

Salt Lake City County Building constructed of Kyune Sandstone



First Presbyterian Church (Salt Lake City) built with Nugget Sandstone



Utelite expanded shale plant, Summit County, Utah



Holnam's Devil's Slide plant, Morgan County, Utah

Proceedings of the 35th Forum on the Geology of Industrial Minerals-The Intermountain West Forum 1999





Miscellaneous Publication 01-2 Utah Geological Survey sion of tah Department of Natural Resources









Proceedings of the 35th Forum on the Geology of Industrial Minerals - The Intermountain West Forum 1999

Edited by: Roger L. Bon, Richard F. Riordan, Bryce T. Tripp, and Stanley T. Krukowski

Meeting held May 2-7, 1999 in Salt Lake City, UT

ISBN 1-55791-654-3





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Preface and Acknowledgments

The Forum is an informal organization of geologists dedicated to sharing information on industrial rocks and minerals through an annual meeting, field trips, and a proceedings volume on industrial mineral geology, production, uses, economics, and marketing. The Forum was founded in 1965 by Professor Robert L. Bates of Ohio State University. Dr. Bates legitimized the study of industrial rocks and minerals as a distinct discipline and authored several books on the subject.

The annual meeting has typically been hosted by a U.S. state geological survey or a Canadian provincial survey. The hosting organization forms an Organizing Committee which is responsible for arranging the symposium, field trips, guest events, and publication (within a reasonable time of the meeting) of the proceedings volume. A four-person Steering Committee perpetuates the Forum by selecting new hosting organizations for the annual meetings, advising the hosting organizations, and conducting all other business of the organization. The Steering Committee consists of three members elected at the annual meetings for three-year terms and a fourth member who is the general chair of the current annual meeting. A subcommittee to the Steering Committee administers the Robert L. Bates Scholarship which financially supports attendance of a university student at the Forum annual meeting. The Utah Geological Survey appreciates the time and effort volunteered by the following committee members:

1998 - 1999 Steering Committee Members

G. Robert Ganis (1997-1999), Chair Stan D. Bearden (1998-2000) Ardell W. Rueff (1999-2001) Bryce T. Tripp (1999 host)

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The 35th Forum Annual Meeting, emphasizing Utah and the Intermountain West, was held in Salt Lake City, Utah on May 2nd - 7th, 1999, and consisted of 39 oral presentations, 23 poster sessions, two guest activities, and five mid- or post-meeting field trips. The first guest activity was a full-day tour of the Park City, Utah area to experience it metals mining heritage via an underground mine tour of the Ontario mine and to enjoy the scenery and amenities of a world-class resort area. The second guest activity was a tour of the Salt Lake Valley to experience its history, culture, and recent development. The first half-day, mid-meeting field trip was to the Great Salt Lake and the IMC Kalium solar operation. The second half-day, mid-meeting field trip was a tour of the geology of Little Cottonwood Canyon and the historic Red Butte sandstone quarries. A one-day post-meeting trip included industrial mineral sites of the Salt Lake City area and salt and magnesium plants on the south shore of the Great Salt Lake. A two-day, post-meeting field trip visited industrial mineral operations in west-central Utah. A second two-day, post-meeting field trip through northern Utah and southern Idaho emphasized Idaho phosphate. The Salt Lake City meeting was attended by 216 conferees and 23 guests from 29 of the U.S. states, six Canadian provinces, Chile, England, Greece, Spain, and Turkey.

The annual business meeting took place after the last technical session. At that time, Missouri was selected as the venue for the 38th Forum, Martin Anctil was announced as the 1999 recipient of the Robert L. Bates Scholarship, James Barker was elected as a member of the Steering Committee, and Tom Newman was elected as a member of the Bates Scholarship Subcommittee. The Director of the U.S. Geological Survey, Dr. Charles (Chip) Groat, gave a presentation at the banquet following the business meeting.

The 35th Forum meeting was financially supported by the following organizations:

Co-Organizers

Graymont Western U.S., Inc. (Continental Lime Company) U.S. Geological Survey Utah Geological Survey

Co-Sponsors

Arizona Resources, Inc. Cargill Salt Company Georgia Pacific Corp. d/b/a the Timber Company IMC Kalium Ogden Corp. Magnesium Corporation of America Monsanto, Inc. (Solutia, Inc.) Montgomery Watson SRK Consultants Staker Paving and Construction Company U.S. Bureau of Indian Affairs Utah Geological Association Utah Division of Forestry, Fire and State Lands Utah Division of Oil, Gas and Mining

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Several organizations sponsored attendance of students at the 35th Forum by covering meeting registration costs. The Utah Division of Forestry, Fire and State lands sponsored Martin Anctil of the University of Laval in Quebec, Canada. Solutia, Inc. sponsored Steve Young of the University of Arizona. The U.S. Geological Survey sponsored Mustafa Kumral from Istanbul Technical University, Istanbul, Turkey.

The Organizing Committee also thanks: (1) the many oral and poster session presenters and authors of proceedings papers, (2) symposium session chairs including: James Kohler, Lance Mead, Jeff Machamer, Craig Pfingsten, Aldo Barsotti, Andrew Regis, David Lindsey, Mitch Hart, and Dan Hora, (3) Tom Munson and Lynn Kunzler of the Utah Division of Oil, Gas and Mining who helped with field trip transportation, (4) Jon King who helped compile and check the 35th Forum mailing list, (5) Kevin McClure and Jim Telford who handled audiovisual and other logistical tasks, (6) Michele Hoskins, Cheryl Gustin, and Cheryl Ostlund who worked on registration and mailing, and (7) the editorial and illustrations staff of the Utah Geological Survey who added to this volume.

General Chair, 35th Forum Bryce T. Tripp

Proceedings Volumes

Forum on the Geology of Industrial Minerals

Vol #	Year	Location	Publication
1	1965	Columbus OH	1966 Ohio Journal of Science, y 66, n, 2, n, 97-191
2	1966	Bloomington, IN	1966, Indiana Geological Survey, 197 p. (no publication number given)
3	1967	Lawrence, KS	1967, State Geological Survey of Kansas Special Distribution Publication 34, 183 p
4	1968	Austin, TX	1968, Texas Bureau of Economic Geology, 174 p. (no publication number given)
5	1969	Harrisburg, PA	1970, Pennsylvania Geological Survey, 4th Series, Bulletin M 64, 271 p.
6	1970	Ann Arbor, MI	1970, Michigan Geological Survey Miscellany 1, 155 p.
7	1971	Tampa, FL	1972, Florida Bureau of Geology Special Publication 17, 228 p.
8	1972	Iowa City, IA	1973, Iowa Geological Survey Public Information Circular 5, 189 p.
9	1973	Paducah, KY	1974, Kentucky Geological Survey Series X, Special Publication 22, 107 p.
10	1974	Columbus, OH	1974, Ohio Geological Survey Miscellaneous Report 1, 100 p.
11	1975	Kalispell, MT	1976, Montana Bureau of Mines and Geology Special Publication 74, 186 p.
12	1976	Atlanta, GA	1978, Georgia Geologic Survey Information Circular 49, 78 p.
13	1977	Norman, OK	1978, Oklahoma Geological Survey Circular 79, 107 p.
14	1978	Albany, NY	1980, New York State Museum Bulletin 436, 120 p.
15	1979	Golden, CO	1980, Colorado Geological Survey Resource Series 8, 126 p.
16	1980	St. Louis, MO	1980, Missouri Division of Geology and Land Survey Special Publication 7, 78 p.
17	1981	Albuquerque, NM	1982, New Mexico Bureau of Mines & Mineral Resources Circ- ular 182, 108 p.
18	1982	Bloomington, IN	1983, Indiana Geological Survey Occasional Paper 37, 251 p.
19	1983	Toronto, Ontario, CAN	1983, Ontario Geological Survey Miscellaneous Paper 114, 216 p.
20	1984	Baltimore, MD	1985, Maryland Geological Survey Special Publication 2, 152 p.
21	1985	Tucson, AZ	1987, Arizona Geological Survey Special Paper 4, 134 p.
22	1986	Little Rock, AR	1988, Arkansas Geological Commission Miscellaneous Publication MP- 21, 115 p.
23	1987	North Aurora, IL	1989, Illinois State Geological Survey IMN 102, 105 p.
24	1988	Greenville, SC	1990, South Carolina Geological Survey Miscellaneous Publica- tion, 155 p. (no publication number given)
25	1989	Portland, OR	1990, Oregon Department of Geology and Mineral Industries Special Paper 23, 100 p.
26	1990	Charlottesville, VA	1992, Virginia Division of Mineral Resources Publication 119, 188 p.
27	1991	Banff, Alberta, CAN	1992, Alberta Geological Survey, Alberta Research Council, Infor- mation Series 115, 217 p.
28	1992	Martinsburg, WV	1995, West Virginia Geologic and Economic Survey and U.S. Bureau of Mines Circular C-46, 227 p.
29	1993	Long Beach, CA	1995, California Department of Conservation, Division of Mines and Geology Special Publication 110, 355 p.
30	1994	Fredericton, New Brunswick/ Halifax, Nova Scotia, CAN	1995, New Brunswick Department of Natural Resources and Ener- gy, Minerals and Energy Division Miscellaneous Report 16, 261 p.
31	1995	El Paso, TX	1996, New Mexico Bureau of Mines & Mineral Resources Bulletin 154, 330 p.
32	1996	Laramie, WY	1997, Wyoming State Geological Survey Public Information Circular 38, 326 p.
33	1997	Quebec City, Quebec, CAN	1998, Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 50, 288 p.
34	1998	Norman, OK	1999, Oklahoma Geological Survey Circular 102, 364 p.
35	1999	Salt Lake City, UT	2001, Utah Geological Survey Miscellaneous Publication 01-3, 286 p.

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TIDEWATER DEPOSITS OF HIGH-BRIGHTNESS CALCIUM CARBONATE AND HIGH CaCO₃ LIMESTONE IN SOUTHERN SOUTHEASTERN ALASKA

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ABSTRACT

Sealaska Corporation, the Alaska Native Regional Corporation of Southeastern Alaska, was organized under the laws of the state of Alaska pursuant to the federal Alaska Native Claims Settlement Act of 1971. Large areas of Sealaska's 630,000-acre (250,000 hectare [ha]) fee subsurface holdings are underlain by carbonate, and while much of this material is assumed to be common variety limestone and lesser dolomite, at least two areas in the Silurian Heceta Limestone contain high-quality limestone at tidewater. This limestone has many potential commercial uses.

On northern Prince of Wales Island, about 90 miles (144 km) north-northwest of Ketchikan, resource development at Sealaska's Calder deposit has established a reserve of 13 million short tons (st) (12 million metric tonnes [mt]) of carbonate rock containing an average of greater than 98 percent CaCO₃, approximately 0.5 percent MgO, less than 0.5 percent SiO₂, and approximately 0.15 percent Fe₂O₃, with insolubles averaging less than 0.5 percent and an average Hunter Brightness of 92.07 for the -150 mesh grind (with a brightness cutoff of 90). The deposit is open at depth and to the south. Ultimate reserves will likely be several times those currently established. In 1998, Sealaska began mining the Calder deposit, with about 100,000 st (90,000 mt) produced, and also completed a marine terminal one half-mile (800 m) from the deposit. The terminal can load ships up to 680 feet (200 m) in length at a rate of 2,000 st (1,800 mt) per hour.

On Dall Island at Breezy Bay, about 60 miles (100 km) southwest of Ketchikan, Sealaska has identified a limestone reserve in excess of 150 million st (135 million mt) that (based on 18 surface samples distributed evenly over about a section of land) contains about 98 percent CaCO₃, and less than 0.5 percent MgO, 0.5 percent SiO₂, and 0.15 percent Fe₂O₃. Brightness of the Breezy Bay carbonate is considerably less than at Calder. Five samples of brighter material from Breezy Bay returned brightness analyses in the high 80s and low 90s; average brightness is probably below the mid-80s. Sealaska has also identified a deposit containing more than 19 million st (17 million mt) of similar rock near View Cove, a few miles south of Breezy Bay.

INTRODUCTION

Sealaska Corporation Land Base

Sealaska Corporation is one of 13 Alaska Native Regional Corporations that were organized under the laws of the state of Alaska pursuant to the federal Alaska Native Claims Settlement Act of 1971 (ANCSA). Sealaska has 16,000 shareholders who trace their Native American heritage to the Southeastern Alaskan pan handle. The corporation's primary businesses are forest products, mining, precision plastics, and investments. Gross revenues for the corporation during the latter half of the 1990s averaged over \$200,000,000. (Sealaska Corporation, 1999).

Under the provisions of ANCSA, Sealaska will receive fee title to approximately 330,000 acres (132,000 ha) of land located throughout Southeastern Alaska. Approximately 300,000 acres (120,000 ha) of this entitlement have been conveyed thus far. In addition to the surface and subsurface estate of its own lands, Sealaska will also receive the subsurface estate to underlying lands selected by the 12 native village and urban corporations in Southeastern Alaska. Each village or urban corporation will receive 23,040 acres (9,328 ha). Through these village and urban corporation selections, Sealaska will receive subsurface-only ownership in the region to about 300,000 acres (120,000 ha). The corporation's total subsurface ownership in Southeastern Alaska will eventually exceed 630,000 acres (250,000 ha).

Sealaska lands have generally been selected for their timber development potential. The lands often have been recently logged, are usually roaded, and are almost always close to tidewater. The land base is primarily on Prince of Wales Island, Chichagof Island, Kupreanof Island, and Dall Island in the southern portion of the Southeastern Alaskan pan handle. These lands are located strategically close to potential timber and mineral markets. Prince of Wales Island is approximately 3,500 miles (5,600 km) across the Pacific Ocean from Tokyo (for comparison, San Francisco is about 4,500 miles [7,200 km] from Tokyo) and 600 miles (960 km) from Seattle.

CALDER DEPOSIT

Location

The Calder high-brightness carbonate deposit is located about 90 air miles (144 km) north-northwest of Ketchikan, on Prince of Wales Island, between Marble Creek and the west end of Dry Pass in sections 1, 2, 3, 11, and 12, T. 66 S., R. 77 E., Copper River Meridian (CRM) (figure 1). Elevations range from tidewater to 900 feet (275 m) on the property. Access to the property is via the Prince of Wales Island road system, by water, and by float plane.



Figure 1. Index map of southern Southeastern Alaska showing locations of the Calder, Breezy Bay, and View Cove North deposits.

History

The Marble Creek deposits at Calder Bay were the first marble deposits in Southeastern Alaska to be commercially developed. The first claims were staked in 1896, and development work commenced shortly thereafter. Shipments of marble from Calder Bay by the Alaska Marble Company began in 1901 and continued until 1910. In 1905, the property contained warehouses and shops as well as boarding houses and homes for 60 workers. A 3,200-foot (975 m) surface tramway carried limestone blocks from the quarries to a 65-foot by 90-foot (20 m by 28 m) dock near the mouth of Marble Creek. From the dock, the blocks were loaded onto large steamers and shipped mostly to the northwest U.S. In 1906, a post office was opened at Calder.

In 1921, the Vermont Marble Company purchased the property. Production from 1926 filled an order for the new Washington state capitol building at Olympia. No rock was produced from the Calder/Marble Creek deposits from 1926 until 1998. The early history and development of the Calder marble deposits is well described in Roppel (1991).

Sealaska Exploration and Development

The Calder property, consisting of a group of nine patented mining claims comprising 573 acres (230 ha) surrounded by Tongass National Forest lands, was purchased by Sealaska Corporation in 1988.

Sealaska geologists first examined the Calder limestone in 1990 and recognized the high-brightness potential of the deposit (Glavinovich, 1991). Surface sampling and market studies were performed in 1991 and 1992, and in 1993 seven core holes totaling 1,471 feet (448 m) were drilled on the property (Hedderly-Smith, 1993). In 1994, an additional 13 core holes totaling 1,770 feet (539 m) were drilled (Hedderly-Smith, 1995), and in 1995, 15 core holes totaling 4,013 feet (1,223 m) were drilled and a bulk sample was collected. In total, 35 core holes totaling 7,254 feet (2,211 m) were drilled on the property prior to Sealaska's decision to develop the deposit.

Tables 1 and 2 contain chemical and brightness analyses from the drilling. Sealaska's reserve calculation indicate 13.31 million st (12 million mt) of high quality limestone averaging greater than 98 percent calcium carbonate with minimal magnesium, silica, iron, and insolubles. The Hunter Brightness of the material averages 92 units for -150 mesh grind and 95 units for the 325 mesh grind (Dick and Wysocki, 1999).

Table 1. Average chemical analyses of the Calder high-brightness carbonate deposit.
Calcium carbonate $(CaCO_3) > 98\%$ Magnesium carbonate $(MgCO_3) \sim 1.0\%$ Silica $(SiO_2) < 0.5\%$ Iron $(Fe_2O_3) \sim 0.15\%$ insoluble fraction (74 samples) $\sim 0.5\%^*$
* with median analyses substantially lower Data from Dick and Wysocki, 1999.

Hunter Brightness analyses of the Calder high-brightness carbonate deposit.						
<u>Mesh</u> -150 -325	<u>Hunter Brightness</u> average 92 units average 95 units					
Data from Dick a	nd Wysocki, 1999.					

The deposit is open at depth and to the south. A second zone of high-brightness material has been identified in reconnaissance work to the southeast of the developed deposit near Dry Pass. Ultimate reserves will probably exceed 50 million st (45 million mt) and may reach 100 million st (90 million mt) or more of high-brightness material.

Construction of the Calder mine started in 1997 and was completed in 1998. The Calder camp consists of a boat and float plane dock, a bunkhouse/cookhouse for 18 personnel, an office with a full laboratory, a power house, maintenance shops, a crushing and screening plant, and a marine terminal.

Production from the deposit is relatively straightforward. Overburden is drilled with an Air Trak 350 drill, shot, and stripped. Ore is drilled with an Ingersol Rand 590 drill, shot, and loaded with an Hitachi 700 excavator, or Caterpiller 988 or 966 loaders into one of three Volvo A35 (35 st [31.5 mt]) trucks. The ore is hauled a half-mile (800 m) to the crushing and screening plant. After crushing and screening, the carbonate ore is stockpiled at the marine terminal. The terminal can load ships up to 680 feet (200 m) in length at a rate of 2,000 st (1,800 mt) per hour. In 1998, over 100,000 st (90,000 mt) of ore were mined, processed, and stockpiled.

Grade control is proactively managed at the property with continuous sampling and monitoring at the face of the mine bench, in drill cuttings, at the crusher, and at the stockpile. Grade maps of the mine bench enable blending of ore as it is loaded into the haul trucks.

Calder Geology

Figure 2 is a geologic map of the Calder area of northern Prince of Wales Island and Kosciusko Island. Silurian limestone and marble (Sch), probably correlative to the Heceta Limestone, is ostensibly overlain by graywacke and mudstone turbidites (Ss), probably of the Silurian Bay of Pillars Formation. These rocks are intruded by Cretaceous granodiorites and quartz monzonites (Kgd). (Gehrels and Berg, 1992; Brew and others,1984).

The Calder claims are underlain by a gray-weathering, white to mottled gray, crystalline limestone or marble of the Heceta Limestone. The high-brightness carbonate deposit apparently is in a very pure, weakly thermally metamorphosed unit of the Heceta. Several basalt dikes ranging in thickness from six inches to 2 feet (15 to 60 centimeters) occur locally within the deposit, as does a single, 15-foot (4.5 m) wide, quartz monzonite dike. A quartz monzonite dike has also been noted in a borrow pit to the east of the deposit.

The carbonate rock is commonly white, fine-grained, recrystallized, sparry limestone (marble). Fine- to mediumgrained, sparry limestone is also present, and locally the car-



Figure 2. Geologic map of the Calder Bay - Dry Pass area, southern Southeastern Alaska. Geology modified after Gehrels and Berg (1992) and Brew (1996).

bonate can be coarse-grained. Bedding is usually absent, although minor apparent bedding has been noted in the quarry.

Two types of limestone breccia have also been noted locally. The more common breccia consists of clasts of white, sparry limestone in a breccia of somewhat grayer limestone. This breccia appears to be similar to the formational breccia noted by Glavinovich (1991). A second breccia consisting of white limestone clasts in a matrix of limestone with disseminated, fine-grained pyrite has also been noted but is uncommon.

Color of the limestone in the project area varies from a bright white to light gray to gray. Within the Calder deposit the gray color appears to be caused by grain size (finegrained sparry limestone is usually slightly whiter than fineto medium-grained varieties) and by the impurities which appear to be predominantly very fine-grained pyrite and/or hematite.

BREEZY BAY AND VIEW COVE NORTH DEPOSITS

Location

The Breezy Bay and View Cove North high-CaCO₃ limestone deposits are located on northeastern Dall Island, southwest of Prince of Wales Island, about 60 air miles (96 km) east southeast of Ketchikan, Alaska (figure 1). The

Breezy Bay deposit is located in sections 31 and 32, T. 77 S., R. 82 E., and the View Cove North deposit is located in section 23, T. 78 S., R. 82 E. Elevations range from tidewater to about 500 feet (150 m) on the two properties.

Access to Dall Island is by boat or float plane. The deposits are both accessible from Sealaska's decommissioned logging camp at View Cove via logging roads. The View Cove North deposit is adjacent to the camp and the Breezy Bay deposit is eight road miles (13 km) to the north.

History

In the mid-1920s, a survey by the Pacific Coast Cement Company identified limestone deposits at View Cove on Dall Island to be a promising source for the company's proposed cement manufacturing plant in Seattle. In the ensuing years, a large reserve of 97.5 percent CaCO₃ rock was identified, and in 1928, the company began shipping View Cove cement-grade limestone to Seattle. Pacific Coast Cement and its successor, the Superior Portland Cement Company, mined limestone at View Cove intermittently between 1928 and 1941. In 1947 and 1948, the property was operated by the Permanente Cement Company, a lessee from the Superior Portland Cement Company. During the 20 years in which the View Cove quarry operated, an estimated 2.15 million st (1.93 million mt) of cement-grade limestone were produced (Roppel, 1991). The early history and development of the View Cove deposit is well documented in Roppel (1991).

The View Cove property, including 422 acres (168 ha) of contiguous patented federal mining claims, is presently owned by Ashgrove Cement Company. Sealaska and Ashgrove have several agreements pertaining to joint development of the limestone resources on View Cove claims and on Sealaska-owned land between the View Cove claims and Reef Point to the southeast (Glavinovich, 1991).

Sealaska Exploration and Development

The Breezy Bay and View Cove North limestone deposits on Dall Island are located within lands selected by Sealaska under the provisions of ANCSA. Sealaska's evaluation of these deposits was initiated in 1990, along with examination of potential chemical-grade limestone resources in several other areas of Sealaska's subsurface ownership (Glavinovich, 1991). Work in the Breezy Bay and View Cove North areas has continued intermittently in the ensuing years.

At Breezy Bay, a resource of 150 million st (135 million mt) of light-gray micrite assaying 98-99 percent $CaCO_3$, 0.34 percent MgO, 0.33 percent SiO₂, and 0.11 percent Fe₂O₃ is conservatively estimated, based on 17 surface rock-chip samples collected in 1990 and 1991 (Glavinovich, 1996a).

Brightness tests from five of the whiter 1990 samples returned dry-brightness analyses in the high 80s and low 90s. Average brightness of this resource is probably in the middle 80s or lower.

Table 3 includes whole rock geochemical data from those 17 samples; figure 3 shows their locations. The CaO analyses in table 3 are obviously high - some of these samples ostensibly contain 101 and 102 percent CaCO₃. However, in each of the sample's analyses, the total of all other oxides (including Al_2O_3 , Fe_2O_3 , MgO, Na_2O , TiO_2 , P_2O_5 , MnO, and Cr_2O_3) is usually about 1 percent and always less than 2 percent. Hence, an estimate of an average of 98 to 99 percent CaCO₃ is warranted for the resource.

In 1996, Sealaska wanted to identify a chemical-grade limestone resource on the order of 10 million st (9 million mt) on Sealaska land; as close as possible to the View Cove camp and barge-loading bulkhead. A single sample, collected in 1993 from an area immediately northeast of the View Cove camp (figure 3), contained 99 percent CaCO₃, 0.71 percent MgCO₃, 0.30 percent SiO₂, and less than 0.01 percent Fe₂O₃. Relatively few mafic dikes had been noted in previous examinations of the area. Twelve additional samples of gray to gray-tan micrite were collected from the View Cove North area (figure 3) in 1996.

