and no intermingling, crops out on the north side of Carrara Canyon, also a quarry area, and extends southward over the white marble at higher elevations. The footprint of the exposed marble resource is roughly 2,000 by 1,200 feet, and varies in elevation from 4,100 to 4,600 feet in steep, rugged terrain.

The white marble exceeds 96% $CaCO_3$. This, along with high brightness and low magnesium, iron, silica, and aluminum, makes this deposit suitable for many specialized uses such as in the filler and extender markets. Sandia Labs reported carbonate from Bare Mountain to be superior material for portland cement. The black marble and beds above it are excellent quality dolomite, suitable for uses where high magnesium and low iron and aluminum are desired. Sand and gravel deposits at the base of Carrara Canyon contain grade A concrete aggregate.

Enhanced In Situ Recovery of Soluble Evaporite Minerals Using Heat

Dipti Barari and Avery A. Richardson,
IMC Chemicals, Inc.

Solution mining of evaporite minerals, specifically salt, has been taking place for thousands of years throughout the world. However, recent advances in the fields of chemistry, geology, and drilling have brought this mining process to the forefront as a potentially low-cost and environmentally sound method of extracting soluble minerals. The addition of heat to the solution mining process can increase mineral solubility and enhance recoveries, sometimes at very little cost to the producer. This is especially true when low-cost heat is available.

Many factors contribute to the success of solution mining operations, but none is more critical than the hydrologic and geologic setting of the deposit. Evaporite minerals or natural brines must be hydrologically isolated to allow for adequate recovery of solutions to maximize profitability and minimize environmental impact through leakage. Additionally, deposits need to be of sufficient grade and volume to justify initial investment.

Adding heat to the solution mining process has the potential to increase recoveries in nacholite ($NaHCO_3$), borate minerals, sylvite (KCl) and several other species. About half of the evaporite minerals display a directly proportional increase in solubility with rising temperatures. Notable exceptions are halite (NaCl) and thenardite (Na_2SO_4), which are present in many evaporite deposits. This differential in solubility with temperature facilitates increasing the concentrations of desired species while not loading the solution to capacity with materials of little or no interest.

Solution mining with added heat is only viable when a communication path between injection and production wells can be achieved. Some deposits, such as Searles Lake in Trona, California, have a very high transmissivity that allows vertical injection and production wells to easily communicate with each other over substantial distances. Other deposits with low transmissivity require establishing an initial communication path, using other more costly technology.

An Overview of the Minerals Industry of Utah with an Emphasis on Industrial Rocks and Minerals

Roger Lee Bon, Utah Geological Survey

Utah has always been one of the leading mineral-producing states in the U.S. Even from the time of the arrival of the Mormon pioneers in 1847, industrial minerals such as salt, sand, gravel, clay, lime, and cement were sought-after commodities, long before the first mineral claim was filed in 1863, and some 49 years before Utah was granted statehood.

Following the completion of the transcontinental railroad in 1869 through the early 20th century, Utah was a leading producer of base and precious metals and was a leader in smelting capacity. While Utah's "heydays" of metal mining are something of the past, industrial minerals continue to provide a significant and increasingly larger portion of the value of Utah's mineral production each year.

In 2002, Utah mineral operators produced about $1.77 billion worth of rock and mineral commodities from about

200 operations, not including the many sand and gravel operations that under state law are not required to be permitted (and thus are not tracked). These commodities range from the most common (copper, clay, limestone, and sand and gravel), to the rare (gold and silver), to the unusual (gilsonite and beryllium), and in the past have included the elements gallium and germanium.

The Utah Geological Survey divides Utah's mineral industry into four segments: base metals, precious metals, energy minerals, and industrial minerals. The estimated total value of all rock and mineral commodities produced annually from 1993 through 2002 ranged from $1.77 billion (2002) to $2.42 billion (1995). Over the same time period, the value of industrial minerals has ranged from a low of $410 million (22% of total) in 1993 to a high of $583 million (32% of total) in 1999. Out of a total of 220 mines and mineral facilities that reported production in 2001 (latest year of complete data), about 200 were industrial minerals operations. The number and diversity of industrial mineral producers goes a long way in guaranteeing the longevity of this segment of Utah's minerals industry.

The Lincoln Hill Dumortierite Deposit, Rochester District, Pershing County, Nevada [Poster]

Tom Callicrate and Lane Griffin, Nevada Natural Stone Supply, Inc.