Eleven of the twelve samples contained high-purity



Figure 3. Geologic map of the View Cove - Breezy Bay area, southern Southeastern Alaska. Geology modified after Gehrels and Berg (1992) and Brew (1996).

Selected Breezy Bay limestone analyses.								
Sample No.	CaO(%)	MgO(%)	SiO ₂ (%)	Fe ₂ O ₃ (%				
1098B	56.80	0.33	0.25	0.04				
1099B	55.89	0.36	0.51	0.15				
1100B	56.45	0.35	0.33	0.10				
1239G	56.54	0.33	0.20	0.02				
1301B	55.92	0.32	0.32	0.05				
1302B	56.33	0.28	0.24	0.07				
1303B	56.58	0.28	0.16	0.05				
4255B	55.24	0.46	0.78	0.21				
4256B	55.37	0.39	0.55	0.23				
4257B	55.51	0.37	0.53	0.19				
4258B	57.31	0.29	0.18	0.06				
4259B	56.28	0.33	0.33	0.11				
4260B	56.87	0.35	0.34	0.09				
261B	56.59	0.43	0.38	0.19				
4262B	56.72	0.31	0.29	0.14				
4272B	57.20	0.31	0.12	0.08				
4273B	57.54	0.27	0.11	0.05				
Averages:	56.42	0.34	0.33	0.11				

limestone. The twelfth sample was collected near the end of the logging road spur in an area of basalt dikes accompanied by apparent dolomitization of the limestone.

Table 4 includes whole rock geochemical data from the 11 surface rock chip samples collected in 1996 from the View Cove North area, and figure 3 shows the locations of the 11 samples. Again, several of the analyses suggest a CaCO₃ content of over 100 percent; however, the sum of the oxides, other than CaO, is, again, always less than 1.5 percent. These samples returned incrementally higher MgO and SiO2 analyses than did the Breezy Bay samples. However, the rock still qualifies as chemical-grade limestone at an estimated 98 percent-plus CaCO₃, 0.96 percent MgCO₃, 0.45 percent SiO₂, and 0.05 percent Fe₂O₃. The amount of highpurity rock present in this area above 150 feet m.s.l. (60 m) (the elevation of the road in the area) is estimated to be 19 million st (17.1 million mt); the total limestone resource estimate above 50 feet m.s.l. in section 23 is 96 million st (86.4 million mt) (Glavinovich, 1996b).

Breezy Bay-View Cove North Geology

Figure 3 is a geologic map of the Breezy Bay-View Cove area of Dall Island. Silurian limestone and marble (Sc), pro-

Sample No.	CaO(%)	MgO(%)	SiO ₂ (%)	Fe ₂ O ₃ (%)
6984H	55.01	0.37	0.69	0.20
6985H	55.86	0.46	0.53	0.06
6986H	56.55	0.42	0.48	0.04
6987H	56.56	0.37	0.79	0.04
6988H	56.65	0.31	0.57	0.06
6989H	55.86	0.36	0.59	0.03
6990H	56.14	0.30	0.33	< 0.01
6991H	54.88	1.19	0.28	< 0.01
6992H	55.54	0.22	0.27	0.09
6994H	55.87	0.37	0.28	< 0.01
6995H	56.00	0.64	0.18	< 0.01
Averages:	55.90	0.46	0.45	0.05

bably correlative to the Heceta Limestone, overlies graywackes which are tentatively correlated with the Silurian to Ordovician Descon Formation (SOd). East of View Cove these units are intruded by Cretaceous granodiorites (Kgd) (Gehrels and Berg, 1992).

The Sealaska lands at Breezy Bay and View Cove North are underlain by a gray to gray-tan micrite with common sparry veinlets. Sealaska has sampled limestone from several other areas within the Breezy Bay-View Cove area; generally the limestones contain substantially more silica, magnesium, and other impurities than at the Breezy Bay and View Cove North prospects (Glavinovich, 1991; Glavinovich, 1993). Basalt dikes are locally present in the limestones in the area, but are relatively rare at both Breezy Bay and View Cove North.

Immediately north of Breezy Bay, Descon Formation graywackes are thrust over Devonian Port Refugio mudstones and graywackes (Gehrels and Berg, 1992; Brew, 1996).

CONCLUSIONS

Sealaska Corporation's high-brightness carbonate deposit at Calder on Prince of Wales Island is fully developed and poised to become a significant producer of high-brightness carbonate material to Pacific Rim markets.

The company's chemical-grade limestone deposits at Breezy Bay and View Cove North on Dall Island contain substantial reserves of high-purity material that will certainly see development early in the new millennium.

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HIGH PURITY LIMESTONE AND DOLOMITE RESERVES AT MONARCH QUARRY, CHAFFEE COUNTY, COLORADO

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ABSTRACT

High-calcium limestone has been intermittently produced from the Monarch quarry since the late 1800s. Initial production was used in sugar processing and for a smelter located near Salida, Colorado. During the 1920s, Colorado Fuel and Iron Company (CF&I) began to exploit the deposit as a source of flux stone for its blast furnace steel operations at Pueblo. The deposit was operated for many years as a captive quarry by CF&I. In 1984, CF&I closed the quarrying operations at Monarch; flux stone was no longer required since the blast furnaces were taken off line in 1981. In 1994, Colorado Lime Company, a subsidiary of United States Lime and Minerals, Inc. acquired the property.

Limestone was mined from the Castle Butte Member of the Leadville Limestone (Lower Missippian). Some highmagnesium dolomite was also mined during WWII from the Redcliff Dolomite Member which directly underlies the Castle Butte. Past production was from both an upper and lower quarry at elevations ranging from 10,000 to 11,000 feet (3,048 m-3,353 m) mean sea level (m.s.l.).

The reserves at Monarch quarry are in a dip slope deposit, occupying the northwest slope of Monarch Hill. The structural geology of the deposit is complex on both a regional and mine scale. The reserves are located on the eastern limb of the Syncline Hill syncline. The beds on this limb of the structure strike to the northeast and dip to the northwest from 30 to 45 degrees. A major reverse fault separates the reserves into an upper and lower deposit. Numerous smaller normal and reverse faults cut the deposit, requiring a flexible mine plan.

At the Monarch quarry, the Castle Butte Member consists of two stratigraphic units. The Upper unit (Mlu) is a thick-bedded, fine-grained crystalline dolomitic limestone from 0 to 300 feet (0-90 m) thick. The unit generally has an SiO2 content of less than 4 percent. A bedded chert horizon and a karst horizon at the base of the unit locally raise the SiO2 content as high as 20 percent. The underlying Quarry Stone unit (Mlq) is a light-gray, massive, bedded, calcilutite/micrite limestone from 90 to 130 feet (27-40 m) thick. The Quarry Stone unit is remarkably uniform chemically throughout it's entire thickness. Average analysis is CaCO₃ - 95 percent, MgCO₃ - 3.5 percent, and SiO₂ - 0.5 percent.

The Footwall dolomite unit (Mld) of the Redcliff Member of the Leadville Limestone is a dark gray to black, blocky, medium-to-thick-bedded, calcilutite/micrite dolomite from 150 to 180 feet thick (46-55 m). The upper 100 feet (30 m) of the unit is a low-silica facies with an average SiO_2 content of less than 0.5 percent. MgCO₃ content is consistent at 39.8 percent throughout the upper 50 feet (15 m) of the unit but varies from 15 percent to 39.8 percent in the lower portion (50 to 100 feet [15-30 m]) of the low-silica facies. The lowest portion of the unit, 100 feet (30 m) to base of unit is high in silica and is not considered chemical grade.

Current in-place, surface-minable reserves at the quarry are estimated to be 14 million short tons (st) (13 million metric tons [mt]) of limestone and 50 million st (45 million mt) of dolomite. A 1.4 million st (1.3 million mt) stockpile of finely crushed limestone is also present on the property. Colorado Lime is presently processing approximately 2,000 st (1,800 mt) per month from the crushed limestone stockpile. This material is pulverized and sold to underground coal mines for use as rock dust, some of this product is also used for environmental purposes. Limestone mining is scheduled to resume in spring of 2000.

LOCATION AND GEOGRAPHY

The Monarch quarry is located in the southern part of Chaffee County, Colorado, in section 4, T. 49 N., R. 6 E. and section 33, T. 50 N., R. 6 E., New Mexico Principal Meridian. The quarry is located approximately one mile (1.6 km) east of Monarch Pass, just south of U.S. Highway 50, near the Continental Divide (figure 1). The quarry lies within the head waters of the West Fork of the Arkansas River.



Figure 1. Location map of Monarch quarry, Chaffee County, Colorado.

The pit area occupies most of the north slope of Monarch Mountain; from an elevation of 10,000 feet (3,048 m) along the river to approximately 11,000 feet (3,353 m) near the top. Two quarries are present at the property, the Lower quarry from 10,000 to approximately 10,500 feet (3,048-3,200 m) elevation, and the Upper quarry from 10,600 to 11,000 feet (3,231-3,353 m) elevation. Due to the high altitude, snowfall can be a major concern for both exploration and operational activities. Snowfall can occur at any time of year on the property. The snow months are commonly from September to June. Historically, CF&I would shut down operations from January to April during heavy snow winters (Wark, 1980).

GEOLOGY

The geology of the Monarch quarry is complex for a limestone quarry. The quarry site lies within the Colorado mineral belt, a major belt of intrusions and associated hydrothermal ore bodies which trends from southwest to northeast through the Rocky Mountains of Colorado. The sedimentary rocks within the quarry have been preserved in a tight synclinal fold bounded by major faults (figure 2).

Generally speaking, the target formations strike to the northeast and dip to the southwest from 30 to 45 degrees. This general scenario is disrupted by numerous faults, normal and reverse, which strike through the property at various angles. These faults affect reserves and disrupt the regional strike and dip. A major reverse fault separates the property into an upper and lower quarry. Major northwesterly striking normal faults form a graben which defines the minable limits of the property.

Stratigraphy

The minable reserves and resources at the Monarch quarry are contained in two informally named units of the Mississippian Leadville Limestone. The upper unit, Quarry Stone, is a high purity, low-silica, high-calcium limestone. The Quarry Stone overlies the Footwall dolomite (lower unit), a high-purity, low-silica dolomite. The limestone is in the Castle Butte Member of the Leadville. The dolomite directly underlies the limestone and is in the basal Red Cliff Member of the Leadville. A depositional unconformity separates the Castle Butte from the underlying Red Cliff (figure 3).

The Quarry Stone limestone ranges from 80 to 120 feet (24-37 m) in thickness and averages approximately 100 feet (30 m) thick over most of the Lower quarry area. In some areas of the subsurface, the minable thickness of the limestone is locally doubled to 200 feet (60 m) by reverse faulting. In the Upper quarry area, the limestone has been partially eroded in places; the thickness varies from 0 to 100 feet (0-30 m), averaging approximately 75 feet (23 m). There are also portions of the Upper quarry where the Footwall dolomite appears to be interbedded with the Quarry Stone limestone within the Castle Butte Member (discussed in more detail later). The Quarry Stone limestone in the vicinity of the property is thought to have been deposited in a sub tidal, marine environment as nearly pure lime muds (Samsela, 1980).

The Footwall dolomite is separated from the overlying

limestone by a zone of breccia, approximately 5 feet (2 m) thick. The dolomite is estimated to be 95 feet (29 m) thick, based on a single core hole. Outcrop relationships of the dolomite as mapped by both CF&I and Henkle and Associates geologists suggest this thickness estimate is realistic. The Footwall dolomite in the vicinity of the property was deposited as thinly bedded lime muds, in a tidal environment, in waters which were periodically brackish (Samsela, 1980). This probably allowed for preferential dolomitization of some of the interbeds. Stratigraphic sections of the Footwall interval in southern Chaffee County, show a series of rhythmically bedded limestones and dolomites (Samsela, 1980). Our interpretation is that the first pulse of dolomitization appears to have altered approximately half of the Footwall dolomite, and that the first pulse occurred slightly after deposition of the sediments.

The available drilling data for the property consists of 20 drill holes in the Upper quarry, only one of which fully penetrates the Footwall dolomite (CF&I drill hole #5), and five drill holes in the Lower quarry area. In the Lower quarry area, one hole completely penetrates the Footwall dolomite (Colorado Lime drill hole # 95-1). The dolomite section penetrated by this drill hole appears to have been thinned by faulting (figure 3).

Chemical analyses from CF&I drill hole #5 show 95 feet (29 m) of high-purity, low-silica dolomite (no limestone). Analyses from Colorado Lime drill hole # 95-1 in the Lower quarry, show a 55-foot (17 m)-thick, high-magnesium, low-silica dolomite (39 percent MgCO₃) overlying a 25-foot (8 m)-thick, low-magnesium, low-silica dolomite (15.5 percent MgCO₃).

Our theory is that any original limestone interbeds in the Footwall dolomite at or near the location of CF&I drill hole #5 were probably changed diagenetically to dolomite by hydrothermal fluids during a second pulse of dolomitization, most likely during the Laramide orogeny.

Clear evidence for hydrothermal dolomitization can be seen in the overlying Quarry Stone limestone, as exposed in portions of the Upper quarry area below an elevation of 10,700 feet (3,300 m). Here, low-silica dolomite is interbedded with the low-silica limestone in a limited area. Dolomitization in these beds is clearly related to the major reverse fault which separates the Upper and Lower quarries. Selective diagenesis is stronger near the fault, and dies out uphill from the fault.

Structure

The strata in the Monarch quarry area have been moderately folded and intensely faulted. The quarry is located on the eastern limb of the Syncline Hill syncline, a tight, asymmetric fold which plunges to the north at approximately 40 degrees. The target formations strike to the northeast and dip to the northwest. Dips in the Upper quarry are approximately 30 degrees. In the Lower quarry, dips average approximately 45 degrees.

We have identified at least 11 faults which disrupt the target formations in the Upper and Lower quarry areas. These faults range in displacement from tens of feet to thousands of feet. The influence of this faulting on past and future mining operations ranges from negligible to major.







Figure 3. Monarch quarry correlation diagram from Upper to Lower quarry.

Lake Fault

The Lake fault is a major fault of regional significance which forms the southwestern boundary of the deposit. The Lake fault places the Precambrian Silver Plume Granite against a thick sequence of Paleozoic sediments near the property. This fault is a high-angle reverse fault with a minimum displacement of 3,500 feet (1,100 m), which strikes north – south and is reported to dip between 56 and 80 degrees to the west (Dings and Robinson, 1957). We beleive that compressive forces associated with movement of the Lake fault were responsible for formation of the Syncline Hill syncline. We also beleive that these same compressive forces generated the series of reverse faults found at the Monarch quarry property.

Reverse Faults

A series of major reverse faults traverse north-northeasterly across the Monarch property. These faults are found beneath alluvial cover in the southwestern portion of the deposit. A series of northwesterly-striking normal faults cut the reverse faults and progressively raise their topographic expression higher in elevation as they traverse the property to the northeast. Displacement on the reverse faults is as much as 200 feet (60 m), with the northwest side up. The faults dip to the northwest. In the central portion of the property, the most prominent reverse fault expresses itself topographically as a steep scarp approximately 100 feet (30 m) high which transects the property (figure 4). These reverse faults profoundly affect the reserve base of the quarry, dividing it into an upper and lower reserve area. It would be difficult, if not impossible, to open-pit mine across the faults. At least one of these faults appears to have acted as the locus for hydrothermal fluids which definitely dolomitized limestones in the Castle Butte Member and appears to have dolomitized interbedded limestones in the lower Red Cliff member, in the Upper quarry area.

Normal Faults

Three northwesterly-striking normal faults, the April Fool, Snowslide, and Deleware faults cut the central and northeastern portions of the property. The Deleware fault bounds the deposit on the northeast. The April Fool fault bounds the deposit at higher elevations in the southwest. The April Fool fault intersects the Postulated Reverse fault which appears to bound the deposit in the topographically lower portions of the southwest extension. The Snowslide fault transects the central portions of the Upper quarry causing a major revision of mining sequences on either side.

Displacements on these three faults are significantly greater in the topographically higher southeast portion of the property. It appears that these are wrench-type faults. Recognition of this wrench-type movement along the Deleware fault allowed for discovery of significant new reserves in the Quarry Stone limestone at the Upper quarry, in the extreme northeastern portion of the property. Numerous, smaller northwesterly and northeasterly trending faults disrupt bedding throughout the remainder of the property. The abundance of faulting at the Monarch quarry requires a flexible mining plan and innovative management.



Figure 4. Northeast-looking cross-section of Monarch quarry area showing lithologic units and locations of major faults.

MINING

Past mining by CF&I was by the open-pit, truck-shovel method from both the Upper and Lower quarry areas. Colorado Fuel and Iron Company mined approximately 300,000 st (272,000 mt) per year from the Monarch quarry. The lime-stone was transported to the Pueblo steel mill by a now abandoned rail spur.

Colorado Lime and its predecessor CALCO can produce up to 100,000 tons (91,000 mt) per year of crushed limestone from a large stockpile of crusher undersize materials left from CF&I's operations. Approximately one million st (0.9 million mt) of this material remain in the stockpile. The crushed limestone is loaded into trucks and hauled 20 miles (32 km) east to the Salida processing plant, where it is pulverized into limestone powder. The powder is sold both in bag and bulk form to underground coal mines for use in rock dusting to prevent coal dust explosions. Some of this production is also sold for environmental end uses.

Colorado Lime plans to begin production of approximately 50,000 tons (45,000 mt) per year of limestone from the Lower quarry in the spring of 2000. This will be produced by truck and shovel and trucked to the Salida plant to be used in the production of quick lime. The limestone and rock dust operations will continue along with the quick lime operation.

An area of exposed dolomite in the southern end of the Lower quarry has been permitted for mining, but there are no immediate plans to produce dolomite from the Lower quarry.

QUALITY AND RESERVES

Weighted averages of chemical analyses and reserves of the Quarry Stone limestone and the Footwall dolomite are shown in tables 1 and 2. Quality data shown in table 2 is heavily skewed by the fact that there are only two full drillhole penetrations of the entire 100-foot (30 m) thickness of the Footwall dolomite at the quarry (figure 3). We conclude that a considerable tonnage of dolomite with an MgCO₃ content of approximately 35 to 40 percent is present at the Monarch quarry. However, a considerable amount of drilling will be necessary to delineate those resources. Hence, the lumping of the resource figures for both the Upper and Lower quarries for this unit.

Upper q	uarry-	Lower quarry-				
7.2 milli	on st	6.82 million st				
(6.5 mill	ion mt)	(6.19 million mt)				
CaCO ₃	94.91%	CaCO ₃	95.92%			
MgCO ₃	4.02%	MgCO ₃	3.22%			
SiO ₂	0.42%	SiO ₂	0.64%			
Balance	0.65%	Balance	0.92%			

Notes:

 Cumulative weighted averages of individual CF&I core holes assayed for each five-foot increment (CF&I, unpublished data).

2. Balance of analysis is primarily reactive oxides (Fe₂O₃ and Al₂O₃).

Table 2.

Resources and average chemical analyses - Footwall dolomite.

Upper and Lower quarries - 50.1 million st (45.5 million mt) resource potential.

CaCO ₃	60.6%
MgCO ₃	36.64%
SiO ₂	0.55%
Balance	2.25%

Notes:

1. Cumulative weighted averages of individual CF&I core holes assayed for each five-foot increment (CF&I, unpublished data).

2. Balance of analysis is primarily reactive oxides (Fe2O3 and Al2O3)

and probably organic carbon.

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FACTORS IN PREDICTING ALLUVIAL GRAVEL COMPOSITION USING DIGITAL GEOLOGIC MAP AND ELEVATION IMAGES: AN EXAMPLE FROM THE COLORADO FRONT RANGE

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ABSTRACT

Estimating the lithologic composition of gravel deposits for aggregate quality using standard field and laboratory techniques is costly and time-consuming. As an alternative, digital geologic maps and elevation models may provide a means for predicting the lithologic composition of channel and terrace deposits. Digital geologic maps can be used to evaluate the distribution of map units, their geomorphic setting, and the physical properties of the gravel source. To test this concept, the lithologies and topography of the upper drainage basin of the Big Thompson River along the Colorado Front Range were used to examine various factors that may control the final lithologic composition of channel and terrace gravels downstream.

The simplest factor is the area of each of the map units in the upper drainage basin area, which can be easily measured from the digital geologic map. The percentage of each map unit within the total area provides a estimate of the proportions of each map unit that might be expected to occur in the downstream gravels. Published estimates of the hardness and durability of each map unit were used to calculate physical property-weighted areas; these areas are an estimate of the potential of each unit to be eroded and transported as gravel-sized particles.

The areas of each map unit at 1-kilometer intervals from the drainage basin exit point were used to calculate a distance-weighted area for each map unit. For this study, a simple inverse relationship (area/distance) was used for distance weighting, but a more complicated distance function may ultimately be required.

The topographic setting of exposed rock units should exert a significant influence on whether material will move slowly or rapidly through the drainage system. Two topographic factors were examined: gradient and slope. A simple gradient between map unit occurrences and the exit point of the drainage basin was used to calculate a gradient-weighted area estimate for each map unit. The slope-weighted area estimate uses the slope steepness (in degrees) in the immediate vicinity of each map unit occurrence as a measure of the tendency of material to begin moving into the sediment transport system.

The primary intent of this study was to test the concept of using digital geologic map and elevation images to estimate gravel composition, rather than actually producing a useful analysis of a drainage basin. Each of the controlling factors was examined independently to gain an understanding of the magnitude of the effect of each factor. Ultimately, a comprehensive predictive model will be constructed using a combination of the various controlling factors.

INTRODUCTION

Assessing the physical properties of gravel material for aggregate specifications usually involves measuring the Los Angeles (LA) abrasion test values for representative samples (Meininger, 1994); however, an estimate of how a gravel particle might perform as concrete aggregate may be made based on the particle lithology alone. Some lithologies are typically hard, dense, tough, and produce gravels that are an excellent source of natural aggregate. Other lithologies are soft, absorptive, and friable and form inferior aggregate gravels. Still other lithologies have excellent physical properties for natural aggregate, but contain reactive minerals that make them unsuitable for use in Portland cement concrete (Langer and Knepper, 1995). By identifying the type and proportions of the lithologies making up a gravel deposit, an evaluation of the potential of the gravel for various applications may be made.

Identifying the type and proportions of lithologies making up a gravel deposit is a laborious and time consuming job involving the collection of representative samples (45 kilograms [100 lbs] or more for each sample), sieving to isolate various size fractions, and identifying and tallying the lithology of each pebble or cobble (Lindsey and others, 1998). Several to numerous samples may be required to obtain a representative estimate of the lithologic composition depending on the complexity and variability of the gravel deposit. The same samples are commonly used to measure the size and shape of representative pebbles and cobbles.

The growing availability of digital geologic maps (such as Green, 1992) and digital elevation models (DEM), along with the software for conducting spatial analyses of these data, may provide the means for estimating gravel composition, with appropriate field verification, without the timeconsuming and costly field measurements. This report illustrates how these digital datasets can be used to evaluate several factors that determine the lithologic composition of gravel deposits. The study is intended to be more of a proof of concept that an actual detailed analysis of a specific group of gravel deposits.

The drainage basin and gravel deposits of the Big Thompson River (figure 1) were chosen as an area to investigate the possibility of predicting gravel composition from existing digital spatial data to help fulfill requirements of the on-going U.S. Geological Survey (USGS) studies of the natural aggregate potential along the Colorado Front Range urban corridor. This area was chosen because it is representative of numerous drainage basins and associated gravel deposits along the Front Range, and because of the lack of detailed composition information for the gravels; generalized observations made by Colton and Fitch (1974) are summarized in table 1. Fieldwork conducted during the summer and fall of 1999 will eventually provide the detailed data necessary for better evaluating the results of this investigation and assist in determining the appropriate ways to use and combine the results of the analyses.