The Lincoln Hill decorative stone deposit, located in the Humboldt Range near Lovelock, Nevada is a unique occurrence of lavender, pink, blue, and purple dumortierite, an aluminum borosilicate. The deposit is a large occurrence of a relatively rare mineral and rock type that formed as veins, streaks, and foliated masses of dumortierite-andalusite-quartz developed by hydrothermal alteration and metamorphism of rhyolite flows and tuffs. The uniqueness, durable quality, and beautiful color of this limited material makes this deposit exceptional for dimension stone, ornamental jewelry and carvings, and landscaping products.

At Lincoln Hill, two potential economic systems have been identified: an industrial dumortierite stone deposit; and a high-grade, gold-silver-quartz-tourmaline precious metal stockwork deposit. The main dumortierite deposit, a shallowly dipping mass along the southwest side of Lincoln Hill, is one of the largest deposits of the mineral known in North America at five million tons. Down slope from this deposit, an elluvial deposit contains an estimated one million tons of cobbles and boulders. A smaller bedrock deposit occurs north of High Grade Canyon.

Strata in the southern Humboldt Mountains form a broad, asymmetrical antiform. Late extensional structures appear to have overprinted the regional, northwest trending foliation structures in the Lincoln Hill area. The most extensive rocks in the Rochester district are regionally and contact metamorphosed members of the volcanic Triassic Koipato Group. The oldest unit in this group, the Limerick Greenstone, consists of andesite flows, flow breccias, tuffs, sedimentary units, and intrusive rocks. The overlying Rochester Rhyolite, which consists of ash-flow tuffs, flows, intrusive bodies, tuffaceous sediments, and pyroclastic breccias, hosts the dumortierite and gold mineralization at Lincoln Hill. Carbonate rocks of the Star Peak Group unconformably overlie and are in fault contact with the Koipato Group. Locally, leucogranite, aplite, porphyritic rhyolite, intermediate, and mafic intrusions cut Koipato rocks and are believed to be the source of the mineralizing fluids for the gold-silver deposits.

Preliminary evaluation at Lincoln Hill indicates excellent potential for a world-class, high-end, stone quarry operation. This rare and unique property has the potential to provide a variety of valuable stone products to users throughout the world for many years.

The Future of the Florida Phosphate Industry

Paul R. Clifford, The Florida Institute of Phosphate Research

The Florida phosphate industry faces an uncertain future. Florida has been the world's dominant source of phosphate fertilizer for many years. Although demand for phosphate fertilizer is likely to increase due to population growth and dietary changes in developing countries, sophisticated new fertilizers and technological improvements in agriculture may reduce the amount of phosphate fertilizer required for crop production.

There are many factors that will limit the lifetime of phosphate mining in Florida. The highest quality rock has been mined and it is more costly to convert the lower quality rock that remains into fertilizer. Regulatory and environmental concerns are making permitting of new mines extremely difficult. At some point, imported phosphate rock is likely to replace Florida rock as the feedstock for the chemical plants producing phosphate fertilizer.

The future of the chemical plants in Florida is also uncertain. The cost of shipping imported rock to central Florida may lead to the demise of the plants located there. However, they will continue to operate as long as the cost of replacing them is prohibitive.

Energy Efficiency Tools and Support for Industry

Chris Cockrill, U.S. Department of Energy

This presentation will provide information on industrial decision making tools and information resources available through the U.S. Department of Energy, Energy Efficiency and Renewable Energy's BestPractices Program. BestPractices offers a variety of program initiatives, technical information, software tools, and training on industrial systems such as compressed air, motor, pump, process heating and steam systems. The presentation will touch on how these tools and resources may assist industry in identifying energy efficiency and cost savings opportunities through energy management best practices.

Land Use Conflicts/NIMBYs

Richard F. DeLong, Enviroscientists, Inc.

The United States suffers from a classic love-hate relationship with the mining industry concerning land use conflicts in modern society. NIMBYs (Not-In-My-Backyard) and NOPEs (Not-On-Planet-Earth) characterize the industry as rapists, pillagers, and environmental degraders while utilizing products produced by mining. NIMBYs and NOPEs love the benefits of mining but because of ignorance, reliance on emotional issues, and/or lack of scientific knowledge, fight mineral development in the U.S.

NIMBYs and NOPEs that habitually oppose mining in the U.S. but advocate the extraction of minerals in other countries practice environmental racism. These ill-informed individuals believe that human activities are outside of nature, creating a situation that requires addressing in the development of mineral resources, whether that development involves metals, aggregate, or industrial minerals.

The U.S. has the most highly regulated and environmentally responsible manufacturing industry in the world. A democratic society allows mining through a social compact in the form of laws implemented by federal, state, and local governments. No other country produces the variety of mineral products with the least environmental harm. In order to address the emotional campaigns propagated by environmental groups, the industry needs to educate the public. Basic education is currently provided by groups such as the Nevada Mining Association, National Mining Association, and Geological Society of Nevada; however, the main responsibility for project success falls on the project proponent. Two recent projects discussed in this paper, the Reno Clay Plant Project in Reno, Nevada and the Solidad Canyon Aggregate Project east of Santa Clarita, California have been victims of radical environmental groups and ill-informed local governments. This presentation addresses issues and approaches that may be used to expand society’s knowledge at the project level by reviewing the tactics of the NIMBYs and NOPEs and thereby attempting to minimize the effects of these groups.

Geology of the Western U.S. Cordillera: A Long-Lived Orogenic Belt

James E. Faulds, Nevada Bureau of Mines and Geology

The geology of the western US cordillera reflects more than one billion years of tectonism along the western margin of North America. The plate margin originated during Late Proterozoic rifting. A broad passive continental margin developed in the wake of this rifting. Thick sections (>10 km) of Late Proterozoic to Late Devonian, shallow marine sedimentary strata accumulated on the continental shelf. Breakup of the passive margin began with the Late Devonian-Mississippian Antler orogeny, whereby east-directed thrusting placed deep-water sediments over portions of the continental shelf. Convergent tectonism persisted through the Mesozoic and into the early Tertiary, involving accretion of exotic terranes, subduction of oceanic lithosphere (Farallon plate), and arc volcanism. Facilitated by abundant subhorizontal discontinuities, broad fold and thrust belts developed in the thick miogeoclinal sediments, transforming the Paleozoic continental shelf into a broad mountainous terrane, perhaps rivaling parts of the present-day Andes. By mid-Tertiary time, the Pacific plate came into contact with North America, as much of the Farallon plate had been subducted. Relative motions between the North American and Pacific plates induced development of a transform boundary and right-lateral San Andreas fault. As the western Cordillera evolved from a convergent to a transform plate boundary in Neogene time, voluminous magmatism and east-west extension swept across the western Cordillera. Foundering of the subducted Farallon plate placed warm asthenosphere (previously insulated by subducted slab) against the base of the lithosphere, thus triggering much of the magmatism. Relaxation of compressional stress coupled with gravitational collapse of overthickened and elevated crust drove extension. As more of the Pacific plate came into contact with North America, the transform boundary lengthened and strike-slip deformation stepped inland, transferring parts of North America to the Pacific plate. More than 400 km of right-slip have accumulated on the San Andreas fault system while parts of the Basin and Range have extended more than 100%. The Walker Lane in western Nevada currently accommodates 20% of the dextral plate motion in anticipation perhaps of an eventual transfer of the Sierra Nevada block to the Pacific plate. Evolution of this long-lived plate margin is clearly far from complete.

Turkish Magnesite Deposits [Poster]

Atasever Gedikoğlu, Becktaş,Uz, and Mustafa Kumral, ITU Mining Faculty, Istanbul, Turkey

Magnesite is one of the most important industrial materials. It is used in production of refractory brick for iron/steel furnaces and also in the production of cement, paper, fertilizer, insulators, paints, ceramics, and chemicals. According to 2001 data from Turkish mining import associations, Turkey ranks third in the world with 225 million metric tons of magnesite reserves, and second in production at 576,000 metric tons (14.8% of world production). In 2001 Turkey’s imports of magnesite and its derivatives were 212,250 metric tons.

Turkish magnesites are of high quality because of low contents of undesirable compounds (SiO_2< 3%, Fe_2O_3 < 1%, and CaO< 3%). In additional to natural magnesite, sintered magnesia, caustic magnesia, sedimentary carbonate, magnesium hydroxide, and magnesium sulfate are produced from natural magnesite in Turkey.

Turkey contains three major types of magnesite deposits:

1. Amorphous magnesite: Most magnesite deposits in Turkey are of this type. Research on these deposits has demonstrated that they form in ultrabasic rocks overlying carbonate beds. Deposit formation started with metamorphism of carbonate beds at depth, producing hydrothermal fluids rich in CO_2 and Mg^{+2} ions. Later chemical reaction resulted in precipitation of $MgCO_3$. Amorphous magnesite occurs in veins and vein stockworks in massive, rounded, and cauliflower forms. The deposits are in three regions:
   a. Kutahya-Eskisehir-Bursa Region with 28% of total reserves, has the most magnesite deposits and highest production.
   b. Konya Region with 50% of total reserves. Even though deposits here are few, they are large.
   c. Middle and East Anatolia region with 6% of total reserves. Deposits here are few and relatively small.
2. Crystalline metamorphic magnesite: Somewhat similar to amorphous magnesite deposits but formed by metamorphism of dolomites and limestone. This kind of magnesite is rare in Turkey.
3. Crystalline sedimentary magnesites: These deposits, formed as a result of precipitation of magnesium carbonate in closed basins fed by surface waters, occur in the Denizli and Cankiri regions in Turkey.