The available digital geologic map, the Geologic Map of Colorado (Green, 1992), is probably too generalized and coarsely scaled (600 meters resolution) to allow a detailed analysis of this drainage basin, but is sufficient for developing the methodology and identifying trends (figure 2). Table 2 contains the generalized lithologies of the map units for figure 2. The available USGS digital elevation model of the Greeley, Colorado, 1° X 2° quadrangle has a resolution of 30 meters and would be sufficient for detailed analyses as well.

GEOMORPHIC SETTING

Commercial gravel deposits along the Colorado Front Range urban corridor are associated with the major streams that head in the predominantly Precambrian crystalline rocks of the Front Range and empty eastward onto the plains (figure 1). Most of the pebbles and cobbles in these gravel deposits are composed of the crystalline rocks exposed in the headward drainage basins of the associated streams; a very small percentage of the gravel particles is composed of sedimentary rocks, mostly sandstone and carbonate rock, that are exposed along the eastern flank of the Front Range.

COMPOSITION CONTROLLING VARIABLES

The composition of stream gravels along the east flank of the Colorado Front Range are representative of the rocks exposed in the associated drainage basins upstream from the gravel deposits. Four classes of variables were considered as potentially significant influences on which of those mapped lithologic units are represented, and in what proportion, in the gravel deposits: (1) the amount of each lithologic unit in the drainage basin, (2) the physical properties of each lithologic unit, (3) the distance of each exposure from the gravel deposit, and (4) the topography of the drainage basin.



Figure 1. Sun-shaded relief map of the upper Big Thompson drainage basin and vicinity made from the 30-meter digital elevation model of the Greeley, Colorado, 1° X 2° quadrangle. Commercial channel and terrace gravel deposits occur along the Big Thompson River from its exit point from the upper drainage basin to its confluence with the South Platte River. This geomorphic configuration is similar for all of the east-flowing major streams along the east flank of the Front Range.

Table 1.

Percentages of lithologies in gravels reported by Colton and Fitch (1974) at five sites along the Big Thompson River between Loveland, Colorado, and its confluence with the Little Thompson River.

Lithology	West Loveland, Colorado Little Thom								<i>East</i> pson River	
	Site 1		Site 2		Site 3		Site 4		Site 5	
Pegmatite				1		1	40		40	
Granite	78	1	55		61 24	04	9	- 90	5	99
Gneiss	14	05	25	100			9		33	
Quartzite	3		12	100	9		23		18	
Schist]	6							
Aphanite			2				9		3	
Sandstone						3	1	0		
Gabbro	4									
Conglomerate									1	
Other				1		3				
	9	9	1	01	1	00	100		101	

Lithologic Amount

Ideally, a measure of the volume of each lithologic unit that has been removed from the drainage basin would indicate how much of each unit should be represented in the resulting gravel deposit; however, the original configuration of the lithologic units, prior to erosion, is unknown. As an alternative, the area of each lithologic unit on the geologic map of the drainage basin can be used as an estimate of how much of each lithologic unit might have contributed to the gravel deposit. With a rasterized geologic map of the drainage basin, most modern image processing software can provide a measurement of the area of each data number in the image, where a unique data number represents each of the map units.



Figure 2. Generalized geologic map of the upper Big Thompson River drainage basin, Colorado, from the digital Geologic Map of Colorado (Green, 1992). This rasterized version of the geologic map has a resolution of 600 meters and the coarse mapping units may contain several lithologies; the units are identified in table 2. Units Qe and Ku are exposed over such small areas that they cannot be displayed at this scale.

Table 2.

Generalized lithologies of the map units on the geologic map of the upper Big Thompson River drainage basin (figure 2).

Qg	Older gravels and alluvium	
Qe	Eolian deposits	Unconsolidated
Qd	Glacial drift	sediments
Tg	Bouldery gravel on old erosion surfaces	
Τv	Mainly intermediate volcanic rocks	Volcanic rocks
Ku	Upper Pierre Shale	
Km	Middle Pierre Shale	Mostly shale
КІ	Lower Pierre Shale	
Kc	Colorado Group	Limestone and shale
KJ	Dakota, Morrison, and Sundance Fms.	
Pj	Jelm, Lykins, Lyons, and Satanka Fms.	Mostly sandstone
Pf	Fountain Fm.	
Xb	Biotitic gneiss, schist, and migmatite	
Xfh	Felsic and hornblendic gneisses	Metamorphic rocks
Yg	Granitic rocks of 1,400-M.Y. age group	
Xg	Granitic rocks of 1,700-M.Y. age group	Granitic rocks

The results of area measurements of each lithologic unit in the Big Thompson River drainage basin from the rasterized Geologic Map of Colorado (Tweto, 1979; digital version by Green, 1992) are shown in table 3. The area measurements have been converted to a percentage of the total area, which can be used as an estimate of the percentage of each lithologic unit that may be found in the gravel deposits.

Physical Properties

Regardless of the volume of a lithologic unit in the drainage basin, if the unit is soft or friable, material eroded from the unit is unlikely to survive transport to downstream sand and gravel deposits. Consequently, altering the area estimate by a factor that expresses the hardness and durability of the lithologic unit would presumably provide a better estimate of the downstream gravel composition. Langer and Knepper (1995) and Knepper and others (1999) estimated the physical and chemical suitability of each lithologic unit on the digital geologic map of Colorado (Green, 1992) for use as aggregate in Portland cement concrete. These estimates are based on the hardness of the rocks in the unit, their fracturing and surface texture characteristics, their permeability and absorption tendencies, and their susceptibility to volume changes under alternate wetting and drying and changes in temperature (Langer and Knepper, 1995). These properties also influence the probability that material from any given map unit will be eroded, transported, and incorporated into downstream deposits in gravelsized particles.

These physical property estimates were translated into numeric estimates of 4, 3, 2, and 1, respectively, for weighting purposes and multiplied with the appropriate previous area estimates for each lithologic unit. The resulting area estimates for each unit, modified by the appropriate physical property factors and normalized to percent of the total physical property-weighted area, is shown in table 3. As more is understood about the influence of physical properties on gravel composition, perhaps more scientifically sound measurements, such as Los Angeles (LA) abrasion test values, could be applied as the physical property weighting factor if they are available for the appropriate map units.

Distance

The distance that an outcrop of a particular map unit occurs from the downstream gravels derived from that bedrock source should have an influence on whether the rocks from that map unit will be represented in the gravels, and in what size and proportion. To evaluate this factor, the DEM was used to generate a distance image consisting of concentric rings at 1-kilometer intervals outward from the point where Big Thompson exits the upper drainage basin. The distance image was used to assign a distance (in kilometers) from the exit point to each pixel of each map unit in the digital Geologic Map of Colorado. The area of each map unit at each 1-kilometer interval was measured and the distance-weighted area of each map unit was calculated by dividing the areas by their respective distances (inverse relationship). The results of the distance-weighted analysis are in table 3.

Topography

Two aspects of the topography of the drainage basin were investigated as possibly exerting control over the final downstream gravel composition: (1) the overall gradient between each pixel of each lithologic unit on the geologic map and the exit point of the river from the drainage basin and (2) the steepness of the slope in the immediate vicinity of each pixel of each lithologic unit in the drainage basin. These simple measurements did not consider the actual path that material eroded from the drainage basin may have taken to become incorporated into the downstream gravel deposits.

Gradient

Gradient is the change in elevation as a function of distance. For this study, the straight-line distance between points was used to calculate the gradient, rather than the distance along the drainage system. Intuitively, materials in areas with higher (steeper) gradients would seem to have a greater chance of entering and moving along the drainage system to the point where gravels are deposited. The DEM image, in combination with the digital geologic map, was used to calculate the gradient between each pixel of each lithologic unit on the digital geologic map and the exit point from the drainage basin. The area of each pixel of each lithologic unit was multiplied by its corresponding gradient, summed, and normalized to percent of the total gradientweighted area. Results of the gradient-weighted analysis are in table 3.

Slope

Slope is the steepness of the terrain in the immediate vicinity of each pixel on the digital geologic map. Steep

 Table 3.

 Percentage of the composition-controlling factor weighted areas for each map unit on the digital geologic map of the upper Big Thompson River drainage basin. Each controlling factor analysis is an independent estimate of the proportion of the geologic map units predicted to be in the downstream channel and terrace gravel deposits along the Big Thompson River.

UNIT	PHYSICAL Property Factor (1-4)	AF	REA	PHYSICAL PROPERTY WEIGHTED AREA		DISTANCE Weighted Area		GRADIENT WEIGHTED AREA		SLOPE Weighted Area	
Qg	2	0.4	151	0.304		1.942		0.073		0.040	
Qe	1	0.0	51	0.017		0.964		0.003		0.005	
Qd	1	3.3	98	1.1	44	1.440		0.917		2.903	
Tg	2	0.2	.94	0.1	98	0.251		0.294		0.168	
Tv	4	0.0)26	0.035		0.008		0.031		0.037	
Ku	1	0.028		0.009		0.519		0.002		0.002	
Km	1	0.6	599	0.235		8.001		0.210		0.118	
KI	1	2.7	780	0.936		13.	964	0.7	712	0.3	311
Kc	3	1.7	/24	1.741		5.2	237	0.5	589	0.3	329
KJ	1	1.5	535	0.517		3.795		0.723		0.555	
Pj	1	2.7	786	0.9	938	5.193		1.352		1.012	
Pf	1	3.6	572	1.236		5.296		2.093		1.780	
Xb	3	48.006		48.488		34.416		53.425		52.060	
Xfh	4	0.427	82,555	0.575	92.688	0.424	53,392	0.435	92.999	0.439	92.741
Yg	4	27.207	02.000	36.640	2.000	13.050	55.572	32.089	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	33.688	74.171
Xg	3	6.915		6.985		5.502		7.050		6.554	
Total		10	0.0	100.0		10	100.0		100.0		0.0

slopes suggest that material in the area will have an increased tendency to begin moving in response to gravity (talus slopes, for example); however, to continue moving into the drainage system and being transported and eventually deposited with the stream alluvium, possibly as gravels, requires a sufficient gradient along the path to maintain downstream movement. For this study, slope was calculated in degrees for each pixel of each lithologic unit exposed in the Big Thompson drainage basin and multiplied by the area of the pixel. The slope-weighted areas of each lithologic unit were summed and normalized to the percent of the total slope-weighted area. The results of the slope-weighted analysis are in table 3.

DISCUSSION

Although detailed measurements of the actual lithologic composition of the terrace and channel deposits along the Big Thompson River east of the Front Range will not be available until the fall of 1999, it is useful to speculate on the differences seen in the analyses of the various factors that might influence the lithologic composition of the gravels. The generalized observations by Colton and Fitch (1974) shown in table 1 provide a preliminary measure of the effects of the various factors on the gravel composition estimates.

Map Units

Most of the upper drainage basin of the Big Thompson River is in Precambrian crystalline rocks of the Front Range. These rocks are Proterozoic metamorphic and igneous rocks. Small remnants of Tertiary volcanic rocks are perched high along the drainage divide (Continental Divide) to the west and upturned Paleozoic and Mesozoic sedimentary rocks are exposed along the eastern flank of the Front Range to the east. To assist in evaluating the results of the various analyses, the general lithologic character of the units are shown in table 2.

Analyses

The simple analyses designed to illuminate the broad effects of various parameters on the composition of terrace and channel gravels along the Big Thompson River reveal the magnitude of the effects of the various factors, but not their interrelationships. Ultimately, a single predictive model using these factors will be developed, and the results of these analyses will aid in determining the nature and structure of that model.

Area

The analysis considering only the area of the exposed lithologic units from the digital Geologic Map of Colorado is the simplest and most straightforward of the various analyses. Consequently, this analysis is used as a basis for comparing the results of the other analyses. From the area analysis shown in table 3, the composition of most (75 percent) of the gravel particles in the terraces and channel of the Big Thompson River should reflect the lithologies associated with Proterozoic biotite gneiss and schist (Xb) and Proterozoic granite (Yg) units. Since the Xb unit also contains migmatite (table 2), a substantial amount of quartz and feldspar, separately or in combination, may also be included in the gravels in addition to the gneiss, schist, and granitic rocks. The next most abundant unit, in terms of area, is the Proterozoic Xg granite unit at 7 percent of the total drainage basin area. So, approximately 82 percent of the drainage basin area consists of these three Proterozoic crystalline units and, in the simplest case, 82 percent of the terrace and channel gravel particles should consist of these readily identifiable lithologic units.

The next most abundantly exposed units are the Qd, Kl, Pj, and Pf units (table 3), which together make up about 13 percent of the drainage basin area. The Kl, Pj, and Pf units are Paleozoic and Mesozoic shale, sandstone, and conglomerate rocks that are generally not found in the Front Range gravel deposits; as will be seen below, the physical property factor accounts for scarcity of these units in existing gravels and emphasizes the need to consider more than just the area in gravel composition prediction.

The Qd unit is Pleistocene glacial drift that contains blocks, boulders, pebbles, and cobbles of the Proterozoic crystalline rocks. Today, the drift represents only a small percentage (3.398 percent) of the material exposed in the drainage basin, but during extensive mountain glaciation in the Pleistocene, reworked drift was the primary raw material for the formation of the downstream terrace gravels; the channel gravels are composed of reworked terrace gravels (Lindsey and Langer, 1999).

The remaining units constitute the final 5 percent of the drainage basin area, and most of them are unlikely to contribute to the gravels. As a practical matter, the Tv unit (table 2) is the only unit that might contain microcrystalline quartz that would promote the alkali-silica reaction in Portland cement concrete if used as aggregate. However, Tv is exposed over only about 0.4 sq km of the drainage basin, which constitutes less than 0.03 percent of the total area, so the Tv is not likely to be abundant enough to degrade the quality of the gravels for use as aggregate.

Physical Property-Weighted Area

The physical property factor allows for an adjustment of the abundance of the lithologic units based on the physical character of the rock unit. Therefore, a unit that is soft and friable (physical property factor = 1 or 2) will be less likely to be incorporated into the gravel deposits than it's abundance would suggest. By comparing the area and physical property-weighted area results in table 3, the effect of the physical property factor is easily recognized.

Although the same mapping units (Xb and Yg) dominate the physical property weighted area, their contribution has increased to about 85 percent of the total because they are widely exposed and they have high physical property factor estimates. Together, the Precambrian crystalline rocks (Xb, Xfh, Xg, and Yg) account for about 93 percent of the physical property-weighted area, which is similar to the observed percentages in table 1. The percentages of less abundant units with high physical property factors changed very little (Xg, Xfh, Kc, and Tv on table 3), while low abundance units with low physical property factors actually decreased in relative importance. The three most abundant Proterozoic units (Xb, Yg, and Xg) in the area analysis now account for over 92 percent of the total physical property weighted area and should dominate the downstream gravel composition. The contribution of the alkali-silica reactive rocks (Tv) has increased to about 0.04 percent, which is still insignificant in the consideration of the possible use of the gravel as aggregate in Portland cement concrete.

Distance-Weighted Area

Compared to the area analysis, distance weighting produced the most drastic changes in the unit percentages of all the weighting factors. For this study, a linear, inverse function was used for the distance weighting (area/distance), but a more complicated distance function, such as 1/distance², may better reflect the effects of distance on the final gravel composition.

Not surprisingly, the percentages of the Paleozoic and Mesozoic units (Ku-Pf on table 3) closest to the gravel deposits show a dramatic increase in the distance-weighted analysis, while the more abundant Xb and Yg units show a significant decrease; these units occur over a broad range of distances, but are the most prominent farther away from the gravel deposits. Even so, the Xb and Yg units still combine for almost 48 percent of the total distance-weighted area and would be predicted from this analysis to dominate the overall composition of the downstream gravels.

Intuitively, the addition of the physical property factor to the distance factor in the analysis would appropriately diminish the importance of soft and friable, nearby units and increase the significance of the harder, more durable units even though they occur further away. The exact manner of combining these factors in the analysis will be addressed in future research to develop a broadly applicable predictive model that uses each of the tested variables.

Considering the relative distance-weighted abundance of the Tv unit further emphasizes the importance of the distance factor in any predictive model. Although the unit has the smallest actual area of any of the map units, it has a high physical property factor and is not the lowest percentage in the physical property weighted analysis. In the distance weighted analysis, however, Tv almost disappears from consideration with only 0.008 percent of the distance weighted area. Tv occurs at the farthest reaches of the upper Big Thompson drainage basin, 59 kilometers from the drainage basin exit point (figure 2).

Gradient-Weighted Area

The gradient analysis is a simple analysis that considered only the difference in elevation between the unit pixel and the exit point from the basin divided by the straight line distance between the points. No attempt was made to measure the actual path material eroded from the pixel area might have taken to the basin exit point. Consequently, the calculated gradients are probably somewhat inflated because the actual paths were longer than the straight line distance, but they will serve to identify the general effect of gradient on predicted gravel composition.

Because the overall gradient within the drainage basin

increases rapidly westward at the Front Range mountain front, the units exposed westward in the mountains have much higher gradients than the units exposed at or near the mountain front; the rock units exposed in the mountains (Xb, Xfh, Yg, Xg, or Tv) each have gradient-weighted area percentages greater that their simple area percentages, while the units closer to the mountain front have gradient-weighted area percentages below their simple area percentages (table 3). Considering only the gradient factor, 93 percent of the predicted gravel composition would consist of the Xb, Xfh, Yg, and Xg units, which is slightly less than the combined observed crystalline rocks in table 1, but very similar to the physical property-weighted results.

Slope-Weighted Area

The slope weighting only provides a measure of the tendency for eroded material to initially enter the drainage system and not whether it will continue to move along the system. For example, blocks on a very steep slope might roll, slide, or fall onto a relatively flat surface and remain there for a long time before continuing along the erosional train. Ideally, the slope weighting should probably be combined with a gradient measurement along the potential erosional path to provide a better, if more complex, indicator of the tendency of material to move along the erosional train.

The slope-weighted percentages are remarkably similar to the gradient-weighted and physical property-weighted percentages for most of the units. The Precambrian crystalline rocks (Xb, Xfh, Yg, and Xg) make up about 93 percent of the slope-weighted area and would be expected to dominate the downstream gravel composition in an abundance only slightly less than the observed percentages in table 1.

Map Unit to Lithology Conversion

A geologist studying the composition of stream or terrace gravels for potential aggregate use looks at large samples of the gravel material and identifies the lithology of each pebble, cobble, and boulder and compiles a tally of the percentage of each lithology. Units on geologic maps are usually composed of more than one lithology, even though a single lithology may dominate the unit. For example, a hornblende gneiss unit may contain layers of schist and quartzite, as well as pegmatites. The geologist would identify each of these lithologies separately in the gravels. The adjacent map unit, a quartz-muscovite schist for example, may also contain gneissic layers, quartzite, and pegmatites. The geologist identifying gravel composition probably would not, or could not, tell which recognized map unit the various gravel lithologies came from, nor would it be necessary for evaluating aggregate quality.

In order to predict gravel composition using the digital geologic map of the drainage basin area, a breakdown of the actual lithologies occurring in each map unit, and their proportions, would greatly facilitate the geologist's estimate of the products of erosion and would be more useful in evaluating aggregate potential. To approach this ideal situation, it seems clear that the most detailed geologic map available should be used. In addition, published lithologic descriptions of each of the map units should be consulted, if they are available. Otherwise, reconnaissance fieldwork would be required to identify the lithologies represented in by each map unit and their proportions.

SUMMARY

The generalized observations of gravel lithology (table 1) provided by Colton and Fitch (1974) compared to the results of this investigation (table 3) suggest that the concept of estimating gravel composition from drainage basin geology and topography may have some merit. The physical property-weighted area, the gradient-weighted area, and the slope-weighted area analyses each produced similar results that are reasonably close to the observed percentages. The cause for these similar results is probably because the hardest, most durable units (high physical property weighting factor) are also the most resistant and make up the highest terrain (high gradient weighted factor) and form the steepest slopes (high slope weighting factor). The independent distance-weighted analysis gave undue significance to soft, friable units (shale and sandstone) in its estimate, and probably needs to be combined with one or more of the other factors to produce results similar to the observed percentages.

Almost certainly, an accurate predictive model will ultimately consists of a combination of the various factors tested in the investigation. The availability of actual lithologic measurements being conducted during the summer and fall of 1999 will provide the information necessary for determining how the various factors should be combined, weighted, and used in a final predictive model.

ACKNOWLEDGMENTS

I thank my USGS colleagues, W.H. Langer and D.A. Lindsey, for insightful reviews of the manuscript that helped focus the investigation and identify additional geologic parameters that were not originally considered.

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THE ANTLER CHLORITE MINE, SOUTHWESTERN MONTANA: REDISCOVERY, GEOLOGY, AND CLOSURE

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ABSTRACT

Until its closure in 1999, the Antler was North America's only active chlorite mine. The mine is located 25 miles (40 km) southeast of Butte in the Silver Star district - an old Montana gold mining district. In 1975, two prospectors searching for talc re-examined a prospect showing a green, fine-grained mineral resembling talc. Following identification and testing of this magnesian chlorite (variety clinochlore), Cyprus Industrial Minerals began processing ore from this deposit in 1976. Chlorite veins ranging up to 30 feet (9 m) in thickness were formed by essentially complete replacement of Precambrian (Archean?) quartzofeldspathic gneiss. Chlorite replacement was controlled by nearvertical faults. These chlorite veins, typically surrounded by envelopes of sericitic alteration, were formed by the introduction of magnesium-rich hydrothermal fluids, probably related to the Proterozoic talc-forming event in southwestern Montana. Luzenac America, Inc. acquired Cyprus' talc operations in 1992, and continued to mine this deposit until the ore body was mined out in March 1999, and the mine was reclaimed. Total sorted ore production from this deposit is about 250,000 short tons (st) (227,000 metric tons [mt]). Chlorite from this deposit was primarily used in ceramic and paint applications.

INTRODUCTION

The Antler mine, in recent years the only producing chlorite mine in North America, is located in the Silver Star mining district about 25 miles (40 km) southeast of Butte, Montana on the southeast flank of the Highland Mountains (figure 1). The Silver Star district, primarily a gold district, was developed in the 1870s, early in the history of Montana mining. Most metal value was from gold with lesser silver, copper, and lead values. Sahinen (1939) estimated that approximately 100,000 Troy ounces (3,100 kg) of gold were produced from the district, most of it before 1913.

The first attempts to develop what is now known as the Antler chlorite deposit were made in the 1950s when Tri State Minerals, who was then mining and processing talc near Dillon, Montana, attempted to develop a market for this chlorite. Because Tri State was unsuccessful, claims on the deposit were abandoned and it was largely forgotten. In 1975, two local prospectors, Robert Nolte and Sylvan Done-

gan, became interested in the deposit. Following identification of a specimen of chlorite from this deposit by the Montana Bureau of Mines and Geology, the prospectors brought this deposit to the attention of Don Kennedy with Cyprus Industrial Minerals. The timing of their discovery was fortunate. Cyprus had been mining chlorite at the Frisco mine in the Talc City mining district in Inyo County, California, that had been developed by Sierra Talc and Clay Company. Cyprus acquired Sierra Talc and Clay in the late 1960s. Chlorite production came from both underground and open pit operations at the Frisco mine until the late 1970s, when the resource was depleted. Much of the chlorite from this mine was used in the ceramic industry in the manufacture of synthetic cordierite. The timely identification and development of the similar Antler chlorite deposit eased production of chlorite away from the Frisco mine, which was reclaimed in 1982.

Analysis and testing of chlorite from the Antler deposit showed it to be of high purity and satisfactory for Cyprus' chlorite markets. Following leasing of this deposit in 1975, Cyprus received a test shipment of 25 st (23 mt) of Antler chlorite. Favorable results from this test led to the processing of chlorite at Cyprus' mill at Three Forks, Montana, 30 miles (48 km) to the east. A mining lease was negotiated with the claim holders in 1978. The mine was acquired by Luzenac America, Inc. in 1992, as part of their acquisition of Cyprus' talc operations. Mining of this deposit continued until spring of 1999, when the mine was closed because the lower minable limit of the deposit was reached.