Crystal Growth and Formation of Chemical Zoning in Some Egyptian Red-Brown Garnets as Gemstones, Eastern Desert, Egypt [Poster]

H.A. Hegazy, Assiut University, Assiut, Egypt

Red-brown garnets from four occurrences of Egyptian metamorphic rocks are described in terms of chemical composition. The great range in the chemistry of garnets, greater than in any other gem material, is reflected in the diversity of color and other physical properties of its several varieties.

Two distinct zoning patterns are detected; garnet from Wadi Um El- Kheran and Wadi Um Tenadib has Mn-enriched and Mg-Fe-depleted rims. In contrast, Mn-rich and Mg-Fe-poor cores have been observed in the garnets from Wadi Sikait and Wadi Um Shaqila, such changes must be due to changes in PT condition that caused the breakdown of some old minerals and/or the crystallization of new minerals. Variation in Ca content is very weak; this is may related to Rayleigh fractionation and to the disappearance or growth of the Ca-bearing minerals.

The Al^{VI} values are usually close to 2, indicating that these garnets can be considered solid solutions of Alm.-Pyr.-Gross.-Spess. end members. The end member from Wadi Um Tenadib garnets are Alm. 68.3–70.9, Spess. 12.8–14.4, Pyr. 9.7–11.8, Gross. 5.0–5.6; from Wadi Um Shaqila are Alm. 72.9–74.4, Spess. 11.1–12.1, Pyr.10.1–12.7, Gross. 2.2–3.4; from Wadi Um El- Kheran are Alm. 49.1–64.7, Spess. 5.9–17.8, Pyr. 5.1–13.0, Gross. 19.2–25.2 and from Wadi Sikait are Alm. 70.3–76.8, Spess. 1.2–4.2, Pyr. 1.4–7.8, Gross. 17.3–20.6.

All values for the calculated distribution coefficient KDFe-mg ranges from 0.05 to 0.36, which is consistent with the average values for the garnet-staurolite and sillimanite zones. However, these rocks range in metamorphic grade from the amphibolite to granulite facies.

Pleistocene Potash Brine Deposits: Comparison of Six World Commercial Sources

David A. Holmes, Industrial mineral consultant, and
Peter W. Harben, Peter W. Harben, Inc.

Pleistocene brine deposits have proven reliable sources of potash products for nearly a century worldwide. Five commercial sources are discussed herein, including: Searles Lake, California; Great Salt Lake, Utah; Salar de Atacama, Chile; Chott Djerid, Tunisia; and the Dead Sea, Israel and Jordan.

All are continental deposits but only the North American sources were greatly influenced by drainage from glacial sources. All have multi-commodity production, ubiquitously with salt (halite), but with other varying co-products including borates, sodium sulfate, sodium carbonate, lithium carbonate, and magnesium salts. All sources are shallow, easily developed sites and have employed solar evaporation for primary recovery of the salts or pre-concentration for plant-feed into complex evaporation circuits in chemical plants.

The solid-phase evaporite mineralogy of enclosing or lakebed sediments varies widely. For the most part, such accompanying solid-phase minerals such as carnallite, sylvite, glaserite, and hanksite are too low-grade to be recovered profitably. The solid-phase component, however, may contribute to the deposits' resource/reserve potential as dissolution by fluid movements during the mining operations may release additional potassium values.

Other known potash prospects in playa lake and sebkha settings around the world may offer similar commercial potential but have not generally been well explored. Most occur in desert regions in shallow playa, sebkha or continental lake settings. Besides known occurrences such as the Qarhan Lake deposit in Qinghai Province, China, other prospective sources are likely in Iran, Afghanistan, Algeria, Libya, various sebkhas in the Middle East, and playa areas scattered in Central Asia.

Hanson Aggregates East, Cost Savings through System Optimization and Efficiency

Allen R. King and Steve Edgerton, Hanson Aggregates East, and Don Casada, Diagnostic Solutions, LLC

Hanson Aggregates East has over 130 quarries and sand and gravel operations. These operations annually produce over 100 million tons of materials for the construction industries from Georgia to New York, east of the Mississippi

River. In order to produce this material Hanson Aggregates East spends approximately $18,380,000 (from 2002 records) per year on electricity.

In an effort to maximize profitability, Hanson Aggregates East has begun a systematic approach to evaluate the reliability and energy-effectiveness of various pumping systems. Although the extent of pumping loads varies by industry and specific site, studies performed by the U.S. Department of Energy indicate that pumps represent the single largest industrial user of motor-driven energy. Hanson uses a systems (rather than a component) approach in assessing pumping system opportunities. Both the design and normal operating conditions are considered. Field measurements of fluid and electrical data are made to assist in the assessment, using both portable test equipment and permanently installed plant meters.

Case studies will be used to illustrate the methodology employed by Hanson. Example annual energy savings in excess of $100,000 will be described.

Aggregate Availability in California

Susan Kohler, California Geological Survey

The Department of Conservation's California Geological Survey (CGS) has recently completed a map and accompanying report containing information about the availability of California's permitted construction aggregate resources (CGS Map Sheet 52). The map summarizes data from mineral land classification studies conducted by CGS for 32 aggregate resource areas located throughout the state. These aggregate studies were conducted over a period of about 23 years in response to California's Surface Mining and Reclamation Act of 1975 (SMARA). The 32 areas cover about 25% of the state and provide aggregate for roughly 90% of California's population.

The main focus of the map is to compare projected aggregate demand over the next 50 years with current permitted aggregate resources in the more populated regions of the state. A model relating past aggregate consumption and population with projected aggregate demand and population growth was used to forecast 50-year aggregate demand.

The map also shows seven aggregate production areas having less than 10 years of permitted aggregate supply remaining. These areas include western Ventura County (depleted in 1997), San Fernando Valley, the eastern part of Merced County, the northern part of Tulare County, Sacramento County, Orange County, and Stanislaus County. Also included are locations of aggregate production areas and the relative magnitude of annual production from each area.

Map Sheet 52 includes a pie diagram showing end uses of all construction aggregate. California consumes 230 to 240 million tons of construction aggregate annually, or about 7 tons per person. About 43% of construction aggregate is used in public works projects nationwide. The remaining 57% is purchased by the private sector.

The report has a brief discussion of non-permitted aggregate resources, although these are not shown on the map. There are currently an estimated 74 billion tons of non-permitted construction-grade aggregate resources in the 32 aggregate study areas shown on the map.

Sea-floor Barite Deposits at Active Continental Margins: Analogues for Stratiform Deposits in Nevada?

Randolph A. Koski and James R. Hein, U.S. Geological Survey

Paleozoic stratiform barite deposits of Nevada provide most of the barite mined in the U.S., yet their origin remains controversial. Their associated lithologies (siliceous and organic-rich sedimentary strata, minor phosphatic and volcanic rocks), deposit attributes (lensoidal-concretionary, minor sulfides, vent fauna), isotope (S, Sr) systematics, and paleoceanographic and paleotectonic features (high productivity, synmineralization faulting) have led to contrasting genetic models: (1) a hydrothermal-exhalative model in which barite formed around hydrothermal vents in oxygen-poor structural basins, and (2) an ocean circulation model in which barite precipitated along anoxic-oxic boundaries resulting from coastal upwelling and high productivity on the continental slope. Both models involve seawater sulfate reduction in continental margin settings.

Barite deposits are forming in sedimentary environments at modern continental margins by exhalative processes at sea-floor hydrothermal vents and cold seeps and by sub-sea-floor diagenetic processes. Tectonically active settings with sediment-hosted, massive barite deposits include ocean ridges, rifted continental margins, transform margins, marginal basins, and convergent margins. Barite deposits formed on the sea floor have associated chemosynthetic fauna, and some are accompanied by abundant sulfides. Most sites are zones of high productivity. All of the barite deposits are spatially related to fault scarps or tectonically induced slumps on the sea floor. Sulfur isotope data for barite from cold water seeps and for diagenetic barite from the sub-sea floor are consistent with the reduction of seawater sulfate.

Although strict analogues for Nevada barite deposits, especially with respect to thickness and distribution, have not been identified on the modern sea floor, we suggest that deep circulation of fluids within extensional regimes in transform-margin or convergent-margin settings may result in comparable deposits.

Valuation of Stone, Aggregate, and Industrial Mineral Properties

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Mineral property valuations are required for stock assessments, bank financing, eminent domain condemnations, and acquisitions and mergers. In this example, the property is a 1,280-acre tract in northern Texas underlain by limestone that meets Texas DOT specifications. The landowner leased two tracts to two separate limestone producers and requested the value of the property on the open market.