OPERATION, MARKETS, AND RECLAMATION

Mining

The Antler ore body was first identified from surface vein outcrops that probably represented the upper limits of chlorite mineralization and alteration (figure 2). These narrow 3-foot (1 m) wide vertical veins expanded to more than 20 feet (6 m) in width within 30 feet (9 m) of the former land surface. During the first few years of mining, the claim holders chased these veins by excavating narrow trenches. Cyprus first defined the orebody in 1979, when 27 exploratory holes were drilled, all shallower than 100 feet (30 m). Initial pit development began after the 1979 drilling program



Figure 1. Simplified geologic map showing the location of the Antler mine and surrounding areas of chloritic alteration on the southern flank of the Highland Mountains (modified from O'Neill and others, 1986 and O'Neill and others 1996). Areas of chloritic alteration and chlorite occurrences from Berg (1992).



Figure 2. Chlorite vein with typical chippy weathering to the left of watch. The more massive rock to the right is partly altered quartzofeldspathic gneiss.

showed that the defined reserves were more than sufficient to satisfy the 3,000 to 4,000 st (2,700-3,600 mt) per year demand anticipated for the first several years of production.

Nolte and Donegan mined the claims on contract from 1975 until 1984, after which Cyprus employed another mining contractor. The claim holders used an excavator and dump trucks to mine the ore and waste, and a loader to feed the on-site crushing and sorting station where the final crushed chlorite ore was produced. In 1984, as demand for chlorite products increased, Cyprus hired a heavy equipment contractor to perform mining activities on a seasonal basis. The same contractor also assisted with closure and reclamation. All Antler ore was trucked to the Three Forks mill, a distance of 30 miles (48 km).

Mining was conducted from October through April of each year, with no mining or hauling activities allowed during the summer months according to the permit agreement with the U.S. Bureau of Land Management. This schedule was developed to accommodate the increased tourist traffic along a nearby highway during the summer as well as seasonal residents who return to the area each summer. Off-season contract rates were negotiated with the mining contractor who concentrated on highway and other construction jobs in the summer months.

Mining was conducted using 20-foot (6 m) benches, primarily to match the reach of the excavator that was used to selectively mine the ore (figures 3 and 4). Most of the ore occurred in three parallel, near-vertical, north-south trending veins (figure 5). These veins ranged from less than 10 feet (3 m) to almost 30 feet (9 m) wide, with a zone of waste typically 15 to 25 feet (5-8 m) wide between the veins. An Ingersoll Rand, air-track drill was used for drilling both the ore and waste. On each consecutive bench the veins of ore were drilled first on a 6-foot by 8-foot (1.8 m by 2.4 m) pattern with $3^{1}/_{2}$ -inch diameter (8.9 cm) holes. Only those holes intersecting ore were shot when the vein was drilled out.

An excavator with a $2^{3/4}$ -cubic yard (2.1 m³) bucket was used to selectively mine the ore. Because the contact be-



Figure 3. View looking south at the Antler mine showing cut where the thickest chlorite vein is being mined.

tween the chlorite veins and sericitic waste rock was sharp, chlorite would break cleanly from the walls when mined. The experience and skill of the excavator operator were critical to selectively excavate two grades of ore, as well as waste, from the cut.

Ore was mined and stockpiled in two grades that also determined the type of sorting that would be required to produce a quality finished product. Shed-sort or high-grade ore



Figure 4. Selective mining of chlorite vein at Antler mine (behind cab of excavator) with massive gneiss on both sides of the vein.



Figure 5. Simplified map of Antler mine prepared by Luzenac America, Inc., March 1999. Chlorite veins are shown in black. Contour interval is 10 feet.

contained greater than 90 percent chlorite vein material, which was itself greater than 98 percent chlorite.

All high-grade ore was fed to a sorting building on site where a team of three to four sorters manually separated the non-chlorite waste from the chlorite vein ore (figure 6). The chlorite ore readily broke into 12-inch (31 cm) pieces as a result of blasting and handling. A loader fed ore into a 12inch (31 cm) grizzly that fed a vibrating screen unit. For the shed-sort ore, a $1^{1/2}$ -inch (3.8 cm) screen was used with the $+1^{1/2}$ -inch (+3.8 cm) material passing onto a conveyor where water sprayers cleaned the rock and enhanced the visual contrast between the green chlorite and white waste rock. The washed rock entered the enclosed sorting shed where the sorters pulled the waste rock off into side bins that fed into a containment area at ground level. The chlorite ore continued off the end of the belt into a separate containment area.

Sorting of this ore typically produced 300 st (270 mt) of upgraded ore product per day. The ore was removed from the containment area by loader and fed into a jaw crusher that reduced the ore to -6 inch (-15 cm). The product was stockpiled in this form and was hauled by truck to the mill in Three Forks.

The secondary ore that was mined and sorted was pitsort or lean ore. This grade of ore contained between 40 percent and 90 percent chlorite vein material and was segregated from the shed-sort ore in separate stockpiles during mining. This ore was fed to the sorting shed when shed-sort ore was unavailable. The ore was fed to the sorting plant in the same fashion as shed-sort ore, except a 3-inch (7.6 cm) screen was used. When the +3 inch (+7.6 cm) material entered the sorter building, the sorters pulled off the chlorite vein material and allowed the waste to pass off the end of the belt. Sorting of pit-sort ore typically produced 150 st (140 mt) of product per day.

The $-1^{1/2}$ inch (-3.8 cm) screenings from shed-sort ore processing were retained and stockpiled. Because the quartz-sericite waste did not typically end up in the $1^{1/2}$ -inch (3.8 cm) fraction, the screenings were nearly all chlorite vein material and commonly made product grade. Composite Total production of sorted chlorite product from the Antler mine was approximately 250,000 st (230,000 mt) in its short life, 1976-1999. Dozens of other chlorite prospects in the western U.S. have been evaluated as a replacement for the Antler ore body. None has been found with the same uniform, massive veins of nearly pure microcrystalline chlorite, with low iron content.

Processing

All of the Antler chlorite products sold in North America were milled at the Three Forks mill. This accounted for about half of the annual chlorite production from the Antler mine. The balance of the Antler crude ore was shipped to a Luzenac mill in Ghent, Belgium for European chlorite customers. Four grades of chlorite product were ground at Three Forks, either in a roller mill or fluid-energy mill. The particle size distribution of the products ranged from 200 mesh to 600 mesh. Chlorite products were typically shipped in either 50 pound (20 kg) bags or super sacks.

Markets

Most of the Antler chlorite sold in North America was used either in ceramic or paint applications. Chlorite possesses many physical properties comparable to talc, yet is unique in some important physical and chemical characteristics. It is a platy mineral that is hydrophyllic (as compared to talc which is hydrophobic) and relatively low in oil absorption. There is no direct mineral competitor for chlorite either mined or sold in North America. In paint and industrial coating applications, chlorite provides many cost-effective benefits as well as demonstrable advantages over other



Figure 6. Sorting chlorite ore at the Antler mine.

pigments in both processing and product. Chlorite has similar binder demand and viscosity characteristics to calcium carbonate of the same grind, and allows for higher loading in low VOC (volatile organic compounds) paint formulations. Chlorite outperforms calcium carbonate as a TiO₂ spacer in latex paints. Because of its acid resistance, chlorite performs well in primers and corrosion resistant coatings. Chlorite also produces better flatting and higher opacity than calcium carbonate. The median particle size for products used in paints and coatings ranges from 9 μ m down to 1.8 μ m. Depending on grind, the brightness of Antler chlorite products was as high as 90 GEB (General Electric Brightness).

In ceramic applications, Antler chlorite provided a unique, naturally occurring high alumina source. The typical chemical analysis for Antler chlorite is 22 percent Al_2O_3 , 32 percent SiO₂, and 30 percent MgO, with less than 5 percent Fe₂O₃. It worked well as a raw material for cordierite refractories that require low thermal expansion and good thermal shock resistance. In cordierite bodies, a high-temperature, solid-state reaction occurs between clay, chlorite, and pure alumina during the firing process. Antler chlorite was utilized in this process because the alumina in the chlorite reacts at a lower temperature than pure alumina, thus saving cost in the firing process.

Reclamation and Closure

The Antler mine is located within a block of unpatented claims on U.S.Bureau of Land Management (BLM)-administered land. As a result, the Antler mine is regulated by both the BLM and Montana Department of Environmental Quality (DEQ) for permitting and reclamation issues. Luzenac has maintained a closure plan for the Antler mine that has been reviewed and approved by both the BLM and DEQ. Over the past several years Luzenac initiated a progressive reclamation plan with the goal of completing most of the required reclamation by the time mining and sorting of the ore was completed. As of spring 1999, Luzenac had recontoured and seeded the south dump, recontoured the northwest dump, and completed the majority of required recontouring on the exposed south face of the north dump that will remain open as a rip rap source for the BLM.

As dumps and roads were developed on site, top soil was isolated and stockpiled for eventual redistribution over the reclaimed dumps. The original surface around the Antler mine is a barren, rocky, semiarid landscape that only supports sparse grasses and vegetation. Luzenac has worked with DEQ to identify seed mixtures based on hardy local varieties and will seed the reclaimed and re-soiled areas with that mixture as reclamation nears completion. Luzenac will also be responsible for weed management over the next few years until the planted grasses have become well established.

Reclamation of the pit area involves distribution of topsoil on the ramps and remaining benches and seeding to stabilize the soils. Berms and fences in and around the pit will prevent access and provide a safety barrier. Modular buildings and equipment will be removed and relocated to the Yellowstone mine (a major talc mine in southwestern Montana also owned by Luzenac). All other buildings and foundations will be demolished and removed from the site. Postclosure monitoring will consist of sampling and analysis of two on-site wells. No surface water occurs on the property or within the mine.

GEOLOGY

Regional Geology

Archean metamorphic rocks of the Wyoming province are exposed throughout the mountain ranges of southwestern Montana. Regional metamorphism produced a sequence of predominately amphibolite facies rocks about 2.7 Ga (James and Hedge, 1980). Common metamorphic rocks are dolomitic marble, calcitic marble, quartzite, schist, amphibolite, and various gneisses; some of igneous protolith. Dolomitic marble within this metamorphic sequence hosts the economically important talc deposits mined in southwestern Montana. Chloritic alteration associated with talc mineralization is found where aluminum-bearing rocks such as quartzofeldspathic gneiss or schist occur adjacent to dolomitic marble. However, these chlorite occurrences do not exhibit the high purity and low iron content typical of chlorite from the Antler mine. Precambrian metamorphic rocks exposed on the southeast flank of the Highland Mountains consist mainly of gneisses. Uranium-lead determinations on zircons separated from these gneisses suggest metamorphic growth at about 1.8 Ga, perhaps related to early Proterozoic deformation (O'Neill, Duncan, and Zartman, 1988). Mafic dikes and sills intruded these rocks during the Proterozoic. Numerous scattered occurrences of chlorite occur in the Rochester mining district south of the Antler mine (figure 1), but none represents a minable ore body. Much of this chloritic alteration occurs along two major northwest-trending faults, the Twin Bridges fault and the South Rochester fault. O'Neill and others (1986) cite evidence for recurrent movement along these faults beginning in the Proterozoic and continuing with reactivation in the late Tertiary and Quaternary. Although some alteration in the Rochester district is associated with metalliferous veins, most veins lack this chloritic alteration.

Geology of the Antler Mine

The geology of the Antler mine is simple in general appearance, but complicated in detail. The vertical dimension of the major veins is 300 feet (90 m) and the strike length is 500 feet (150 m) (figure 5). Toward the margins of the chlorite mineralization zone, chlorite veins pinch out and virtually no chlorite mineralization occurs except for a thin chlorite veinlet that extends south from the pit. At the margins of the pit, the biotite gneiss host rock displays propylitic alteration, demonstrated by the replacement of biotite with chlorite. Only occasional, minor chlorite veins are noted within the gneissic parent rock.

A mafic dike cuts nearly east-west across the north-south trending chlorite veins approximately 150 feet (46 m) south of the northern limit of the pit. This dike appears to be younger than chlorite mineralization and has created a halo of brown chlorite accompanied by elevated levels of mica within the intersected chlorite veins. Chlorite within 5 feet (2 m) of the dike was typically not retained for sorting. The dike dips steeply, and irregularly, to the north and occasion-ally contains rusty red to brown oxidized zones.

Within the zone of chlorite mineralization, between the eastern and western veins, there is little rock that is readily identified as biotite gneiss. The majority of the rock adjacent to the chlorite veins is sericitically altered with a pale green to white appearance. The contact between the chlorite vein and sericitic waste is very sharp and the rock readily separated along this contact during mining.

The three major chlorite veins typically trended northsouth and were essentially vertical, except for the lowermost 120 feet (37 m) exposed during mining where the dip lessens and the strike shifts to the northwest. The central and primary chlorite vein is controlled by a shear zone or fault through the middle of the current pit. This vein was at least 30 feet (9 m) wide through most of its projection and is cut off by the intersection of two faults at the north end. To the south, the central vein pinches down to 18 inches (46 cm) before it disappears under surficial cover. The central vein contained most of the recovered ore and was the primary control feature in designing the mine plan. Drill results showed no chlorite mineralization deeper than 100 feet (30 m) below the final mining level. Within the final bench at the 4,640-foot (1,410 m) elevation, only one-third of the central vein contained minable chlorite ore.

The eastern and western veins were typically less than 25 feet (7.6 m) wide and paralleled the central vein at a distance of 40 to 50 feet (10 to 20 m). Faulting, that undoubtedly controlled the mineralization of these two peripheral veins, is not obvious. Both of these veins pinch out within the confines of the pit. The south end of the eastern vein was enriched in mica in the lower portion of the pit, but the remainder of the chlorite from these veins was comparable to that from the main vein.

Chlorite mined at the Antler mine is the IIB polytype of clinochlore, the magnesian variety of chlorite (table 1). It is green gray (5G6/1) in hand specimen and breaks into platy fragments that are almost colorless when examined on a thin edge with a hand lens. Rutile, zircon, limonite, and sericite are trace constituents. Chlorite veins and pods are surrounded by an alteration envelope. Propylitic alteration, recognized by a faint greenish cast of the quartzofeldspathic gneiss and characterized by chlorite, epidote, and albite, is most distant from the chlorite veins (figure 7). This diffuse alteration grades into a sericitic zone which is light in tone and characterized by alteration of the feldspars to sericite. Near the chlorite vein, sericite is replaced by chlorite to form a rock in which relict quartz porphyroblasts retain the original gneissic texture (figure 8A).

Table 1. Chemical analyses of chlorite from the Antler mine given in weight percent (Berg, 1986).				
Specimen No.	3968	4056		
SiO ₂	29.79	29.93		
TiO2	0.21	0.22		
A12O3	22.03	21.83		
Fe2O3	1.03	0.78		
FeO	1.95	2.55		
MnO	0.07	0.08		
MgO	29.49	29.80		
CaO	0.09	0.11		
Na2O	0.09	0.03		
K2O	0.16	< 0.01		
P2O5	0.05	< 0.05		
H20+	13.6	13.5		
H2O-	0.04	< 0.01		
Total	98.6	98.99		



Figure 7. Alteration sequence at the Antler mine.



Figure 8. Photomicrographs taken with crossed polars of thin sections from the Antler mine; A shows alteration of quartzofeldspathic gneiss next to chlorite vein where feldspars and biotite have been replaced by chlorite leaving relict quartz porphyroblasts; B shows chlorite veins with irregular patches of coarse-grained chlorite (white) in finegrained chlorite (black).

Further alteration leads to the replacement of quartz to form a rock that consists essentially of chlorite. This chlorite is very fine grained with most grains less than 2 μ m, but cut by microveinlets and irregular patches of coarser-grained chlorite (figure 8B). The transition from the zone of sericitic alteration to the chlorite vein is abrupt, with complete replacement of the gneiss taking place over just a few millimeters.

Origin of the Deposit

Chloritic alteration is widespread in Archean metamorphic rocks of southwestern Montana, but in spite of a considerable amount of prospecting for this mineral, the Antler deposit is the only minable deposit of high-purity chlorite that has been found. Some generalizations can be made about chlorite occurrences in southwestern Montana that may help in understanding the formation of the Antler deposit.

With the exception of a few chlorite veinlets in metasedimentary rocks of the Proterozoic Belt Supergroup, chlorite occurrences are limited to the Precambrian basement. Small chlorite veinlets occur in the LaHood Formation of the Belt Supergroup, both on the southwest flank of the Tobacco Root Mountains and in Jefferson Canyon, 25 miles (40 km) northeast of the Antler mine. Along Camp Creek on the southwest flank of the Tobacco Root Mountains, a quartz-chlorite vein is abruptly truncated by the unconformity between the Archean metamorphic rocks and the overlying Middle Cambrian Flathead Sandstone. Field evidence indicates that chloritic alteration throughout southwestern Montana is younger than the amphibolite-facies metamorphism of the Precambrian basement, and as described above, older than the Middle Cambrian Flathead Sandstone, and older than the mafic dike exposed at the Antler mine. Although this dike has not been dated, it is presumably of Proterozoic age, as are similar dikes in Archean metamorphic rocks exposed 20 miles (30 km) southeast in the Tobacco Root Mountains (Wooden and others, 1978).

The same age constraints have been suggested by numerous authors for talc deposits in southwestern Montana. An often-stated argument for Precambrian talc formation is the absence of talc in Paleozoic carbonate formations in southwestern Montana, even though these rocks are exposed in the same areas as talc-bearing Precambrian basement rocks. Although Berg (1983) initially suggested that the Antler chlorite deposit was related to the Cretaceous/Tertiary Rader Creek and Hell Canyon plutons, it now seems more plausible that chlorite formation in this area is Proterozoic. Also, it seems most likely that chlorite formation, including that at the Antler mine, was part of the talc-forming event that affected southwestern Montana. Where aluminum was available in the metamorphic rocks (such as gneiss and schist) alteration to chlorite occurred, whereas in the aluminum-deficient marble, talc was formed. Anderson and others (1990) indicate that the replacement of marble by talc required not only the addition of SiO₂ and H₂O, but also Mg to maintain constant volume during talc formation. Constant volume replacement is indicated by the preservation of metamorphic textures and the formation of pseudomorphs of talc after metamorphic minerals. Although they studied talc deposits in the Ruby Range 45 miles (72 km) south of the Antler mine, their conclusions and observations probably apply to most, if not all, of the talc deposits in southwestern Montana.

In addition to lithologic control on talc and chlorite formation in southwestern Montana, structural control is impor-

tant, particularly for chlorite formation. As shown in figure 1, chloritic alteration in the Rochester district is concentrated along two northwest-trending faults. Some 60 miles (100 km) southeast of the Antler mine, chlorite occurrences have been recognized along the range-front Sweetwater fault (Berg, 1996). More to the point, two north-northwest-trending faults are exposed at the Antler mine, and it seems very likely that they controlled formation of this deposit (O'Neill and others, 1996). At the present stage of our understanding of chlorite formation in southwestern Montana, we conclude that the Antler deposit formed during the Proterozoic by the introduction of magnesium-bearing fluids controlled by steeply inclined faults. The introduction of a substantial quantity of magnesium was obviously necessary to alter quartzofeldspathic gneiss that contains only 0.6 percent MgO in the vicinity of the deposit to a magnesian chlorite that contains more than 29 percent MgO (table 1). The source of this magnesium is somewhat hypothetical. The Proterozoic Belt sea that covered much of western Montana and northern Idaho has been suggested as the most likely source of magnesium (Anderson and others, 1990).

The explanation for the location and unusual concentration of chlorite at the Antler mine is less than obvious. A comparison of Antler chlorite to that found along the South Rochester and Twin Bridges faults shows that chlorite along these faults is less uniform. At many localities along these faults, feldspars and mafic minerals in the gneiss have been altered to chlorite, leaving quartz unreplaced to form a quartz-chlorite rock. The Antler mine is the only deposit where a relatively large volume of gneiss has been completely replaced by chlorite. A possible explanation for this difference is that the faults at the Antler mine are much shorter than either the South Rochester or Twin Bridges faults, which are 11 miles (18 km) and 40 miles (60 km) long respectively (O'Neill and others, 1996). The faults at the Antler mine are exposed for 0.3 mile (0.5 km), but could extend for another 1.2 miles (1.9 km) under a cover of Tertiary sediments. Clearly, the faults at the Antler mine are much shorter than either the South Rochester or Twin Bridges faults. Perhaps, because of this difference in fault length, hydrothermal fluids were more confined along these much shorter faults at the Antler mine and thus alteration was more intense here than along the northwest-trending faults in the Rochester district.

ACKNOWLEDGMENTS

The many courtesies extended to us over the years by Mr. Robert Nolte and Mr. Sylvan Donegan, the owners of this deposit, are sincerely appreciated. We also thank the management of Luzenac America, Inc. for allowing us to publish this paper.

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ISSUES AFFECTING DEVELOPMENT OF NATURAL AGGREGATE NEAR ST. GEORGE AND SURROUNDING COMMUNITIES, WASHINGTON COUNTY, UTAH, USA

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ABSTRACT

To help local governments plan for long-term supplies of sand and gravel for buildings and infrastructure, the Utah Geological Survey is assessing natural aggregate resources (mainly sand and gravel) in the St. George, Utah area. Whereas much of the aggregate in the study area is adequate for road-base construction, high-quality aggregate for Portland cement concrete is limited due to geology, and also due to land administration and environmental issues. Virgin River alluvial gravels southwest of St. George are generally poor sources of aggregate because they contain clasts of soft sediments and soluble minerals derived from Mesozoic rocks. Elsewhere, widespread secondary calcium carbonate (caliche), as rinds and matrix in gravel, lower the quality of material.

Young river-terrace deposits in Fort Pearce Wash, and along the Virgin River above St. George are the primary sources of sand and gravel for the area. Alluvial fans on the east side of the Beaver Dam Mountains, and on the west side of the Hurricane Cliffs are also sources of aggregate. Stream-channel deposits associated with "inverted valleys" north of the towns of St. George and Hurricane, Utah, and older pediment gravels on the west flank of the Beaver Dam Mountains may be future sources of high-quality aggregate.

Accelerated urban development during the 1980s and early 1990s has caused St. George and other communities in Washington County to encroach upon sand and gravel pits originally located in rural, undeveloped areas. Urban residents often view nearby sand and gravel operations as undesirable neighbors and pressure elected officials to close the pits. Pit closures effectively eliminate the remaining reserve from the sand and gravel resource base of the area. Moreover, resources may also be lost as new homes are built upon undeveloped sand and gravel deposits.

The St. George area is particularly susceptible to loss of aggregate resources because high-quality natural aggregate for construction is already in short supply. Moreover, most of the land in the study area is administered by the U.S. Bureau of Land Management and subject to various land-use restrictions. Much of this public land cannot be developed for mineral materials, such as sand and gravel, because of federal regulations protecting rare plants and animals, archaeological sites, and important watershed areas. Of particular concern to resource development are areas designated as Areas of Critical Environmental Concern, Wilderness Areas, and Wilderness Study Areas. Protection for Endangered Species is a critical element in all planning efforts. Those species present in the St. George area or in areas nearby include: the desert tortoise, southwestern willow flycatcher, Virgin River chub, and dwarf bearclaw poppy.

As the St. George area is depleted and/or deprived of sand and gravel resources through extraction and urbanization respectively, construction costs will rise unless conservation measures are instituted. To avoid the loss of aggregate resources, the UGS is pursuing a program of data gathering and field surveying of surficial deposits to determine tonnage and quality of the remaining sand and gravel resources. The resource information from this program will help land planners, developers, and government officials make informed decisions concerning urban development throughout the region.

INTRODUCTION AND BACKGROUND

As seen throughout the United States, urban growth diminishes the area available for natural aggregate resource mining necessary for continued community economic development (Beeby, 1988; Mikulic, 1995). With growth, increasingly large amounts of aggregate are required for building roads, parking lots, houses, and other structures. As new structures are built atop potential aggregate resources, access to those resources is lost, and aggregate is effectively removed from the resource base. This situation inevitably requires communities to haul aggregate longer distances, which increases the cost of future development.

In the early 1970s, the construction aggregate industry of California experienced backlash from its own success as accelerated urban growth created land-use pressures that caused the premature closure of pits and quarries at the urban fringe. Following the release of an urban-geology master plan by the California Division of Mines and Geology (CDMG) (Alfors and others, 1973), the State of California inventoried aggregate resources in metropolitan regions of California. The findings startled land-use planners. The CDMG estimated that \$17 billion worth of resources, primarily construction aggregate, would be excluded from mining by the year 2000 if existing land-use practices were continued. The CDMG also estimated 90 percent of this loss was preventable if economic geologic data, compiled in a systematic, resource-deposit inventory, were used in the local planning process. Consequently, the California Surface Mining and Reclamation Act of 1975 (SMARA), incorporating the master-plan recommendations, was passed into law. Under SMARA, nearly 50 billion short tons (45 billion metric tons) of high-quality aggregate resources in 15 regions were identified by 1988 and designated "regionally significant," giving those deposits a level of protection from urbanization previously unavailable (Beeby, 1988).

Utah is now experiencing this same type of accelerated growth. In order to avoid future shortages of low-cost aggregate for construction, local, federal, and state government agencies will need to coordinate efforts to identify and conserve sand and gravel resources, particularly in resourcepoor regions.

Rapid urban expansion has resulted in a significant loss of aggregate resources in St. George, Utah and surrounding communities. These communities had relatively little highquality aggregate available initially, and mineable reserves were further restricted by institutional requirements and environmental laws. In the summer of 1995, the Utah Geological Survey (UGS) began a study of the availability of natural aggregate in the St. George region, starting with informal meetings with personnel from the Utah Department of Transportation (UDOT), Washington County Planning Department, and U.S. Bureau of Land Management (BLM). Workers in other government agencies had also recognized conflicts between rapid urban growth and the continuing need for construction aggregate. Areas protected under the Endangered Species Act of 1973 as amended (ESA) and lands withdrawn for wilderness or other preservation also became a major issue in southwestern Utah as uses, including mining of aggregate, are restricted, or in many cases prohibited in these protected areas.

Purpose and Scope

The goal of the UGS study is to delineate all known deposits of good-quality aggregate, and identify areas where potentially high-quality resources may occur. The first phase of the UGS study involves compiling information on individual sand and gravel pits, surficial geology, land-status issues, and protection zones for both endangered and candidate species. Initially, the study area included all of Washington County. However, the first phase was later limited to the area covered by the St. George and Hurricane 15-minute quadrangles (figure 1) in order to remain within a manageable scope. Depending on funding and personnel resources, this phase will identify target areas for later, detailed geologic field mapping, surveying, and deposit sampling.

Location, Physiography, and Climate

St. George is a city of about 40,000 people located in extreme southwestern Utah. The population of the area exceeds 65,000 when the surrounding communities are included. Interstate Highway 15 connects St. George with Las Vegas, Nevada, 117 miles (188 km) to the southwest, and Salt Lake City, Utah, 303 miles (488 km) to the north. The St. George basin, the area included in the first phase of the study, is a low-lying region surrounding the Santa Clara and Virgin River Valleys (figure 1). The study area is near the west margin of the Colorado Plateau, just southeast of the Basin and Range-Colorado Plateau Transition Zone (Stokes, 1977). Geographic boundaries are the Pine Valley Mountains and Bull Valley Mountains to the north, the Beaver Dam Mountains to the west, and the Hurricane Cliffs to the east. The Utah-Arizona state line forms the southern boundary about 6 miles (10 km) south of St. George.

The Virgin River is the principal drainage of the Kolob Terrace, a highland region north and east of the Hurricane Cliffs that includes part of Zion National Park. The main stem of the Virgin River flows into the study area from the east, cutting through the Hurricane Cliffs. Many tributary streams drain the southeast flanks of the Pine Valley Mountains, flowing southward into the Virgin River. The Virgin River flows southwest out of the study area and has cut a deep gorge (Virgin River Gorge) through sedimentary rock formations southwest of St. George. From there, the river flows into Lake Mead along the Arizona-Nevada border.

The Santa Clara River drains the west and southwest flanks of the Pine Valley Mountains, the southeast flank of the Bull Valley Mountains, and the west flank of the Beaver Dam Mountains. This river flows into the study area from the northwest and joins the Virgin River just south of St. George.

The climate of St. George is temperate, with a mean annual temperature of 61.1° F (16.2° C), or about 8° to 15° F (4.4° - 8.3° C) warmer than other parts of Utah. For example, the mean annual temperature for Salt Lake City is 51.3° F (10.7° C). Average annual precipitation for St. George is 7.8 inches (19.8 cm) (Greer and others, 1981).

The area is surrounded by abundant natural beauty that includes desert ecosystems and spectacular landforms and vistas. Moreover, the region is relatively pollution free.

SOCIOECONOMIC CONDITIONS

The warm climate, clean environment, and surrounding natural beauty have led to changes in the economy of the area. The traditional mining/agriculture-based economy has changed to a more trade/service-based economy over the past decade, supporting retirement communities, recreation activities, and tourism.

The population of Washington County, centered around St. George, increased nearly 201 percent between 1980 and 1998, making it one of the fastest growing counties in Utah (Utah Governor's Office of Planning and Budget, 1999). The Utah Governor's Office of Planning and Budget (1999) reported the 1998 population to be 79,831, and projected additional growth of 122 percent by the year 2020 (table 1).

Table 2 compares economic sectors in Washington County and shows a shift from resource-based to servicebased employment between 1980 and 1997 (U.S. Bureau of Economic Analysis, 1999). The largest sectors of the Washington County economy are services (legal, personal, professional, and others) and trade (wholesale and retail). The services and construction sectors account for the largest percentage increases in economic activity over the same 17-year period. Construction-sector employment increased by 34 percent and now accounts for almost 12 percent of the total county economy. The construction sector consists of building construction (by general contractors or operative builders), heavy construction (other than building by general contractors and special trade contractors), and construction activity by other specialized-trade contractors (Duffy-Deno and Brill, 1995).

GEOLOGIC SETTING

Regional Structure

The St. George area lies within a zone of structural tran-



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Figure 1. Location map of the study area showing geographic features, principal rivers, and geologic structures.

Table 1.

Human population projections for Washington County, (calender year end) 1990 to 2020 (Utah Governor's Office of Planning and Budget, website www.qget.state.ut.us.programs).

Year	Total	PercentChange	Year	Total	Percent Change
1990	49,100	_	2006	111,120	9.0
1992	55,004	12.0	2008	120,537	8.5
1994	63,403	15.3	2010	130,529	8.3
1996	72,861	14.9	2012	140,496	7.6
1998	79,831	9.6	2014	150,314	7.0
2000	86,222	8.0	2016	159,589	6.2
2002	93,388	8.3	2018	168,572	5.6
2004	101,917	9.1	2020	177,570	5.3

This projection is based on the Utah Process Economic and Demographic Model, which projects population and employment growth in the state based upon analysis of births, deaths, in/out migration, and economic activity.

Summary of activity	by major econor 1980	and 1997.	shington Count	ty between
Economic Sector	conomic Sector Employment		Earnings	
	1997	Percent	1997	Percent
	Percent	Change	Percent	Change
	Total	·80-·97	Total	'80-' 9 7
Agriculture	3.5	-66.0	3.5	-34.0
Mining	0.5	-37.5	.7	-75.0
Construction	11.9	33.7	7.0	14.8
Manufacturing	6.1	-22.8	10.9	-16.8
TCPU	4.4	22.7	4.9	7.5
Trade	27.1	5.0	22.0	2.8
FIRE	8.4	-20.8	7.8	5.4
Services	28.3	58.1	29.7	44.9
Government	10.8	-41.0	14.6	-27.4

sition between generally flat-lying sedimentary rocks to the east, typical of the Colorado Plateau, and fault-bounded mountain blocks to the west, characteristic of the Basin and Range Province. Within the St. George basin, sedimentary rocks are gently folded along northeast-trending axes. The Virgin anticline trends northeastward across the basin, extending from about 5 miles (8 km) south of St. George northeastward for more than 20 miles (32 km). The anticlinal fold is warped, and forms three doubly plunging anticlines respectively referred to as the Bloomington, Washington, and Harrisburg domes (figure 1).

The basin is bounded on the east by the prominent westfacing Hurricane Cliffs, which form the hanging wall of the Hurricane fault. The Grand Wash fault, mapped by Hammond (1991) west of the St. George basin, is en echelon with the Hurricane fault and was suggested by Longwell (1952) to be the west edge of the Colorado Plateau in Arizona. The block between these two faults dips gently to the northeast (Petersen, 1983) (figure 1).

Sedimentary Stratigraphy

Paleozoic sedimentary rocks are exposed in the Beaver Dam Mountains, Virgin River Canyon, and the Hurricane Cliffs. In the Beaver Dam Mountains, more than 13,000 feet (4,000 m) of Cambrian through Permian quartzite, shale, and carbonate formations rest unconformably on Precambrian schist, gneiss, and pegmatite (Hammond, 1991). The Permian Kaibab Formation is exposed extensively south-eastward from the Beaver Dam Mountains through the Virgin River Canyon. The Permian Toroweap and Kaibab Formations crop out along the Hurricane Cliffs.

Sedimentary rocks exposed in the study area are mainly Mesozoic units, and have a combined thickness of about 19,000 feet (5,800 m) (figure 2). These rocks include the Triassic Moenkopi Formation, and Shinarump and Petrified Forest Members of the Chinle Formation; and the Jurassic Moenave Formation, Kayenta Formation, Navajo Sandstone, and Carmel Formation (Cook, 1960; Hintze, 1988; Higgins



Figure 2. Stratigraphic column for the St. George basin and surrounding area (generalized from Hintze, 1988, charts 94 and 96). Unit thicknesses are in feet.

and Willis, 1995; Hamblin, unpublished maps). Triassic and Lower Jurassic rocks (Moenave and Kayenta Formations) are primarily fine-grained clastic deposits of pluvial/marginal marine origin. The massive eolian Navajo Sandstone overlies the Kayenta Formation, and marine deposits of the Middle Jurassic Carmel Formation, in turn, unconformably overlie the Navajo Sandstone.

Cenozoic Igneous Rocks

Oligocene and Miocene calc-alkaline ash-flow tuffs, erupted from calderas in southern Nevada, are widespread in the northwestern part of Washington County in the Bull Valley Mountains, and in the northern part of the Pine Valley Mountains (Best and others, 1987). Grant (1991) described the igneous mass of the Pine Valley Mountains, separating it into an upper extrusive latite and a lower intrusive monzonite, both of Miocene age. The Pine Valley latite is a complex of flows and domes as much as 1,600 feet (490 m) thick. The Pine Valley monzonite, thought to be either a sill or a laccolith, is about 1,000 feet (300 m) thick (Grant, 1991). Blank (1959) showed that a similar pluton occupies the core of an eruptive center in the Bull Valley Mountains.

Cenozoic volcanic rocks in the study area are mostly Pliocene dacite and basalt, and Pleistocene and Holocene basalt. Hamblin (1970) provided a classification and estimated ages of these units based on relative elevation of flows and potassium-argon dating. Basalt flows originating from vents in and around the southern flanks of the Pine Valley Mountains flowed south down paleovalleys toward the St. George basin. The flows eventually cooled and solidified. The solidified flows diverted drainages, causing erosion and downcutting in less resistant sedimentary rock. This process was repeated several times over the past two million years, resulting in many long, narrow, basalt-capped sinuous ridges called inverted valleys (Hamblin, 1970). Successively younger basalt flows filled the new valleys, and now older flows lie topographically above younger flows (figure 3).

Unconsolidated and Semi-Consolidated Material

Cook (1960) described Quaternary sediments in general terms throughout Washington County, and categorized them as old pediment gravels and young alluvial channels. He described older gravels as generally coarse, poorly sorted, and commonly occurring at higher elevations than younger alluvial deposits. He described younger deposits as forming "narrow alluvial strips, bars, and benches in modern valleys." Cook (1960) lumped both deposit types into one map unit.

Christenson and Deen (1983) separated Quaternary sediments on the basis of grain size and age, and discussed the availability of construction materials (sand and gravel) in the St. George area. Channel and flood-plain deposits of the Santa Clara and Virgin Rivers and their tributaries are principally sand with varying percentages of gravel, silt, and clay. Eolian sand deposits are scattered throughout the study area. Christenson and Deen (1983) delineated older Quaternary gravel terraces at several levels above modern channels, mostly associated with the Santa Clara and Virgin Rivers, and Fort Pearce Wash.

Hamblin (unpublished maps) prepared fairly detailed geologic maps of the St. George (west half of figure 4) and Hurricane (east half of figure 4) 15-minute quadrangles. He divided surficial deposits into four categories based on relative age, elevation, and association with the present drainage system (table 3). The two youngest mapped units are streamchannel and flood-plain deposits, and the two older mapped units consist of Holocene, Pleistocene, and Pliocene alluvialterrace gravels positioned at levels high above present stream channels. The older deposits commonly do not appear associated with present drainage systems, and may be equivalent in age to the older, inverted valleys capped by Hamblin's (1970) stage I, basalt flows. Surficial deposits have been differentiated into dozens of units by recent workers mapping geology at a scale of 1:24,000 (Higgins and Willis, 1995; Willis and Higgins, 1995, 1996; Biek, 1997, 1998; Higgins, 1997, 1998, 2000). For ease of presentation at our smaller map scales, surficial deposits discussed herein mostly follow the simpler descriptions by Hamblin (unpublished data).



Figure 3. Northward view from Webb Hill across St. George and Virgin River valley. The Pine Valley Mountains are seen in the upper right. Outcrops in the foreground are the Shinarump Member of the Chinle Formation. Outcrops on the north side of the valley are part of the Kayenta Formation. A sinuous, erosional surface extending southward from the Pine Valley Mountains is the Middleton flow, a poorly dated basalt probably a few hundred thousand years old.



Figure 4. Surficial geology map of the study area. Symbols for the various geologic units are explained in table 3. Geologic contacts are based upon the mapping of Hamblin (unpublished maps). Some of Hamblin's units are combined for presentation purposes.

Description	Table 3. Description of surficial deposits and basalt flows in the St. George and Hurricane 15-minute quadrangles (after Hamblin, unpublished data). Map symbols correspond to units shown on figure 4.		
MAP SYMBOL	DESCRIPTION OF GEOLOGIC UNIT		
Qa:	Holocene alluvium. Sand and minor gravel and mud deposited in stream channels and adjacent flood plain.		
Qb:	Holocene basalt flows and cinder cones. Dense, black olivine basalt flows that retain original flow structures. This basalt comprises the Santa Clara flow, which originated at two cinder cones just northeast of Snow Canyon and flowed down (south ward) Snow Canyon to the Santa Clara River. Although there are no definitive age-estimates, Hamblin (1970) suggests that the Santa Clara flow may be as young as 1,000 years.		
	Pleistocene basalt. Medium-grained basalt flows extruded onto a pediment. Basalt slightly modified by weathering and ero- sion.		
Qt:	Holocene and late Pleistocene alluvial terraces. Low-level, approximately 23 feet (7 m) above the present drainage. Sand and gravel deposited in stream channels, and in alluvial fans. Most deposits are in strike valleys eroded into the Chinle, Moenave, and Moenkopi Formations, and in depressions on downthrown blocks. Includes minor colluvium.		
QTt:	Pleistocene and Pliocene high-level alluvial terrace deposits. Gravel and sand preserved in stream terraces up to 200 feet (60 m) above present stream channels. Deposits are as much as 100 feet (30 m) thick.		
	Alluvial terrace deposits (Early Pleistocene and Pliocene). Gravel and sand capping the highest terraces not obviously associated with present drainage systems. These deposits are probably equivalent in age to the oldest and highest inverted valleys capped by Tertiary basalt.		
Tb:	Younger Tertiary basalt. Black to medium gray, vesicular basalt flows which form inverted valleys as high as 230 feet (70 m) above the present drainage. Most flows were extruded near the base of the Pine Valley Mountains and flowed southward toward the Virgin River. Upper flow surfaces are smooth, flat, and covered by well-developed soils.		
	Older Tertiary basalt. Dense, black, vesicular basalt flows preserved as segments of dissected inverted valleys as high as 660 feet (200 m) above the adjacent drainage. Original margins and surface features are destroyed by weathering and erosion.		

SUITABILITY OF AGGREGATE MATERIALS

Known Aggregate Sources

The Utah Department of Transportation (1966) prepared an inventory of aggregate pits and quarries for Washington County that included material test data for representative samples. The UDOT study provides a basis for assessing the suitability of material mainly for highway construction. Considerable quantities of aggregate suitable for roadbed construction are present in the St. George area, but sources of concrete aggregate are much less common. Most source areas contain unsuitable clasts of either silicic volcanic rocks, or sedimentary units with soft or soluble minerals. The quality of gravel deposits along the Santa Clara and Virgin Rivers, and Fort Pearce Wash is variable, although most deposits are suitable for use in roadbeds and asphalt. Clasts in these deposits tend to be coated with calcium carbonate and the deposits commonly contain gypsum or other soft minerals making them marginal for use in concrete. The deposits along Fort Pearce Wash, however, are reportedly used as concrete aggregate (Larry Gore, Recreation Planner, BLM Dixie Field Office, verbal communication, September 26, 1995).

Gravel from terraces along the Virgin River and tributaries southwest of St. George was used in the construction of Interstate 15. The Utah Department of Transportation (1966) reports this gravel was derived from Cenozoic basalt and Mesozoic sedimentary rock, and was of poor quality. Because they are older, higher level terrace deposits generally contain more calcium carbonate than younger deposits nearer the present stream level (Christenson and Deen, 1983).

Christenson and Deen (1983) reported that the higher quality gravel in the area is found in younger, lower terraces along the Virgin River east of St. George. Older, higher terrace deposits, particularly those near Washington south of the Virgin River, are carbonate cemented and of lower quality. With the exception of Fort Pearce Wash, previous studies indicate that the better sources of aggregate are in young, lower terrace deposits along the Virgin River east of St. George.

The young terrace deposits along Fort Pearce Wash are mined extensively for a variety of uses, including concrete aggregate. Most of the aggregate supply for the area comes from these terrace deposits because they: (1) are close to St. George, (2) are relatively thick, (3) have a more desirable clast-size distribution than most other deposits, and (4) contain fewer deleterious, soft, and soluble clasts than are found in other areas. The source areas for Fort Pearce Wash deposits are outcrops of Paleozoic carbonate and quartzite located mainly to the southeast in Arizona.

Potential Aggregate Sources

Alluvial and colluvial deposits derived from the Kaibab and Toroweap Formations are potential aggregate sources.

The Kaibab and Toroweap Formations could also be used as bedrock sources of aggregate. These carbonate units are primarily hard, Permian limestones that crop out in the Beaver Dam Mountains, Virgin River Canyon, and along the Hurricane Cliffs. During recent reconnaissance work along the Hurricane Cliffs, deposits of alluvium and colluvium were observed that primarily contained clasts of Kaibab Limestone and some clasts of quartzite and basalt (figure 5). These deposits have potential for additional development; at least two pits currently produce aggregate from these deposits.

The Kaibab and Toroweap Formations contain chert and gypsum horizons that would be detrimental in Portland cement concrete. Detailed studies are needed to determine the extent of deleterious materials in talus, colluvium, and alluvial-fan sand and gravel shed from these rock units.

Besides the Kaibab and Toroweap units, Christenson and Deen (1983) suggested that the Shinarump Member of the Chinle Formation, and Tertiary/Quaternary basalts are additional potential bedrock sources of aggregate. Bedrock sources require increased excavation and crushing costs, and also require separate sources of sand. An advantage is that crushed bedrock can provide coarse aggregate of more uniform size and shape.

The coarse-grained igneous rocks (quartz monzonite) of the Pine Valley intrusive body reportedly make excellent aggregate for road base (Utah Department of Transportation, 1966). Clasts of the Pine Valley intrusive are in alluvial fans and stream channels extending downslope on the southeast and southwest flanks of the Pine Valley Mountains. However, these deposits also contain clasts of the less desirable Pine Valley latite, and soft Mesozoic sandstone and siltstone, which crop out on the south flank of the range. These deposits also may contain detrital gypsum, or other undesirable, soluble minerals derived from the Mesozoic units.

Extensive pediment gravels up to 300 feet (100 m) thick accumulated from the late Pliocene to the Pleistocene (?) along the west slope of the Beaver Dam Mountains (Beaver Dam Slope) (Hintze, 1985). These deposits consist of silt, sand, gravel, and boulders derived mostly from Precambrian metamorphic and Paleozoic sedimentary rocks of the Beaver Dam Mountains. They also include clasts of volcanic rocks from the Bull Valley Mountains. Large-scale mine development may be precluded, however, because the deposits locally contain siliceous material in volcanic rock clasts (detrimental as concrete aggregate). Protective regulations for the desert tortoise may also inhibit mining of these deposits along the Beaver Dam Slope.

As much as 100 feet (30 m) of older alluvial gravels cap hilltops and cover hillslopes, mostly along the south slope of the Bull Valley Mountains and the southwest slope of the Pine Valley Mountains. Commonly, these gravels are capped by basalt. The deposits are unconsolidated and poorly sorted, containing clasts as large as boulder size. Clasts of intermediate volcanics, basalt, and quartz monzonite suggest that these deposits are derived from local bedrock units.

LAND MANAGEMENT ISSUES AFFECTING AGGREGATE DEVELOPMENT

Public Lands Administration

The majority of lands within Washington County are public lands administered by the BLM, U.S. Forest Service, and the U.S. National Park Service. Within the study area, the majority of lands are administered by the BLM, whereas the remainder are roughly equal amounts of state and private lands. The south part of Dixie National Forest extends into a small part of the study area. The BLM's Dixie Resource Management Area (RMA) administers public lands in accordance with a Resource Management Plan (RMP) that was developed via preparation of an Environmental Impact Statement (U.S. Bureau of Land Management, 1990). In the RMP, the management strategy for the entire Dixie RMA includes many considerations such as mineral materials, grazing, visual resources, cultural resources, wilderness, recreation, riparian systems, soil conservation, and wildlife habitat.

Natural aggregate is considered by the BLM as saleable mineral material. Mineral material on BLM land is available for extraction at fair-market value, either from established "community pits," or other areas where mineral development is allowed. The Dixie RMA has over 480,000 acres (194,000



Figure 5. Southward view along the Hurricane Cliffs from a point south of the town of Hurricane. Early morning (low-angle) sunlight shows the surface trace of the Hurricane fault where the fault has truncated alluvial fans and talus deposits at the base of the cliffs. The cliffs are composed mostly of Permian carbonate units. The valley floor is underlain by Triassic and Jurassic sedimentary rocks.

ha) open for mineral-material sales pending site-specific review. Part of this acreage is subject, however, to restrictions identified in the Dixie RMP. About 140,000 acres (57,000 ha) in the Dixie RMA are closed to mineral-material sales (U.S. Bureau of Land Management, 1990).

Areas of Critical Environmental Concern

Other than designated wilderness areas, the BLM applies its most intensive conservation management to Areas of Critical Environmental Concern (ACEC). ACEC designations help protect environmentally sensitive areas from activities otherwise permitted under the RMP. ACECs are designated to protect scenic value, threatened and endangered species, archaeological sites, riparian habitat, sensitive soils, and other attributes. Six ACECs enclosing 18,000 acres (7,300 ha) fall within the UGS study area (table 4, figures 6 and 7). All of these ACECs are "closed to mineral material sales."

Wilderness Areas and Wilderness Study Areas

A small part (less than 500 acres [200 ha]) of the Beaver Dam Mountains Wilderness Area lies about 10 miles (16 km) southwest of St. George along the Virgin River Canyon (figure 6). This tract is an outlier of a much larger Wilderness Area that extends northward from Arizona. The area was designated wilderness as part of the Arizona Wilderness Act of 1984.

Two Wilderness Study Areas (WSAs), the Red Mountain WSA (18,290 acres [7,405 ha]) and the Cottonwood Canyon WSA (11,330 acres [4,587 ha]) lie within the study area (figure 6). Until Congress either designates these areas as wilderness, or releases them from wilderness study area status, the BLM manages the WSAs according to an Interim Management Policy. The general rule of this policy is that the only activities permissible are temporary uses that create no new surface disturbance, nor involve permanent placement of structures. Exceptions to the general rule include grandfathered uses such as livestock grazing, mining, and

leases in-place on October 21, 1976 (approval date of the Federal Land Policy and Management Act [FLPMA]). The WSAs are closed to road and trail construction, establishment of permanent rights of way, oil and gas leasing, and post-FLPMA mining claim exploration (U.S. Bureau of Land Management, 1995).