The property has 68 million net tons of limestone reserves. In the market area there are 16 stone mining operations that produce a total of 18 million tons of stone per year. Each stone mining operation has an equivalent production of 1.1 million tons per year. Initial annual production from the Property was 500,000 tons and full production of 1.1 million tons was achieved by year four, resulting in a mine life of 63 years. Lease terms indicate the guaranteed production from the property is 500,000 tons per year and the royalty rate is $0.60 per ton. The guaranteed production royalty capitalization rate (cap rate) is 7% and the incremental production royalty cap rate is 10%. The mid-year cap factors for the guaranteed production royalties and the incremental production royalties are derived from Parry's Valuation Tables, using the Years' Purchase and Years' End Present Value of One valuation tables.

The Net Present Value of the property is the sum of the guaranteed production royalties and incremental production royalties. The guaranteed production royalty is the arithmetic product of the guaranteed advance production (500,000 tons), the royalty rate ($0.60/ton), and the guaranteed advance production mid-year capitalization factor (variable). The incremental production royalty is the arithmetic product of the incremental production (variable), the royalty rate ($0.60/ton), and the incremental production mid-year capitalization factor (variable). The Net Present Value of the property was approximately $7.2 million, which equates to $5,625 per acre and $0.11 per ton.

The Application of Sustainable Development Principles to the Alberta Aggregates Resource Sector [Poster]

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Aggregate, the most widely used mineral resource globally, has attracted the least amount of academic or public acknowledgement. Based on the assumption that there is an infinite supply, the economic and environmental significance of this resource is seldom factored into conservation or resource management decisions. Resource management systems that do include the aggregate resource assessment will have significant advancement towards achieving sustainable development.

According to 1998 world mineral production figures for quantity, aggregates made from crushed rock, along with sand and gravel, amounted to over 20 billion metric tons. Analyzing published data this amount is five times the production of any other mineral including gas and oil equivalents (m3). It has been estimated that in Alberta alone, 5 billion metric tons of aggregate will be needed over the next 50 years to maintain and develop the Alberta's infrastructure.

With such a demand the resource is "being depleted much faster than replacement sources are being approved." Urban and rural development, which creates the resource demand, also creates an access restriction to the resources. This necessitates opening alternate sources. In most cases, alternative sources are greater distances from the market, which means an extra transportation cost; a cost indirectly absorbed mostly by the community consumers and taxpayers. The longer hauls of this material also equate to increased greenhouse gas emissions, increased road maintenance costs, and reduced driving safety standards. Thus economics, environment, and community, the parameters of "sustainability development," are all affected through the degree of resource management applied to the aggregate resources.

Sustainable development "is a process of change in which the exploitation of resources, the direction of investments, the orientation of technical development, and the institutional change are in harmony and enhance both current and future potential to meet human needs and aspirations." Geologic, geophysical or engineering involvement in the aggregate resource sector has been minimal since it has been relatively easy to locate and simple to mine. However, in these days of environmental, economic, and social constraints, the need of technical development is heightening, making the sector an area of opportunity to the scientific community. The magnitude of this opportunity with regards to applying sustainable development principles will be assessed in this article.

A process in change that was recently witnessed in Alberta, as public opposition threatened to shut down one of Edmonton's major aggregate sources, will be used as a bench mark for a sustainable development model. The process is the development of Sturgeon County's Calahoo/ Villenueve Area Structure Plan (ASP) to address the public concern with continued resource extraction operations. This presentation will assess the relevance of the ASP as a tool for harmonizing and enhancing the current and future potential to meet resource needs and how such a plan will require more geoscientific involvement.

The plan development process brought to light the need for detailed resource data, geological and geophysical modeling, and coordinated extraction activities between the operators to address the cumulative environmental impact. Increased employment of this type of process would achieve significant gains towards sustainable development. The ultimate result of the process would be educating public on the necessity of protecting access and development opportunities of the mineral resource to the point that the activity is a desirable addition in any community.

Current Status, Developments and Outlook for the U.S. Soda Ash Industry

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Soda ash is the trade name for sodium carbonate. Three sources of feedstock are used to produce soda ash in the

U.S.: (1) trona (sodium sesquicarbonate), (2) sodium carbonate-rich brines, and (3) nahcolite (sodium bicarbonate). Trona is mined underground by four companies in Wyoming. The Green River Basin in Southwestern Wyoming contains the world's largest trona deposit. Twenty-five major trona or mixed trona and halite beds associated with oil shale are present. The beds currently mined are massive and almost monomineralic. In contrast is the Searles Dry Lake Playa located in southern California. Three major subsurface saline horizons occur that are generally brine-saturated, hard, and very porous. The important ions include sodium, carbonate, and bicarbonate. They are present in various concentrations and have combined to form trona and nahcolite. One company pumps the interstitial brines from selected horizons (solution mines) for soda ash production. The Piceance Creek Basin, in northwestern Colorado, is the third and most recent area of soda ash production. Nahcolite occurs as four major beds and disseminated bodies associated with oil shale. One company solution mines selected subsurface nahcolite horizons. U.S. production of soda ash in 2002 was 10.5 million metric tons (Mt). Based on approximately 14.5 Mt of total nameplate capacity, this equates to a capacity utilization rate of 72%. Production (1995–2002) has ranged from a low of 10.1 Mt to a high of 10.7 Mt. In 2001 (latest complete export data available), 4.09 Mt were exported to 45 countries. U.S. production in 2001 was 10.3 Mt, thus, this represents about 40% of output. Asia was the largest market on a regional basis, followed by North America, South America, Europe, the Middle East, Africa, Oceania, and Central America. China competed with the U.S. for Asian markets. The U.S. consumption of soda ash by end use in 2001 (latest information available) was glass, 48%; chemicals, 26%; soaps and detergents, 11%; distributors, 5%; desulfurization, pulp and paper, and water treatment, 2% each; and other, 4%. The 2002 export and domestic consumption by end use figures are expected to be similar to the 2001 data. There has been a substantial amount of activity in the U.S. soda ash industry during the last five years in regard to acquisitions/divestitures, start-up of a new operation, and a company seeking a joint-venture partner. Examples include: (1) FMC Wyoming Corporation's acquisition of Tg Soda Ash, and subsequent mothballing of the Granger, Wyoming operation; (2) Wold Trona Company seeking a joint-venture partner(s) to develop their Wyoming trona project utilizing their Crystaltron technology or selling the technology to existing Wyoming producers or to potential producers; (3) IMC Global's acquisition of North American Company's Searles Lake soda ash operation, and the subsequent decision to divest of the asset; and (4) The Williams Companies decision to enter the soda ash business via their 60% interest in new start-up company American Soda, LLP, and shortly thereafter, announcing their intention to exit the business. This has resulted in a very interesting and dynamic time for the industry in regard to business transactions and opportunities. The domestic soda ash demand is forecasted to grow between 0.5% and 1% per year for the next several years. World demand growth is projected to range from 2% to 2.5% per year during the same time period. Asia and South America are expected to be the major areas of increased soda ash consumption. China is forecasted to produce 11.0 Mt this year; thus, surpassing the U.S. as the world's largest soda ash producer.

40th Forum on the Geology of Industrial Minerals

Nelson R. Shaffer, Indiana Geological Survey

The Fortieth Forum on the Geology of Industrial Minerals will be held May 2 to 7, 2004 in Bloomington, Indiana. The conference hotel will be the Indiana Memorial Union on the campus of Indiana University. Bloomington is set in the rolling hills and karst of south-central Indiana and is a center of the Salem Limestone dimension stone industry, one of the nation's largest producers of building stone. Field trips to view mining, milling, and even carving of this premier stone will be available. Paleozoic carbonate rocks of the region host significant deposits of crushed stone, high-calcium limestone, and gypsum. Trips will also visit these deposits and plants that produce crushed stone, cement, and gypsum. Ceramic raw materials support cement, brick, and expanded shale operations, some of which will be visited during mid-week trips.

Abundant Pennsylvanian coal is burned to provide electric power. Some coal-fired plants require limestone for scrubbing that can make a gypsum by-product and all produce copious combustion by-products (coal ash) that can be used in many applications. We shall visit a power plant to see limestone use and scrubber and ash by-product beneficiation.

Technical presentations will include sessions about mid-western industrial minerals, dimension stone, mining in karst areas, strategic industrial minerals, geophysical methods for industrial minerals, education initiatives, by-product opportunities, general papers, and poster sessions.

Indiana has had a long tradition of geologic research and trips will include visits to New Harmony, the birthplace of midwestern geology. Spouse trips will feature tours of Indiana's past at Spring Mill pioneer village, the Nashville artist colony, the Lilly Library of rare books, an Amish community, and a turn of the century spa at French Lick in addition to modern attractions in the region including a visit to the famous Indianapolis Motor Speedway home of the Indianapolis 500 race. So come visit Indiana and win with minerals!

Proven Energy Cost Reduction Strategies—The US Magnesium LLC Experience

Roger J. Swenson, E-Quant Consulting LLC

A successful approach to energy cost reduction has been implemented at US Magnesium LLC. The approach concentrates on three levels of strategies. The levels include contractual strategies, preventative/monitoring strategies, and capital intensive strategies. Each respective strategic level involves an increased capital requirement and potentially increased risk. A sound energy cost reduction strategy is built on a clear concise understanding of risks and rewards for actions taken.