Protection for Endangered Species

The Beaver Dam Wash and St. George basin areas encompass the Utah portion of the Mojave Desert. The variety of desert soils and landforms, and the warm, arid climate make this region a unique environment in Utah containing a number of rare plant and animal species (table 5). Urban expansion has resulted in loss of habitat for these species. The greatest number of threatened and endangered species in Utah is in Washington County (Jane Perkins, Native Aquatic Species Biologist, Utah Division of Wildlife Resources, oral communication, August 2, 1995). Mojave Desert animal species either now protected, or soon to be protected through critical habitat designation under the ESA include the desert tortoise (Gopherus agassizii) and the southwestern willow flycatcher (*Empidonax trailli extimus*). The main stem of the Virgin River is protected habitat for the Virgin River chub (Gila seminuda) and the woundfin (Plagopterus argentissimus). Protected plant species in the region include the dwarf bearclaw poppy (Arctomecon humilis) and the Siler pincushion cactus (Pediocactus sileri). In addition, the Virgin spinedace (Lepedomeda mollispinis mollispinis), chuckwalla (Sauromalus obesus), banded gila monster (Heloderma suspectum cinctum), and at least 35 other reptiles, amphibians, small mammals, insects, and birds are considered candidate species. Maddux and others (1995) suggested that many of the candidate species will benefit from critical-habitat designation for endangered species.

Desert Tortoise

The U.S. Fish and Wildlife Service (FWS) (1994) listed the desert tortoise as a threatened species on April 2, 1990. On February 8, 1994, after several years of study, the FWS

Table 4. Areas of critical environmental concern (ACEC) within the phase one study area. The outlines of the ACECs are shown on figure 6 (after U.S Bureau of Land Management, 1990, 1995).			
ACEC NAME	LOCATION	CONCERNS	ACRES
Red Bluff	5 mi. (8 km) SW of St. George	dwarf bearclaw poppy, saline soils	6,010 (2,433 ha)
Warner Ridge-Ft. Pearce	5 mi. (8 km) ESE of St. George	dwarf bearclaw poppy, silver cactus, spotted bat, saline soils, riparian zones	3,690 (1,494 ha)
Santa Clara River - Land Hill	just west of Santa Clara	riparian zones, archeological sites, Virgin spindace	1,770 (717 ha)
Lower Virgin River	6 mi. (10 km) SSW of St. George	riparian zones, woundfin, Virgin River chub, archeological sites	1,460 (591 ha)
Red Mountain	4 mi. (6.5 km) N of Santa Clara	national scenic resources	5,480 (2,219 ha)
City Creek	3 mi. (5 km) N of St. George	desert tortoise, community watershed	2,595 (1,051 ha)



Figure 6. Areas protected for threatened and endangered species, Wilderness Study Areas (WSAs), BLM proposed Areas of Critical Environmental Concern (ACECs), construction material sites and quarries, and principal drainages in the study area. Towns include IV - Ivins, SC - Santa Clara, SG - St. George, WA - Washington, and HU - Hurricane. Compare to figure 7.



Figure 7. Land status map of the study area showing locations of construction-material pits and quarries and principal drainages.

Table 5.

Federal candidate and listed species in Washington County (after U.S. Bureau of Land Management, 1990; Maddux and others, 1995). Endangered = on the verge of extinction; Threatened = on the verge of endangered; Candidate 2 = possibly threatened or endangered but conclusive data not available.

Common Name	Scientific Name	Status
Virgin spinedace	Lepidomeda mollispinis mollispinis	Proposed Threatened
Woundfin	Plagopterus argentissimus	Endangered
Virgin River chub	Gila seminuda	Endangered
Flannelmouth sucker	Catostomus latipinnis	Candidate 2
Desert Sucker	Catostomus (Pantosteus) clarki	Candidate 2
Desert tortoise	Gopherus agassizii	Threatened
Banded gila monster	Heloderma suspectum cinctum	Candidate 2
Chuckwalla	Sauromalus obesus	Candidate 2
Arizona southwestern toad	Bufo microscaphus microscaphus	Candidate 2
Lowland leopard frog	Rana yavapaiensis	Candidate 2
Bald eagle*	Haliaeetus leucocephalus	Threatened
Peregrine falcon	Falco peregrinus	Endangered
Ferruginous hawk	Buteo regalis	Candidate 2
Black tern	Chilidonias niger	Candidate 2
White-faced ibis	Plegadis chihi	Candidate 2
Western least bittern	Ixobrychus exilis hersperis	Candidate 2
Southwestern willow flycatcher	Empidonax traillii extimus	Proposed Endangered
Western snowy plover	Charadrius alexandrinus nivosus	Candidate 2
Mountain plover	Charadrius montanus	Candidate 2
Long-billed curlew	Numenius americanus	Candidate 2
Spotted owl	Strix occidentalis	Candidate 2
Merriams kangaroo rat	Dipodomys merriami frenatus	Candidate 2
Virgin River montane vole	Micotus montanus rivularis	Candidate 2
Small-footed bat	Myotis ciliolabrum	Candidate 2
Fringed bat	Myotis thysanodes	Candidate 2
Yuma bat	Myotis yumanensis	Candidate 2
Big free-tailed bat	Nyctinomops macrotis	Candidate 2
Spotted bat	Euderma maculatum	Candidate 2
California leaf-nose bat	Macrotus californicus	Candidate 2
Utah hydroporus diving beetle	Hygrotus utahensis	Candidate 2
Utah minute moss beetle	Limnebius crassalus	Candidate 2
Utah chaetarthria water scavenger beetle	Chaetarthria utahensis	Candidate 2
Spotted Warner Valley dunes june beetle	Polyphylla aviattat	Candidate 2
MacNeill sooty wing skipper	Nesperopsis gracielae	Candidate 2
Dwarf bearclaw poppy	Arctomecon humilis	Endangered
Siler pincushion cactus	Pediocactus sileri	Threatened
Gumbo milk-vetch	Astragalus ampullarius	Candidate 2
Holmgren milk-vetch	Astragalus holmgreniorum	Candidate 2
Virgin River thistle	Cirsium virginensis	Candidate 2
Jones golden aster	Heterotheca jonesii	Candidate 2
Whipple opuntia	Opuntia whipplei var. multigeniculata	Candidate 2
Virgin phacelia	Phacelia cepahalotes	Candidate 2
Utah spikemoss	Selaginella utahensis	Candidate 2
Zion tansy	Sphaeromeria ruthiae	Candidate 2

designated a large area of Washington County as critical habitat for the Mojave population of the desert tortoise. The FWS also established rules for the desert tortoise's recovery. The desert tortoise lives throughout most of the Mojave desert region, occupying flats or bajadas composed of sandy and gravelly soils. Well adapted to living in the harsh desert, the tortoise spends the majority of time in burrows except to mate and feed in the late winter and early spring. Although the tortoise is described as having delayed maturity and long life, the FWS estimates that pre-reproductive adult mortality approaches 98 percent. If the FWS recovery criteria are met, the earliest that delisting of the species could take place would be in the year 2019 (U.S. Fish and Wildlife Service, 1994).

In Washington County, desert tortoise protection zones, known as Desert Wildlife Management Areas (DWMAs), occupy the west slope of the Beaver Dam Mountains, most of Beaver Dam Wash (designated the Beaver Dam Slope Unit by the BLM), and the southern slopes of the Pine Valley Mountains (Upper Virgin River Unit) (figures 1 and 6). Within the DWMAs, many activities, particularly grazing and offroad vehicle use, are prohibited. Activities such as hiking, camping, and scientific data gathering are allowed. Mining, including sand and gravel extraction, is allowed but reviewed by the FWS on a case-by-case basis. The desert tortoise recovery plan states that the cumulative effects of all mining activities may not significantly impact the habitat of the desert tortoise, and any potential effects on desert tortoise populations must be carefully mitigated during the mining operation. Mined lands also must be restored to their pre-disturbed condition.

Southwestern Willow Flycatcher

The southwestern willow flycatcher was listed in the FWS final rule as an endangered species (U.S. Government Printing Office, 1995a). The willow flycatcher is a small bird approximately 6 inches (15 cm) in length that occupies riparian zones and wetlands in the southwest United States. Willow flycatcher habitat typically contains dense growths of willows and other plants with a scattered overstory of cottonwood. Presently, this type of habitat is rare and widely separated by arid lands in the desert southwest.

Reduced populations of the willow flycatcher in the southwest United States is reportedly due to: (1) loss and modification of habitat, (2) predation, and (3) brood parasitism by the brown-headed cowbird (Marshall, 1995). The cited causes of the loss of habitat in Utah include urban expansion along the Virgin River, inundation by Lake Powell along the Colorado and San Juan Rivers, livestock grazing in riparian zones, and the encroachment of tamarisk throughout the region (Marshall, 1995). Studies summarized by Marshall (1995) indicate that increased predation on willow flycatcher eggs and hatchlings may be indirectly due to habitat fragmentation. The brown-headed cowbird, a transplant from the northern Great Plains, removes eggs from the nests of other birds, laying cowbird eggs for the host bird to hatch and rear. The cowbird now commonly invades flycatcher nests.

No recovery plan for the willow flycatcher had been prepared at the time of this writing. Presumably, areas managed in the recovery plan would include the riparian zones along the Virgin and Santa Clara Rivers.

Endangered Fish

The FWS has recently proposed designation of critical habitat for three fish species endemic to the Virgin River basin (U.S. Government Printing Office, 1995b). The fish include the Virgin River chub, the woundfin, and the Virgin spinedace. The woundfin and Virgin River chub are listed as endangered under the ESA. The Virgin spinedace has been proposed for listing as threatened. Maddux and others (1995) suggested that populations of these fishes have declined as a result of loss of habitat due to lower stream flows caused by water diversions, proliferation of non-native fish, and alterations to natural flow, temperature, and sediment regimes of rivers and streams.

The FWS originally proposed approximately 207 miles (330 km) of overlapping critical habitat along the main stem of the Virgin River and its tributaries in parts of Utah, Arizona, and Nevada for the three listed fishes. In Utah, the overlapping habitat included the main stem of the Virgin

River plus portions of Beaver Dam Wash, Santa Clara River, Ash Creek, La Verkin Creek, Shones Creek, and the North and East Forks of the Virgin River (Maddux and others, 1995).

A revised plan withdraws the critical habitat protection of the Virgin spinedace from the listing. The withdrawal would result in the designation of only the main stem of the Virgin River, from Pah Tempe Hot Springs (near Hurricane) to Lake Mead, as critical habitat for the other species (Henry Maddux, Threated and Endangered Species biologist, FWS, Salt Lake City, verbal communication, August 8, 1995).

Endangered Plants

The Utah Native Plant Society (1989) believes that roughly one-sixth of known Utah native vascular plant species are rare. From these hundreds of species, the dwarf bearclaw poppy is reportedly in the greatest danger of becoming extinct. In Utah, the dwarf bearclaw poppy grows only within a few kilometers surrounding St. George and Bloomington, mostly on state-owned land. The bearclaw poppy was officially listed in 1979 as endangered under the ESA. It is one of only three species in the genus Arctomecon, which are all found in the western United States. All are gypsum loving (gypsophiles) and rare. The rapidly growing urban region of St. George has made the poppy vulnerable to disturbances from off-road vehicles, residential/commercial construction, grazing, and mining (Utah Native Plant Society, 1989). Protected habitat for the bearclaw poppy includes the northeast slopes of the White Hills (Red Bluff ACEC), the west face of Warner Ridge, and several small parcels of land south of St. George (figure 6).

Recovery actions initiated by the BLM have improved the habitat of the Siler pincushion cactus such that its status was proposed to be reclassified from endangered to threatened in March 1993. The Siler cactus is protected within the Warner Ridge-Fort Pearce ACEC.

SUMMARY AND RECOMMENDATIONS

A combination of conditions in the St. George basin contributes to the likelihood of future shortages of low-cost, high-quality aggregate materials needed for continued development. These conditions include, but are not limited to:(1) high population growth and resulting high demand for building sites and infrastructure which restricts access to aggregate resources, (2) relatively little high-quality natural aggregate available due to the geologic setting of the region, (3) large percentages of federal land ownership with some lands having ACEC or other land-use restrictions, and (4) protection of habitat for endangered plants and animals (often included in ACECs). These conditions may affect future availability of aggregate and require that local planners and developers consider aggregate resources in their planning efforts.

As the natural aggregate of the area is removed from the accessible resource base (by extraction, urbanization, and designation of protected areas), construction costs will inevitably rise. The main resource areas along the terraces of the Virgin River and Fort Pearce Wash are experiencing increased extraction of sand and gravel as urban expansion



Figure 8. View looking southwest across Fort Pearce Wash. Sand and gravel operations in the center of the photo mine young stream-terrace deposits. Eroded outcrops in the upper right are the Shnabkaib (gypsiferous) Member of the Triassic Moenkopi Formation. Distant hills are in Arizona and consist of Paleozoic rocks.

and infrastructure development continues (figure 8). Some pit closures, due to encroachment of home building , have already taken place. Moreover, establishment of protected areas for rare plants and animals is an on-going process that will continue to have an effect on aggregate resources. Higher cost alternatives to local sources of aggregate could include transporting aggregate from increasingly distant sources, or crushing stone quarried from favorable bedrock formations.

The availability of low-cost construction materials may eventually place constraints on economic expansion in the St. George area unless measures are taken to conserve the resource. It is recommended that a detailed inventory of alluvial deposits be made to identify and classify them based on suitability, accessibility, and volume. The inventory would include: (1) reviews of geological and geotechnical data on resources throughout the St. George basin; (2) ranking of areas for detailed studies based on deposit volume, quality, and accessibility; (3) detailed mapping and surveying of highly ranked deposits; (4) representative sampling for deposit characterization; and (5) determination of in-place tonnages. With this information, land planners, developers, and government officials will be able to make better informed land-use decisions that recognize natural aggregate as a valued commodity.

ACKNOWLEDGMENTS

Clark Maxwell of UDOT's Cedar City Office assisted in preparing information on sand and gravel resources of Washington County. Larry Gore of the BLM's Dixie Field Office provided information on threatened and endangered species, and sand and gravel operations in the area. Finally, Jeff Rowe of the Utah School and Institutional Trust Lands Administration provided digitized land-grid and land status information.

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THE EXTRACTION OF MINERAL RESOURCES FROM GREAT SALT LAKE, UTAH: HISTORY, DEVELOPMENTAL MILE-STONES, AND FACTORS INFLUENCING SALT EXTRACTION

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ABSTRACT

Salt from Great Salt Lake was probably used by the Native Americans prior to the Jim Bridger Expedition to the lake in 1824-25, and was used by the region's early explorers and trappers after that time. From the arrival of the Mormon pioneers in 1847, salt has been produced from Great Salt Lake, starting first with the collection of crude salt from along its shores, and later by boiling down the lake's brine to obtain crystalline salt.

Since these early beginnings, salt production from the lake has become a substantial commercial enterprise. Since the early 1960s, research and development have led to the economic production of potassium sulfate, magnesium metal, chlorine gas, magnesium chloride products, and nutritional supplements. Many of the salt-production techniques and equipment that were developed prior to 1964 are still being used today. Sodium sulfate has been produced, but is no longer marketed.

Morton Salt, Cargill Salt, and IMC Salt currently extract sodium chloride, which is precipitated during the early stages of evaporation when the brine concentration reaches saturation, or about 26 to 27 percent total dissolved solids. Magnesium Corporation of America produces magnesium metal and chlorine gas, and IMC Kalium Ogden Corporation produces potassium sulfate, as well as magnesium chloride brine and flake products. These salt, gaseous, and metallic products are processed from the sodium-chloride-saturated, highmagnesium-chloride brines, and from the potassium and magnesium salts that are precipitated from the lake brine after it has been further concentrated.

One obstacle to salt production is the fluctuating level of Great Salt Lake. In 1983, the lake level began a dramatic rise from an elevation of 4,200 feet (1,280.16 m) to its historic high of 4,211.85 feet (1,283.77 m) in 1986-87 (uncorrected USGS provisional lake-level records). The State of Utah employed flood-control measures, including breaching the Southern Pacific Railroad causeway in 1984, and pumping lake water to a shallow basin west of the lake in 1987. During the high-water years, the lake's mineral-extraction industries faced many challenges including the need to raise dikes to prevent flooding of facilities, broken dikes which resulted in the inundation of solar ponds, and dealing with the lake's greatly reduced brine salinities which resulted in lower annual salt and concentrated-brine production.

The years following the record-high lake levels have been a time of adaptation, innovation, and change for Great Salt Lake industries. After its solar ponds were flooded in 1986, AMAX, Inc. built a new solar-pond complex near Knolls, and used the concentrated brines from the West Pond, generated by the State's West Desert Pumping Project. Great Salt Lake Minerals built a 21-mile-long (33.8 km) open, underwater canal, called the Behrens Trench, to convey concentrated brines from a new, remote solar pond on the west side of the lake to the east side of the lake, to help increase its production of sulfate-of-potash. There were also numerous changes in corporate ownership and production-facility locations.

EARLY RECOVERY OF SALTS FROM THE LAKE

Pre-1847 Salt Procurement and Use

Before the Mormon pioneers entered the Salt Lake Valley in 1847, Great Salt Lake was probably a source of salt for the Native Americans living around its shores. However, no evidence of any extensive Native American exploitation of the salt resource remains (Clark and Helgren, 1980).

The first Euro-American settlers known to use salt from the lake were mountain men from Ashley's Rocky Mountain Fur Company, including Jim Bridger. During the late fall of 1825, a rendezvous site was established near the present location of Ogden, Utah. While camped in the area, the mountain men boiled away some of the lake brine in a kettle to obtain salt (Clark and Helgren, 1980).

John C. Fremont's memoirs (Fremont, 1887) of his second expedition west (1843-1844) describe a trip in a specially prepared rubber raft from a point near the outlet of the Weber River to what is now called Fremont Island. While returning to the mainland the next morning, Fremont filled a 5-gallon (18.9 L) bucket with brine from which he intended to make salt. Fremont described the salt-making process:

> "Today we remained at this camp, in order to obtain some further observations and to boil down the water which had been brought from the lake for a supply of salt. Roughly evaporated over the fire, the five gallons of water yielded fourteen pints of very fine-grained and very white salt, of which the whole lake may be regarded as a saturated solution."

1847-1870, Mormon-Pioneer Period

On July 28, 1847, the Mormon leader, Brigham Young, and some of his associates made a trip to Great Salt Lake to satisfy their curiosity as to the nature of this well-known landmark, and to bathe in its buoyant water. While there, they gathered some salt off the rocks, which was pure, white, and fine. The salt found on the shore of the lake proved initially to be as important to the pioneers as that found in the water. Later that year, a committee assigned to extract salt from the lake water and to gather salt from along the lake shore left Salt Lake City on August 9th and returned August 13th. During this time they prepared 125 bushels (4,405 L) of coarse white salt, probably from a large bed of salt 6 inches (15.2 cm) deep found lying between two sand bars. The committee reported enough pure salt in this bed to provide at least ten wagon loads without further refining. These shore deposits, however, yielded a poor-quality, bitter-tasting salt due to the other minerals found in them. During this trip, they also boiled down four barrels of salt water to one barrel of fine white table salt (Clark and Helgren, 1980).

The earliest known, permanent salt-boiling operation was established in the spring of 1850 by Charley White according to reports by Lieutenant J.W. Gunnison and Captain Howard Stansbury, who were conducting government surveys on the lake's south shore. Gunnison reported that White could produce 300 pounds (136.2 kg) of salt per day by boiling brine in six 60-gallon (227 L) kettles. Charley White operated this salt company until 1861. In 1870, the Ninth Census reported only one facility producing salt in Utah. This operation may have been owned by the Joseph Griffith and William F. Moss families of "E.T. City" or Lake Point. The Moss and Griffith salt works were a small home industry, most likely run as a sideline to a farm or ranch (Clark and Helgren, 1980).

EARLY DEVELOPMENT OF SALT-EXTRAC-TION METHODS AND EQUIPMENT

Dikes, Solar-Evaporation Ponds, and Use of Pumps

By 1873, the level of Great Salt Lake had risen enough to inundate many of the natural salt beds. A new brine-concentration method was tried; dikes were constructed across the entrances of coves and along the south shore of the lake so that the periodic rise and fall of the lake could fill the diked areas with brine. Early salt makers depended on wind tides resulting from northwest winds, which raised the water level on the southern shore of the lake from 1 to 1.5 feet (0.3 to 0.5 m), thereby filling the diked areas with fresh brine. However, the wind tides were not dependable and some of the stronger storms washed away the dikes and dissolved the salt that had been deposited (Clark and Helgren, 1980).

With experience, the early salt makers learned that earth alone was unsuitable for constructing dikes, and planks would not bear the weight of the heavy brine waves. Jeremy and Company, organized in 1870, successfully constructed its dikes by driving two rows of cottonwood stakes into the ground every 2 feet (0.6 m), placing the two rows of stakes 7 feet (2.1 m) apart. A latticework of willows was then woven on each row of stakes and the willows were backed by several inches of bulrushes. The area between the two rows of stakes was filled with earth, making a substantial dike that proved effective for constructing ponds from 5 to 100 acres (2 to 40.5 ha) in extent (Clark and Helgren, 1980). The remains of a later version of this type of dike are shown in figure 1 wherein wooden planks were used instead of willows and bulrushes.

Natural wind-tide fluctuations of the lake were too unreliable for filling the ponds, and by 1880, some of the salt



Figure 1. Abandoned remains of soil-filled, "stake and plank" solar pond dike from Morton Salt's original ponds at Burmester.

companies began using steam- or horse-powered pumps to fill their ponds with brine. In 1888, the Inland Salt Company had established a central (steam?) power source to run a 10-inch centrifugal pump and the machinery in its mill (Clark and Helgren, 1980).

Fractional Crystallization

The original method of producing solar salt by flooding an area and allowing the brine to completely evaporate produced very bitter-tasting salt. Salt producers learned that by not evaporating all of the water they could precipitate a highquality salt and discard the remaining brine or "bittern" (Clark and Helgren, 1980). This process of controlled evaporation and precipitation, called fractional crystallization, was developed and first implemented by the Inland Salt Company in 1888. Fractional crystallization consists of moving the brine through a series of interconnected evaporation ponds and precipitating only the desired salts in specific ponds as the brine concentration increases (figure 2). First, lake brines are pumped into settling ponds where most of the sediment and debris settle out, and the small amounts of calcium and magnesium carbonates and sulfates are precipitated. Second, the brines are moved from settling ponds into



Figure 2. Schematic diagram illustrating the concept of fractional crystallization. As brine is concentrated, it is moved from pond to pond where the desired minerals are precipitated.

"evaporation" ponds where they are concentrated until the "salt point" is reached. Third, the brines from evaporation ponds are finally moved to the "garden" or "crystallizer" ponds where large quantities of halite (sodium chloride) are precipitated. By draining the remaining brine off the "garden ponds" at the optimum concentration, or before the amount of potassium, magnesium, and sulfate becomes too high, a non-bitter salt is produced. If the ponds are drained below the optimum concentration, good salt is lost (Clark and Helgren, 1980).

The Split

The Inland Salt Company also developed a procedure referred to as creating the "split" or forming a cleavage plane between the pond floor and the new crop of salt. This was done to improve the ease of harvesting new crops of salt. Without a split, the crystals from a new crop would interlock with the large salt crystals on the pond floor, making a hard, continuous layer of salt with no way of breaking the new salt loose. Two types of splits were developed: the mechanical split and the sun split. A "mechanical split" is formed by dragging a heavy object, such as a piece of railroad rail, over the pond floor (figure 3). This knocks the edges off the large salt crystals and forms a layer of fine salt crystals termed the "split" or "cleavage plane" (Clark and Helgren, 1980).

A "sun split" is made by draining or filling the ponds until just a small amount of highly concentrated brine covers the floor. The split is then created by allowing a layer of very fine crystals to precipitate to a depth of 1/8 inch (.32 cm) over the large, jagged salt crystals on the pond floor. After the fine crystals are deposited, fresh, highly concentrated brine is brought into the ponds. The large crystals of the new crop of salt then precipitate upon the layer of fine crystals or the "cleavage plane" (Clark and Helgren, 1980).



Figure 3. Tractor pulling "drags" to form a "mechanical split" in a solar pond (photo courtesy of Morton Salt Company).

Salt-Harvesting Equipment

The use of tractors was introduced at Morton Salt Company's harvesting plant in 1923, when Ed Cassidy brought his farm tractor to the Burmester ponds to replace the horses used in pulling the plows. Machinery had not previously been used for fear that its heavy weight would break through the thin salt floors. Following Cassidy's successful venture, the company purchased some Fordson tractors to plow the salt, though salt was still stockpiled by hand (Clark and Helgren, 1980).

Local inventors contributed various other ideas that helped mechanize salt production. When Morton Salt consolidated its production facilities at Saltair in 1933, salt was still harvested by hand. To implement mechanical harvesting the salt floor thickness had to be increased to 18 inches (0.46 m), and the dikes around the ponds had to be raised. After the pond floors had been thickened, local inventors modified a small farm tractor to scrape salt into a bin that was pulled across the ponds. In 1938, the modified tractor was replaced by a local invention called a "Hootin Nanny." In 1949, another local invention, called a "Jackrabbit," was used until it was replaced by a commercially manufactured machine called the "Scoop-Mobile" (figure 4). The "Scoop-Mobile" was replaced in 1964 by a revolutionary new machine called the "Palmer-Richards Salt Harvesting Combine" (figure 5). This machine was developed locally by James Palmer and A.Z. Richards, Jr. of the Solar Salt Company (Clark and Helgren, 1980). The Palmer-Richards Salt Harvesting Combine, or versions of it, are still in common use today.



Figure 4. "Scoop-Mobile" loading salt (photo courtesy of Morton Salt Company).

low-permeability material, was extended upward into the dike as well.

THE MINERAL-EXTRACTION INDUSTRY TODAY

Sodium Chloride Production and Companies

From the late 1800s until the present, many salt-producing companies have come and gone around Great Salt Lake. Today, three salt producers operate on Great Salt Lake. Morton Salt and Cargill Salt operate at the south end of the lake, while IMC Salt operates at the north end (figure 7). These producers use the basic principles of solar evaporation, developed and perfected over many years, to produce a high-purity product. In modern practice, lake brine is con-

centrated in large evaporation ponds to the point of sodium chloride saturation, which is about 26 to 27 percent total dissolved salts, equivalent to a brine density of about 1.224 g/cc, or approximately 26.53 degrees Baumé (degrees Baumé are often reported by the salt industry instead of density units). The conversion from specific gravity (g/cc) to degrees Baumé is made as follows (Mannar and Bradley, 1983) degrees Baumé = 145 - (145 ÷ specific gravity of the brine at 15.6°C). Salt producers using the less concentrated southarm brine need much larger ponds for pre-concentration than those using the more concentrated north-arm brine to obtain equivalent yields.

When the brine reaches the saturation point, it is moved to the "crystallizers" where sodium chloride precipitates and accumulates on the bottom of the ponds. In general, halite is allowed to precipitate during the major part of the summer until the brine reaches a density of 1.245 g/cc or about 28.53

POND BRINE

B

DIKE



POND BRINE

Figure 6. Schematic cross section showing leakage of brine from solar pond (A) without cutoff trench, and containment of brine in solar pond when a cutoff trench is present (B).

Figure 5. Palmer-Richards salt harvester (center) being moved by tractor (right), loading salt into truck (left) (photo courtesy of Morton Salt Company).

Cutoff Trench

Brine leakage and loss into porous sediments underlying the ponds at Lake Point had presented problems to salt producers since 1901. The Weir Company corrected this problem by digging trenches around the ponds to an impervious clay stratum. The material that was originally excavated from the trenches was then thoroughly mixed and replaced back in the trenches, thus forming a "cutoff" trench (figure 6). The trench-fill material interrupted the lateral continuity of permeable strata, by lowering its permeability relative to the undisturbed sediments. This reduced or prevented brine movement outward from under the pond. If the material excavated from the trench was too sandy, clay from borrow areas was added. Pond dikes were built on top of the cutoff trench (Clark and Helgren, 1980; Gwynn and Sturm, 1980). To prevent leakage through typically coarse dike-construction material, the material used to fill the trench, or other

DIKE





Figure 7. Locations of Great Salt Lake mineral-extraction industries, the Southern Pacific Railroad (SPRR) causeway, and the Behrens Trench.

degrees Baumé (Nate Tuttle, Morton Salt Co., verbal communication, April 1999). At this concentration, the remaining brine is drained from the ponds and returned to the lake. The cutoff point used by the different salt producers may vary slightly from this value, however. If the brines are drained much before reaching a density of 1.245 g/cc good sodium chloride is discarded, and if drained much after this point, elevated amounts of magnesium, potassium, and sulfate in the precipitated salt lower its quality.

The salt industry currently uses more than 80,000 acres (32,000 ha) of solar-evaporation ponds around Great Salt Lake for the annual production of more than two million tons (1.8 million metric tons [mt]) of sodium chloride and other products.

Morton Salt Company

Clark and Helgren (1980) relate the history of the Morton Salt Company and its predecessors from the early 1900s until about 1980. Morton's history since 1980 includes two episodes of flooding and the relocation of its operation. Morton Salt first experienced flooding in the early 1980s, not from the lake, but from a breach in Kennecott Utah Copper Company's tailings-pond dike south of Morton's operation. Then, starting in 1983, Morton Salt experienced minor flooding as the lake level rose, forcing them to raise some of their dikes. As the lake level continued to rise, dilution of the lake brine reduced the amount of salt they were able to produce. In September 1991, the Morton Salt plant and solar ponds adjacent to the Kennecott tailings pond were abandoned, and operations were transferred to the North American Salt facilities near the south end of Stansbury Island (figure 7). This move was brokered by Kennecott as part of its tailings pond expansion program. Morton's old evaporation ponds and salt-processing facilities have since been covered by Kennecott's tailings-pond expansion.

IMC Salt, Incorporated

The history of the IMC Salt company's predecessor, North American Salt Company (preceded by American Salt), from the early 1900s up until about 1980 is reported by Clark and Helgren (1980). During the 1980s, when lake levels rose, American Salt's solar ponds and processing facilities at the south end of the lake were situated high enough above the lake so that its dikes were not breached. American Salt was forced to expand its evaporation ponds to the west in order to recover lost production capacity due to diluted lake brines. For a period of time during the high-water years when American Salt could not produce salt it contracted with AMAX Magnesium Company (a magnesium-from-brine company located northwest of American Salt) to obtain salt from its Stansbury Basin solar evaporation ponds.

In 1991, American Salt was purchased by the Harris Group of New York, and renamed the North American Salt Company. When Morton Salt sold its facilities to Kennecott and took over the south-shore operations of North American Salt, North American Salt's management moved northward and consolidated operations with a sister company's salt production and processing facilities located west of Ogden, Utah. There, North American Salt harvested salt from the early-stage solar ponds of its sister company, Great Salt Lake Minerals (figure 7). In April 1998, North American Salt was sold to IMC Global, and renamed IMC Salt, Inc. Today, IMC Salt is the largest producer of sodium chloride products from Great Salt Lake.

Cargill Salt Company

Cargill Salt Company's Lake Point facility was operated by numerous predecessors (Clark and Helgren, 1980), including AKZO Salt, and the Lakepoint Salt Company, which had purchased the facilities from Hardy Salt Company in 1977. The Lake Point operation (figure 7) was then sold to Domtar Salt Company in 1982, who installed new salt-washing and stockpiling facilities. During 1982-1983, Domtar's entire solar pond system was inundated when the Union Pacific Railroad installed a culvert through its causeway to equalize the water elevations on the north and south sides of the causeway. In 1984, Domtar sold its salt-processing facilities to AMAX and the name of the operation was changed to Sol-Aire Salt and Chemical Company. Sol-Aire Salt immediately prospered by utilizing the salt that had accumulated in AMAX's Stansbury Basin solar ponds over the years. This prosperity was short-lived. On June 7, 1986, AMAX's Stansbury Basin ponds flooded when its northern main dike west of Badger Island broke during a storm. This left Sol-Aire without a source of salt (Bauer, in preparation). Salt was then hauled from Kaiser Chemicals (now Reilly Chemicals) near Wendover, Utah, until AMAX operations resumed on the lake in the fall of 1988.

Diamond Crystal Salt purchased the Sol-Aire Salt plant facilities at Lake Point from AMAX in 1987, and also purchased land west of AMAX's solar ponds that was suitable for a plant site adjacent to the Timpie Waterfowl Management Area (figure 7). A washing facility was soon constructed at the Timpie site, and Diamond Crystal also constructed an east-west dike within the main body of AMAX's Stansbury Basin solar pond. After the new dike was completed, water was pumped from the southern part of the divided pond to expose the residual salt floor. This residual salt was then harvested, washed at the Timpie washing plant, and shipped by truck to the Lake Point facility for further processing (Bauer, in preparation).

In 1989, AKZO Salt, a large European company, purchased International Salt Company, who had purchased Diamond Crystal Salt Company, and changed the name of the Timpie operation to AKZO Salt of Utah. From 1991 to 1994, the present-day facility at Timpie was constructed, and the Lake Point facility was shut down and partially reclaimed. In 1995, AKZO merged with Nobel, a Swedish Corporation, and the resulting company was named AKZO-Nobel. In 1997, Cargill Salt purchased all of the AKZO-Nobel's saltproducing facilities in the U.S., and is the current owner and operator of the Timpie facilities (Bauer, in preparation).

Non-Sodium Chloride Salt Production and Companies

Lake industries that produce non-sodium chloride salts, or more specifically magnesium and potassium salts and highly concentrated magnesium chloride brines, begin their processes the same way as the sodium-chloride salt industries, that is, through the solar evaporation of lake brine. The major differences among the evaporation processes are the greater amounts of water evaporated, the degree to which fractional crystallization is used, and the small percentage of the original total-dissolved-salts and/or lake brine that is produced as final product. To produce high-magnesium-chloride brines, more than 95 percent of the original water must be evaporated from the lake brine to yield a 7 to 8 percent magnesium-chloride brine. These highly concentrated brines are: (1) used by Magnesium Corporation of America (Mag-Corp) as raw materials for a process that ends in the electrowinning of magnesium metal and chlorine gas, (2) sold by IMC Kalium as a dust suppressant, and (3) marketed by North Shore Limited Partnership for making nutritional supplements. By contrast, just over 50 percent of the water in a brine of equivalent concentration must be evaporated to precipitate sodium chloride. In the production of potassium and magnesium salts (kainite, schoenite, carnallite, etc.), such as those used by IMC Kalium for the manufacture of potassium sulfate, less than 5 percent of the original dissolved salts remain in the brines that are fed to the final stages of the ponding operations. Here they precipitate as salts with the proper chemistry and sufficient purity to be harvested and used.

The evaporation process required to produce the potassium and magnesium salts used by IMC Kalium is basically the same as that required to produce the high-magnesiumchloride brine produced by MagCorp. MagCorp uses this brine to produce magnesium metal and chlorine gas, and IMC Kalium uses the potassium and magnesium salts to produce sulfate-of-potash.

To obtain highly concentrated potassium- and magnesium-bearing brines economically, the solar ponds must be very large relative to the pond size required by the sodium chloride industries. Companies also carefully monitor the brine chemistry and the chemistry of salts that precipitate as the brine is moved sequentially from pond to pond.

Magnesium Corporation of America

During World War II, National Lead Industries Inc. began to develop technology for producing magnesium using the ferro-silicon process while operating a magnesium plant for the government at Lucky, Ohio. In 1951, National Lead continued to gain expertise in the production of magnesium metal through the formation of a jointly owned company with Allegheny-Ludlum to form the Titanium Metals Corporation of America (TIMET) at Henderson, Nevada (Toomey, 1980).

In the 1960s, National Lead Industries joined with Hogle-Kearns Inc., a Salt Lake City investment firm, and Hooker Chemical to investigate the possibilities of producing and selling commercial quantities of magnesium metal. In searching for additional sources of magnesium, they became aware of the potential at Great Salt Lake. A review of the various sources of magnesium and economical sources of electrical power led to the selection of the Rowley site on the southwest side of Great Salt Lake as the preferred location for a plant.

During 1965 and 1966, National Lead conducted pilotplant operations to select the best process for use with Great Salt Lake brines. Solar ponds were constructed at Burmester and a pilot plant for producing magnesium chloride brine was built at Lake Point (figure 7). Magnesium chloride from this pilot plant was fed to a prototype electrolytic cell at TIMET in Henderson, Nevada, and the first 200-pound (91 kg) ingot of magnesium metal made from the brine of Great Salt Lake was produced in 1966. By 1967, Hooker Chemical unilaterally left the consortium, and in September 1969, National Lead purchased Hogle-Kearns' interest in the facility, leaving National Lead alone in the project (Haws, 1993). In 1969, after this successful pilot program, National Lead decided to build a full-scale magnesium plant at Rowley to utilize brine from Great Salt Lake. Plant construction began in 1970, and the actual start up of the magnesium operation took place in the summer of 1972. Operations were shut down in 1975 to make process modifications with the assistance of Norsk Hydro, a Norwegian magnesium producer. In the mid-1970s, National Lead changed its name to NL Industries, and in November 1980 NL Industries was sold to AMAX, Inc., a diversified mining and natural resources company, for approximately \$60 million (Toomey, 1980; Tripp, in preparation).

In 1983, three years after the change in ownership, the lake began a rapid rise, and millions of dollars were expended by AMAX to fortify the main dike that separated its Stansbury Basin ponds from Great Salt Lake (figure 7). On June 7, 1986, however, the main northern dike of AMAX's solarponding complex was breached during a severe storm, allowing the dilute lake waters to enter the Stansbury Basin and flood the entire solar-ponding complex. With its solar ponds flooded, AMAX was unable to produce the highly concentrated magnesium chloride brine essential to its magnesiumproduction process. For the next two years, in order to maintain their operations, AMAX purchased magnesium chloride brine from Reilly Chemicals, 90 miles (145 km) to the west near Wendover, Utah, and from Leslie Salt (now owned by Cargill Salt) near San Francisco, California (Tripp, in preparation).

After its ponds were flooded in 1986, AMAX conducted an extensive investigation to find a new source of magnesium chloride brine. Engineers determined that a solar-evaporation complex could be constructed in a timely manner near Knolls, adjacent to the southern end of the West Pond which contained nearly saturated lake brines (figure 8). By December 1987, the Knolls project was completed and concentrated brine was being pumped from the West Pond into the new solar ponds. After the brine was concentrated to the proper density, it was transported by a 41-mile (66 km) pipeline to the magnesium production facility at Rowley. This new source of brine enabled AMAX to continue production of magnesium metal and chlorine gas (Tripp, in preparation).

On September 1, 1989, AMAX sold the Rowley magnesium facility to Renco Inc., a privately held company from New York, and the operation was renamed Magnesium Corporation of America (MagCorp) (Tripp, in preparation). In 1995, MagCorp resumed brine-concentration activities in the Stansbury Basin, as well as periodically utilizing the brines from the Knolls facility.

IMC Kalium Ogden Corporation

During the early 1960s, many of the foremost chemical companies, including Dow Chemical Company, Monsanto Chemical Company, Stauffer Chemical Company, Lithium Corporation of America (Lithcoa), and Salzdetfurth A.G.,



Figure 8. Elements of the state's West Desert Pumping Project, and Magcorp's Knolls solar-ponding complex; Bonneville Salt Flats, Great Salt Lake, and transportation routes are also shown.

scrambled to reserve acreage for lakeside developments on Great Salt Lake (Kerr, 1965). Of these, Lithcoa and Salzdetfurth A.G. were the first to develop commercial brine/salt operations.

The potash facility now operated by IMC Kalium Ogden Corp. (formerly Great Salt Lake Minerals & Chemicals Corp.) was constructed after an exploration project and feasibility study was carried out by Lithcoa. Laboratory studies were conducted in 1963 and 1964, followed by three years of pilot plant testing and construction of pilot evaporation ponds (Industrial Minerals, 1984). During 1964, Lithcoa representatives appeared before the Utah State Land Board (the State agency that regulated lake development, now the Division of Forestry, Fire, and State Lands) in order to acquire permission to extract minerals from Great Salt Lake (Lewis, 1965; Woody, 1982). Within the next year or so, permission was granted.

In 1965, studies continued on methods for extracting minerals from Great Salt Lake. During that same year, Lithcoa entered into a partnership with Salzdetfurth, A.G., of Hannover, West Germany, an important producer of potash and salt, (Lithcoa 51 percent and Salzdetfurth 49 percent ownership) to develop the land and mineral rights on the lake held by Salzdetfurth (Lewis, 1966; Engineering and Mining Journal, 1970).

In 1967, Lithcoa and Chemsalt, Inc., a wholly owned subsidiary of Salzdetfurth, A.G., proceeded with plans to build facilities on the north arm of Great Salt Lake to produce potash, sodium sulfate, magnesium chloride, and salt from the lake brine (Lewis, 1968). Lithcoa was acquired that same year by Gulf Resources and Minerals Co. (Houston, Texas) and at that point Gulf and Salzdetfurth began developing a \$38 million solar evaporation and processing plant west of Ogden (Knudsen, 1980). The new facility began operating in October, 1970. The plant was designed to produce 240,000 short tons (218,000 mt) of potassium sulfate, 150,000 short tons (454,000 mt) of magnesium chloride annually (Gulf Resources & Chemical Corporation, 1970; Eilertsen, 1971).

In May 1973, Gulf Resources bought its German partner's share of the Great Salt Lake project, and changed the name of the operations to Great Salt Lake Minerals and Chemicals Corp. (GSLM). At that time the German partner had also undergone some changes and was known as Kali und Salz A.G. (Gulf Resources & Chemical Corporation, 1973; Behrens, 1980; Industrial Minerals, 1984).

As Great Salt Lake rose to its historic high in the 1980s, GSLM spent \$8.1 million in 1983, \$8.1 million in early 1984, \$3.0 million in 1985, and \$4.8 million in 1986 to protect its evaporation pond system against the rising lake level. On May 5, 1984, a northern dike of the system breached, resulting in severe flooding and damage to about 85 percent of the pond complex. The breach resulted in physical damage to dikes, pond floors, bridges, pump stations, and other structures. In addition, brine inventories were diluted, making them unusable for producing sulfate of potash (Gulf Resources & Chemical Corporation, 1986). During the next five years, GSLM pumped the water from its solar ponds, reconstructed peripheral and interior dikes and roads, replaced pump stations, and laid down new salt floors in order to restart its operation.

As part of GSLM's most recent plans to increase the production of potassium sulfate, a large evaporation pond complex was constructed on the west side of the lake in 1994 (figure 7). The question of how to move concentrated brines from the new western ponds to the main evaporation-pond complex on the east side of the lake (figure 7), produced a unique answer. A 21-mile (33.8 km), open, underwater canal called the Behrens Trench was dredged in the lake's northarm floor, from the western pond's outlet near Strongs Knob to a pump station located just west of the southern tip of Promontory Point. The heavy brine from the west pond is fed into the low-gradient canal, where it flows slowly by gravity eastward, beneath the less-dense Great Salt Lake brine, to the primary pump station. From there, the heavy brine travels around the south end of Promontory Point, then northward, where it begins its journey through the final series of solar-evaporation ponds.

On April 1, 1998, GSLM was purchased by IMC Global and renamed IMC Kalium Ogden Corp. IMC Kalium is presently the largest producer of sulfate of potash in North America.

North Shore Limited Partnership

In 1996, North Shore Limited Partnership refurbished a small, 20-acre (8.1 ha) solar pond complex that had been used for salt harvesting in the early to mid-1900s, with the intent of producing highly concentrated brine (figure 7). Brine was pumped into the ponds in 1997, and the first concentrated bitterns were produced by the end of that year. These brines are processed and refined by a sister corporation, Mineral Resources International, which manufactures an entire line of human dietary supplements. Another sister company, Trace Minerals Research, markets these products.

FACTORS INFLUENCING BRINE CONCEN-TRATION AND SALT EXTRACTION

The initial concentration of the Great Salt Lake brine that is evaporated to produce salts and concentrated brines is of prime importance to mineral producers. This is because (1) the higher the feed-brine concentration, the greater the amount of dissolved salt there is per unit volume of brine that is pumped, and (2) at higher concentrations, less water must be evaporated to reach saturation so saturation can be achieved faster. The concentration of Great Salt Lake brines is influenced by two main factors: first, the natural long- and short-term balance between total inflow to the lake and evaporation, and second, the influence of the Southern Pacific Railroad's (SPRR) rock-fill causeway, which divides the main body of the lake into two parts, a north and a south arm (figure 7).

Two state-financed flood-control projects of the mid-1980s have influenced the salinity of the lake's two arms and salt-load distributions. These two projects were: (1) breaching the SPRR causeway in 1984, and (2) pumping lake water to a shallow desert basin west of the lake, commonly known as the West Desert. This latter project operated from April 1987 through June 1989. Additional information about the Great Salt Lake West Desert pumping project is found in Utah Division of Water Resources (1999).
Natural Rise and Fall of the Lake

The level of Great Salt Lake fluctuates on both an annual and a "long-term" basis (five to 20 years). Annually, the average fluctuation of the lake has been approximately 1.61 feet (0.49 m) for the south arm and about 1.33 feet (0.41 m) for the north arm, according to U.S. Geological Survey (USGS) provisional lake-level records. The lake is normally at its highest level in about May or June, and at its lowest in October or November. Records kept since the arrival of the Mormon pioneers in the Salt Lake Valley in 1847, show Great Salt Lake has exhibited long-term lake-level fluctuations that have a range of about 20 feet (6.1 m), from a low of 4,191.35 feet (1,277.52 m) above mean sea level (msl) in 1963 to a high of 4,211.85 feet (1,283.77 m) msl in 1987.

The salinity of the south arm of the lake rises and falls inversely with lake elevation, that is, as the lake level increases, the salinity decreases. It is interesting to note, however, that from 1966 to 1983, the salinity of the north arm did not follow that relationship as closely as the south arm, and remained relatively close to saturation during this time. This was because evaporation was equal to or greater than the diluting effects of the northward flow of lower salinity, south-arm water through the north-arm causeway into the north arm. During the lake's high-water years (1983-1987), increased precipitation and the lowered salinity of the southarm water flowing into the north arm overcame evaporation, and the north arm's salinity dropped as the lake level increased. From 1987 to the present time, the north-arm elevation has declined, and its salinity has increased to a level somewhat less than pre-1983 levels. Because the higher inflow of dilute south-arm brine through the breach opening equals or exceeds evaporation, north-arm brine salinity is still exhibiting an inverse relationship with lake elevation.

Influence of the SPRR Causeway

In 1960, the SPRR completed construction of a rock-fill railroad causeway across the lake from Promontory Point on the east to Lakeside on the western shore (figure 7). Once constructed, the causeway prevented the free circulation of water within the main body of the lake, and by 1966 had created a significant difference in the brine salinities of the south and north arms of the lake. The main reason for the difference in salinities is that the south arm of the lake receives the majority of the freshwater inflow to the lake (figure 7), while the north arm of the lake receives mainly salty water from the south arm. There was limited exchange of water between the two arms of the lake through the somewhat porous causeway fill and its two 15 x 20-foot (4.6 x 6.1 m) culverts, but not enough to prevent a salinity difference from developing. A hydraulic head differential also formed between the two arms of the lake across the causeway, as the south arm developed a higher surface elevation than the north. The south arm also became much less saline than the north arm. Figures 9a and 9b show lake elevations (uncorrected USGS provisional lake-level records) and lake salinities (UGS brine-chemistry database) for both the south and north arms of Great Salt Lake, respectively, since mid-1966.

The salinity of the south arm of the lake rises and falls inversely with lake elevation. It is interesting to note, however, that from 1966 to 1983, the salinity of the north arm did not follow the inverse relationship as closely as the south arm



Figure 9a. Water levels of the south arm of Great Salt Lake from 1965 to 2000 (top) and average weight percent salt in the brine (bottom).



Figure 9b. Water levels of the north arm of Great Salt Lake from 1965 to 2000 (top) and average weight percent salt in the brine (bottom).

did. Instead, it remained relatively close to saturation during this time. This was because evaporation was equal to or greater than the diluting effects of the northward flow of lower salinity, south-arm water into the north arm. During the lake's high-water years (1983 to 1987), increased precipitation and the lowered salinity of the south-arm water flowing into the north arm overcame evaporation, and the north arm's salinity exhibited an inverse relationship with lake level. From 1987 to the present time, the north arm has increased in salinity concentration to a level somewhat less than pre-1983 levels, but because of the inflow of dilute south-arm brine, it is still exhibiting an inverse relationship with lake elevation.