Contract strategies involve understanding the opportunities to price energy purchases and deliveries in such a way as to minimize costs. These strategies are among the lowest cost alternatives to implement. Preventative/monitoring strategies involve tracking total energy utilization and cost as well as maintaining procedures to track energy utilization at each step within the operation. The focus within this level also involves instituting the three T's of energy management; tune it up, turn it down, turn it off. Capital-intensive energy cost savings alternatives are the most difficult opportunities to implement. These alternatives require careful and clear communication to management of the cost reduction value from specific investments.

US Magnesium LLC has used this approach to save over 30% of annual energy costs. It has successfully used contract strategies and actively participates in all aspects of regulatory matters. Energy usage and costs are actively tracked and anomalies are investigated until they are explained. Capital-intensive projects are evaluated for both expected cost savings as well as for price risk mitigation potential. Capital-intensive projects implemented at the US Magnesium facility include combined heat and power facilities (cogeneration).

Evaluation of Granite and Pegmatite Occurrences of Armutlu Peninsula (Ihsaniye, Karamursel, Kocaeli-Turkey) as a Ceramic Raw Material

[Poster]

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The main topic of this study is the mineralogical, petrographical, and geochemical research and investigation of a granite body and associated feldspar-bearing pegmatite occurrences with respect to potential use as a ceramic raw material. To this purpose, a comprehensive geological map and cross sections were made and mineralogical, petrographical, chemical analysis, and ceramic firing tests were performed on samples collected from the study area.

The Ihsaniye granitic intrusive crops out as partly disintegrated, sandy, arenaceous rock on the surface. On its southern side, the granitic intrusive is massive with a regular fissure system. Metamorphic rocks (mica-schists) and Neogene-age sedimentary series surround the granitic intrusive. Mineralogically, the intrusive is of granodioritic composition on the basis of its quartz+andezine+orthoclase + biotite+opaque mineral composition, and it contains 50% feldspar (plagioclase+alkali feldspar). Pegmatites are observed within the intrusive and along its outer contact with surrounding rocks as regular dikes. Generally, a feldspar+quartz assemblage is observed in the pegmatites and chemically they have high alkali content (8.22%). Geochemically, the granitic and pegmatitic rocks have relatively high potassium content, are of calk-alkali character, and show chemistries typical of island-arc series magmatic associations.

Ceramic firing tests were performed after considering the mineralogic, petrographic, and chemical properties of these granitic and pegmatitic rocks. On the basis of the testing, the granitic rock could be used as a ceramic raw material or as floor-covering material if purified of its clay and iron contents by processing using scrubbing and magnetic separation methods. The pegmatite gives suitable results only for floor-covering material on the basis of the firing tests, provided that it is purified of its clay and iron contents.

Field Trip 2 attendees collecting samples at the U.S. Gypsum mine, Empire, Nevada. ***K. Papke photo.***

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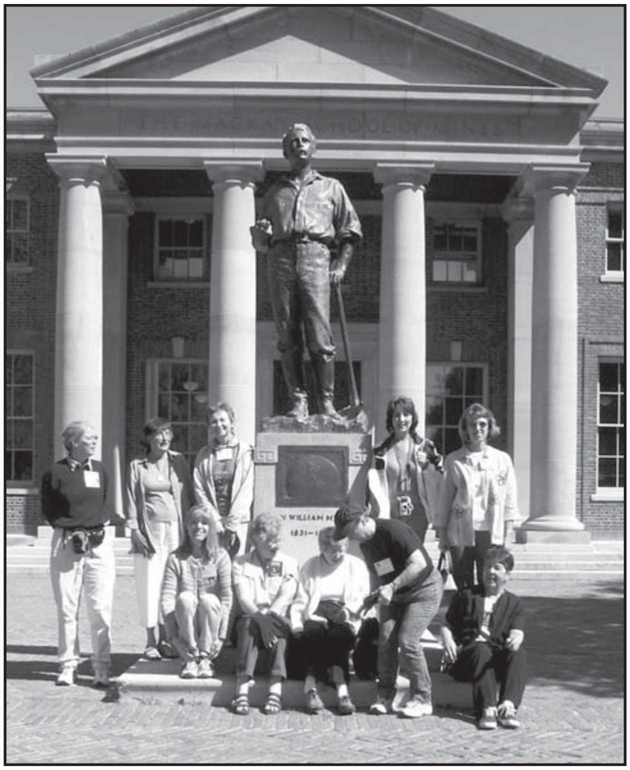
Banquet and silent auction. *D. Bryan photo.*


Guest activity attendees at the Governor's mansion.

Diane Bryan photos.


Guest activity attendees at Donner Summit, California.


Guest activity attendees at the Mackay School of Mines on the University of Nevada campus.


Guest activity attendees at the historic Virginia City, Nevada cemetery.