Breaching the SPRR Causeway

As the lake rose during the 1980s, it flooded, or threatened to flood, many public, private and industrial facilities around the lake. This prompted the State of Utah to investigate a number of flood-control measures, which included: (1) breaching the SPRR causeway, (2) upstream storage, (3) diversions of the Bear River, and (4) pumping water from the lake to the West Desert.

In 1984 the State of Utah first opted to breach the SPRR causeway by constructing a 300-foot (91.4 m) opening (figure 7). This action was designed to allow a greater rate of brine flow from the south arm to the north, and thereby reduce the 3.5-foot (1.06 m) head differential that had developed between the two arms of the lake by the end of 1983. The large head differential between the two arms was caused by the abnormally high inflows of fresh water into the south

arm, and by the rather impermeable nature of the SPRR causeway which restricted south-to-north flow. Within about two months after the causeway was breached on August 1, 1984, the head differential between the south and north arms had been reduced to less than 1 foot (0.3 m).

Shortly after the causeway was breached, bi-directional flow began to take place through the breach opening. Large amounts of low-salinity, south-arm water flowed northward through the upper part of the breach opening into the north arm, while at the same time, high-salinity, north-arm brine moved southward through the bottom part of the breach opening into the depths of the south arm, adding considerable volume to the existing deep, dense south-arm brine (Gwynn and Sturm, 1987). As a result of this bi-directional exchange of brines, the overall salt concentration of the south arm increased while that of the north arm decreased.

From the time the breach was constructed in 1984 until about December 2000, south-to-north flow through the breach opening occurred when the level of the south arm was above the 4,199.5-foot to 4,196-foot (1,280.00 m to 1,278.94 m) bottom elevation of the breach. Bi-directional flow occurred when there was more than six feet of water in the breach opening, and the head differential was low (usually less than 1 foot (0.3 m). In December 2000, the breach was deepened to a bottom elevation of about 4,193.0 feet (1,278.02 m) by the state. This will allow for greater north-to-south return flow.

Pumping to the West Desert

After the causeway was breached in 1984, the lake con-

tinued to rise, and the State of Utah again reviewed its floodcontrol options. In 1986, it opted to pump lake water to a 320,000-acre (130,000 ha) impoundment area in the West Desert, commonly known as the West Pond. The West Pond is located about 6 miles (10 km) east of the Bonneville Salt Flats, or 25 miles (40 km) east of the Utah-Nevada state line, and just north of Interstate Highway 80 (figure 8). The main purpose of this flood-control measure was to provide additional evaporative area for the lake, in addition to removing up to 690,000 acre-feet (850.8 hm³) of water from the lake. Pumping to the West Pond started on April 10, 1987, ended on June 30, 1989, and probably lowered the level of the lake by 1.5 to 2 feet (0.46 to 0.61 m) of the nearly 5.5-foot (1.67 m) drop that took place during that time. A total of 695 million short tons (630 million mt) of dissolved salt was removed from Great Salt Lake during the 26-month pumping period, amounting to about 14 percent of the lake's original salt load (Wold and Waddell, 1994). This removal of salt reduced the lake's (mainly the north arm) salt load and its overall salinity at a given lake elevation. About 386 million short tons (350 million mt) of the salt that was pumped to the West Pond remained there as brine or precipitated as crystalline salt when pumping ceased in June, 1989. This unusually large amount of salt was precipitated in the West Pond because the north-arm brine was relatively close to saturation when it was pumped from Great Salt Lake. Had south-arm water been pumped, as was specified in the initial pumpingproject design, less salt would have precipitated and more of the salt would have returned to the lake after the pumping stopped. North-arm water was pumped rather than southarm water as a project cost-saving measure. In addition to the estimated 386 million short tons (350 million mt) of dissolved salt retained in the West Pond, about 88 million short tons (80 million mt) of salt were diverted from the West Pond by AMAX, 10 million short tons (9 million mt) seeped into the ground, about 123 million tons (112 million mt) flowed out of the West Pond onto the Air Force Test and Training Range, and 88 million short tons (80 million mt) could not be accounted for. Only 94 million short tons (85 million mt) flowed back from the West Pond into Great Salt Lake (Wold and Waddell, 1994).

SUMMARY

Salt from Great Salt Lake was probably used by the Native Americans prior to Jim Bridger's visit to the lake in 1824-25, and was used by the region's early explorers and trappers after that time. The arrival of the Mormon pioneers

in 1847 signaled the beginning of the earliest, rudimentary commercial efforts to collect crude salt from along Great Salt Lake's shores and to boil down the lake's brine to obtain crystalline salt (halite).

From these early beginnings, the production of salt from the lake has grown to a large commercial industry, with development prior to 1964 of many of the salt-production techniques and equipment used today. Beginning in the early 1960s, research led to the development of techniques to produce other commodities such as potassium sulfate, magnesium metal, chlorine gas, magnesium chloride products, and nutritional supplements. Sodium sulfate was produced at one time, but is no longer marketed.

The Morton, Cargill, and IMC Salt Companies currently extract sodium chloride, which is precipitated during the early stages of evaporation when the brine concentration reaches saturation or about 26 percent salt. MagCorp produces magnesium metal and chlorine gas, and IMC Kalium produces potassium sulfate and magnesium chloride brine and flake products. These salt, gaseous, and metallic products are processed from the high-magnesium-chloride brines, and from the potassium and magnesium salts that are precipitated from the lake brine after it has been concentrated to the point where more than 95 percent of the original water has been removed.

In 1983, the lake's surface began its dramatic rise from a level of 4,200 feet (1,280.16 m) above msl to its historic high of 4,211.85 feet (1,283.77 m) msl in 1986-87. The state of Utah employed two flood-control measures to reduce damage caused by the rising lake waters: (1) breaching the SPRR causeway in 1984, and (2) pumping lake water to the West Desert in 1987. During the lake's high-water years, the mineral-extraction industries faced many challenges such as: (1) the need to raise dike heights to prevent flooding of facilities, (2) broken dikes that resulted in the inundation and loss of solar ponds, and (3) reduced brine salinities that resulted in lower annual salt production. Innovations and adaptations developed during and since the flooding years include the following: AMAX Corporation's utilization of the concentrated brines from the West Pond created through the state's West Desert Pumping Project, and Great Salt Lake Mineral's underwater Behrens Trench which conveys concentrated brines from a remote solar pond on the west side of the lake to the east side of the lake. There have also been numerous changes in corporate ownership and production-facility locations during the past 20 years.

It must be recognized that Great Salt Lake is a dynamic, hydrologic system, that is capable of supplying not only a long-term supply of minerals to the extractive industries, but its share of challenges for them as well.

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REAL ESTATE DEVELOPMENT, TRANSPORTATION COSTS, AND WASATCH FRONT GRAVEL OPERATIONS

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ABSTRACT

Extensive gravel deposits exist within a six-county area in the mountains surrounding the Salt Lake Valley, and in the mountain ranges to the west. The six-county area includes Davis, Salt Lake, Summit, Tooele, Utah, and Wasatch Counties. The majority of these are beach deposits from prehistoric Lake Bonneville. However, real estate development associated with a projected population increase of 54 percent over the next 20 years is expected to remove most gravel deposits in Salt Lake County from consideration for mining, forcing gravel operations to relocate from eastern Salt Lake Valley to the Oquirrh and Stansbury Mountains farther west. The gravels in these ranges are of lower quality and require additional processing to manufacture asphalt and concrete. Replacing gravel resources along the Wasatch Front with resources in the Oquirrh and Stansbury Mountains over the next 20 years has the potential to increase construction costs by nearly \$1 billion. The majority of this cost (82 percent) is the result of increased transportation costs due to longer distances to market. The remainder of the cost is attributable to lower quality gravels that will require additional processing in the manufacture of asphalt and concrete.

The following analysis and discussion does not take into consideration the amount of crushed stone that is currently being used in the construction industry in northern Utah, its use as a substitute for lower quality gravels, or as a factor in the base case projection.

ECONOMIC GROWTH AND REAL ESTATE DEVELOPMENT

Historically, the Wasatch Front cities of Salt Lake, Ogden, and Provo were the only urbanized areas in Utah (figure 1). Areas outside these three cities remained rural. However, rapid growth in the past ten years has resulted in large portions of the remaining rural areas of the Provo-Salt Lake City-Ogden corridor becoming developed. This development resulted in community pressure against current and proposed gravel operations. A citizens group in the cities of Highland and Alpine convinced city governments to oppose plans for a new gravel operation at the mouth of American Fork Canyon (Haney, 1998). Municipal planners for Salt Lake City and North Salt Lake have developed plans for reclaiming gravel operations on the Salt Lake-Davis county line, even though the deposits are estimated to contain several decades of reserves (Loomis, 1998), and operators were required to alter operating procedures for 24-hour operation to meet local demands (Loftin, 1998). A major local cement company abandoned plans for a pit on the Weber-Box Elder county line, north of Salt Lake City, citing "large public resistance" (Associated Press, 1998).

Development is also spreading east and west of the Wasatch Front. Summit County, east of Salt Lake City, is projected to have a 110 percent population increase in the next 20 years; while Tooele County, west of Salt Lake, is projected to have a 92 percent population increase in the next 20 years. Wasatch County, southeast of Salt Lake City, is projected to have a 102 percent population increase in the same time period (Utah State Governor's Office of Planning and Budget, 1999). Development in Summit, Tooele, and Utah Counties will affect the geographic location of gravel demand. Therefore, two phenomena will alter transportation costs associated with hauling gravel. First, the pits will be located in different areas and secondly, construction activities, the major use of gravel, will become more geographically diverse.

Rapid development and population increases have necessitated major highway reconstruction projects and associated large uses of gravel. The Interstate 15 (I-15) freeway through the Salt Lake Valley (figure 2), originally built during the 1960s, is currently being rebuilt. This project was started in 1996 and is scheduled for completion in 2001. The project includes completely rebuilding 16.5 miles (26.4 km) of freeway, increasing the number of traffic lanes from three lanes in each direction to six lanes in each direction, and replacing 130 bridges and several major interchanges. The project will require over 5 million cubic yards (3.8 million m³) of fill material.

Additional major freeway reconstruction projects are planned for the future. The Utah Department of Transportation (UDOT) is finalizing plans to reconstruct an additional 21 miles (34 km) of I-15 north of Salt Lake City. This I-15 North project will increase the number of traffic lanes from three lanes in each direction to five lanes in each direction. In addition, the state has plans to build an additional fourlane, limited-access, divided highway, designated the Legacy Highway, west of I-15. This highway will extend 13 miles (21 km) from Interstate 215 (I-215) in Salt Lake County north to I-15 and U.S. Highway 89 in the center of Davis County (Utah Department of Transportation, 1999). Envi-



Figure 1. The six-county study area in northern Utah showing current and future gravel sources and centers of consumption.



Figure 2. The location of major U.S. highways and interstate freeways in Salt Lake and Davis Counties, Utah.

ronmental groups are currently challenging the alignment of this highway on the basis of potential damage to wetlands adjacent to Great Salt Lake. Rebuilding Interstate 80 (I-80) from the I-15 interchange eastward to the edge of the Salt Lake Valley is also being considered. The I-15 reconstruction has had a major impact on gravel consumption in northern Utah, and future highway reconstruction projects undoubtedly will continue to consume large amounts of gravel.

WASATCH FRONT GRAVEL DEPOSITS

Extensive gravel deposits exist within the Salt Lake Valley, along the Wasatch Front (eastern Davis, Salt Lake, and Utah Counties), and in the mountain ranges to the west of Salt Lake City (the Oquirrh Mountains along the Salt Lake-Tooele county line and the Stansbury Mountains farther west). The majority of these deposits are lake shorelines (benches) formed by prehistoric Lake Bonneville. Three major benches were deposited by ancient Lake Bonneville at various elevations; the Bonneville bench (upper), the Provo bench (middle), and the Stansbury bench (lower). Not all Lake Bonneville benches are suitable for mining gravel. The Bonneville bench has the largest extent of gravel resources. Most of the gravel deposits associated with the benches are well classified due to wave action. In Salt Lake County, the Bonneville bench is prominent, but the gravel deposits associated with it are small. The Provo bench has a greater volume of gravel, with beds up to 80 feet (24 m) thick (Utah State Department of Highways, 1964a). In Davis County, the Bonneville bench contains a high percentage of sand (Utah State Department of Highways, 1964b). There are also some deposits along the Wasatch Front associated with alluvial fans and river deltas. The gravel pits at the mouth of Weber Canyon are producing from river delta deposits. These pits extend six to eight miles (10 to 13 km) north, west, and south of the mouth of Weber Canyon. The pits are worked for gravel, and, within individual beds, tend to have a fairly uniform size distribution (Utah State Department of Highways, 1971a).

Tooele County contains large amounts of lake bench, spit, and bar deposits. The best example is the bar near Stockton, which separates Tooele Valley from Rush Valley. There are also some silica, oolite, and gypsum sand dunes around the southern shore of Great Salt Lake and areas west of the lake which have been used for fill (Utah State Department of Highways, 1971b).

The majority of the gravel deposits in western Utah County are Lake Bonneville benches, spits, bars, and deltas; however, some more recent stream deltas and channel deposits also have been mined for gravel. Summit County, Wasatch County, and eastern Salt Lake and Utah Counties are in the middle Rocky Mountains and were not covered by Lake Bonneville; thus lacking the large lake bench deposits found to the west. The major deposits in these areas are river terrace deposits, although there are some deposits in alluvial fans and glacial moraines (Utah State Department of Highways, 1971c; Utah State Department of Highways, 1964c).

Gravel for Portland cement concrete must be resistant to physical and chemical alterations. Cherts common in the southern and western Salt Lake Valley react with alkali cement. Many gravel deposits along the Wasatch Front contain weathered quartz monzonite, which readily crumbles. Schists often are unsuitable for concrete gravel because of cleavage (Utah State Department of Highways, 1964a).

Current Wasatch Front Gravel Operations

There were 33 full time and 47 intermittent gravel operations located within Salt Lake County and adjoining Davis, Summit, Tooele, Utah, and Wasatch Counties in 1998 (table 1). About half of the full-time operations (17 of the 33) were concentrated in Salt Lake County. An additional 7 operations (21 percent) were in Utah County. The intermittent operations were similarly concentrated in Salt Lake and Utah Counties. Each of these counties contained 21 intermittent gravel operations, or 45 percent of total intermittent operations.

Gravel pit employment was concentrated in Salt Lake and Utah Counties. Of the 460 persons employed by fulltime operations, 246 (53 percent) are employed in Salt Lake County. An additional 101 persons (22 percent) were employed in Utah County. Salt Lake and Utah Counties were also responsible for 96 percent of the intermittent employment. The employment numbers listed are only the Mine Safety and Health Administration (MSHA)-regulated employees; there are additional employees, notably truck drivers, that are not MSHA regulated.

Table 1.Number of gravel operations and MSHA-regulated employees at those operations along the Wasatch Front, Utah in 1998 (data from Mine, Safety and Health Administration, written communication, 1998).							
Number of Operations Number of Employees							
County	Full Time	Intermittent	Full Time	Intermittent			
Davis	4	0	51	0			
Salt Lake	17	21	246	96			
Summit	1	1	6	1			
Tooele	2	3	52	3			
Utah	7	21	101	101			
Wasatch	2	1	4	4			
Total	33	47	460	205			

Gravel Usage

Uses of gravel by category in Utah have been fairly consistent since 1974 (table 2) (U.S. Bureau of Mines, 1997). The primary use of gravel was for general construction aggregate; consuming 53 percent of mined gravel from 1974 through 1996. The primary uses for this aggregate were for fill material and road base, although smaller amounts were used for snow and ice control and other miscellaneous applications. About 32 percent of the gravel produced in Utah is used as concrete aggregate; while the remainder, approximately 15 percent, is used as asphalt aggregate. The average percentage uses of gravel in table 2 were utilized to forecast future gravel production in Utah.

Table 2.Uses of gravel in Utah (percent of total) from 1974 through 1996 (U.S.B.M., 1997).						
Year	General construction	Asphalt	Concrete			
1974	48%	13%	39%			
1977	52%	19%	29%			
1978	49%	18%	33%			
1979	50%	17%	33%			
1980	45%	13%	42%			
1982	42%	17%	41%			
1984	49%	17%	34%			
1986	67%	17%	16%			
1988	62%	15%	23%			
1990	47%	17%	36%			
1992	53%	15%	32%			
1994	59%	14%	27%			
1995	59%	15%	26%			
1996	55%	10%	35%			
Average	53%	15%	32%			
Std. Dev.	. 7%	2%	7%			

Future Wasatch Front Gravel Consumption

Utah's gravel production has increased substantially since 1971 (figure 3) (U.S. Geological Survey, 1999). Gravel production in 1971 was 10.5 million tons (9.4 million mt); by 1998 production had increased to 44.0 million tons (40 million mt). The significant increase from 27.2 million tons (24.5 million mt) in 1996 to 44.0 million tons (40 million mt) in 1998 coincided with the reconstruction of I-15. While production has increased over time, it has also been cyclic with general economic conditions. For instance, the 1973 production of 15.4 million tons (13.9 million mt) was 96 percent greater than the long-term trend line. Similarly, the 1982 production of 7.6 million tons (6.8 million mt) was only 52 percent of the long-term trend line. The long-term trend line was derived using a linear regression of production from 1971 through 1998 versus the year of production. The trend can be expressed mathematically as:

Production = 751.4285 X Year - 1,474,728

with production being expressed in thousands of tons and the year being greater than 1970. This equation was used to project Utah gravel production into the future. Over time, the cyclicity in production tends to cancel, with the actual production nearing that predicted by the trend line. From 1971 through 1998, cumulative gravel production in Utah was 461.5 million tons (415.4 million mt), and the trend line predicted exactly the same amount. This equation was developed using production data for 1997 and 1998, which included the massive I-15 reconstruction project. Future highway projects, I-15 North through Davis County and the Legacy Highway among others, undoubtedly will continue to influence Utah gravel production in the foreseeable future.

Future Gravel Operations

Future gravel operations serving the six-county area examined in this study will most likely be located in the southern portion of the Oquirrh Mountains, near Cedar Valley, Rush Valley, and the Stansbury Mountains west of Tooele. Increased land use for housing is removing the deposits along the Wasatch Front, and the few large, high quality deposits that exist farther east, from consideration for development. Davis County is experiencing rapid real estate development creating conflicts between proposed gravel operations along the Wasatch Front north of Davis County and new home owners (Associated Press, 1998); therefore, most gravel used in Davis County in the future will come from the nearest available deposits in northern Tooele County.

In Salt Lake County, there are few high-quality gravel deposits east of the Salt Lake Valley (Utah State Department of Highways, 1964a). In addition, large portions of this area are U.S. Forest Service lands that receive high recreational use so it is unlikely that sand and gravel extraction would be allowed. Therefore, the majority of gravel used in Salt Lake County in the future will be from deposits in northern Tooele Valley, or from deposits in the southern Oquirrh Mountains.

In Utah County, the cities of Saratoga Springs (at the north end of Utah Lake), and Eagle Mountain (in the northern end of Cedar Valley) recently incorporated. The societal pressure on the current gravel operations in eastern Utah County, coupled with projected real estate development in the newly incorporated cities, will force future gravel operations west, into the Five Mile Pass area on the Utah-Tooele county line.

Tooele County is projected to have a 78 percent population increase in the next 20 years (Utah State Governor's Office of Planning and Budget, 1999). The majority of the growth will occur at the north end of Tooele Valley which allows easy access to Salt Lake City via I-80. This development will preclude gravel operations in the northwest Oquirrh Mountains. In the future, gravel used in Tooele Valley will be mined in the Stansbury Mountains to the west or in the Oquirrh Mountains farther south.

Wasatch and Summit Counties have few high-quality gravel deposits (Utah State Department of Highways, 1971d; Utah State Department of Highways, 1964c), and have projected population increases of 86 percent and 91 percent, respectively, by the year 2020 (Utah State Governor's Office of Planning and Budget, 1999). The resultant increase in real estate development most likely will preclude the future use of river-terrace gravel deposits, the best deposits available in these counties (also prime real estate development potential), forcing gravel to be brought in from other areas.

METHODOLOGY AND CALCULATIONS

To estimate future costs incurred by using sources of gravel in Tooele County and western Utah County instead of those along the Wasatch Front, several base-case assumptions were made. These include:

- Utah gravel production increases linearly according to the long-term trend described in figure 3;
- (2) Individual county gravel consumption is proportional to population. Population estimates from the Utah Governor's Office of Planning and Budget (1999)were used;
- (3) Use of gravel is 52 percent for general construction aggregate, 32 percent for concrete aggregate, and 16 percent for asphalt aggregate;
- (4) New sources will provide gravel for the major uses in proportions equal to the end use of gravel;
- (5) Trucking costs and capacity for the three main uses of gravel are:
 (a) general construction aggregate \$75/hr truck operating costs and 40 ton (36 mt) truck capacity,
 (b) asphalt aggregate \$75/hr truck operating costs and 40 ton (36 mt) truck capacity, and
 (c) concrete aggregate \$65/hr truck operating costs and 7.4 cubic yard (5.7 m³) truck capacity;
- (6) An average speed of 35 miles (56 km) per hour is used for gravel haul trucks (this is the average speed for operating the truck, including loading, unloading, and travel time);
- (7) Lower quality gravel deposits from the Oquirrh and Stansbury Mountains will require an additional expenditure of \$4.20 per ton (\$4.62 per mt) of gravel used to make them suitable for use in manufacturing asphalt. This additional cost includes additional liquid asphalt, lime, and screening. An additional \$1.58 per ton (\$1.74 per mt) of gravel used for manufacturing concrete will be required for the cost of additional cement;
- (8) Real estate development and societal pressures will force gravel production from the Wasatch Front to the Oquirrh and Stansbury Mountains over the next 20 years;
- (9) Gravel production will move to new sites in a linear manner; and
- (10) Future cash flows are discounted at 5 percent.

Haulage distances and sources of gravel for the six subject counties are described below. A spreadsheet model was



Figure 3. Past Utah gravel production (through 1998) and future trend with confidence limits.

developed to predict the additional cost, incorporating the above assumptions. The model was developed allowing each assumption to vary in order to examine different scenarios.

Haulage Distances

Haulage distances were determined by identifying central points in each of the six counties and measuring the highway distances from major gravel operations supplying those counties. This method was used in estimating current haulage distances (table 3) as well as distances in 20 years under two scenarios; first, the center of population changes, but the source of gravel does not (table 4), and secondly, both the source of gravel and the center of population changes (table 5). Haulage distances for intervening years were estimated by assuming that travel distances change linearly with time. For several counties, Davis, Salt Lake, Summit, Utah, and Wasatch, two sources of gravel were assumed and the haul distances were averaged.

Future centers of gravel consumption were determined using "centers of population density" determined by population density estimates, and the amount and location of developable land in the subject counties. In four counties, Davis, Salt Lake, Tooele, and Wasatch, the center of consumption did not change. Davis, Salt Lake, and Wasatch Counties all have a central valley bounded by mountains, or the Great Salt Lake in the case of western Davis County. Large portions of these mountains are also protected U.S. Forest Service lands. Therefore, it was assumed that development would be focused in the valleys of these counties.

Tooele County development is occurring north of the city of Tooele; therefore, Mills Junction was selected as the future center of gravel consumption for Tooele County. The

Table 3. Current gravel sources and centers of gravel consumption in six counties in northern Utah.						
County	Gravel Source	Center of Consumption	Distance, miles (km)			
Davis	 Salt Lake-Davis county line and I-15 Intersection of I 84 and U.S. Highway 89 	I-15, U.S. Highway 89 junction in Farmington	8.9 (14.2)			
Salt Lake	 Salt Lake-Davis county line and I-15 Salt Lake-Utah county line and I-15 	7200 South and State Street	17.1 (27.4)			
Summit	 Salt Lake-Davis county line and I-15 Mouth of Big Cottonwood Canyon 	I-80 and U.S. Highway 40 interchange	30.7 (49.1)			
Tooele	Tooele City	Mills Junction	8.3 (13.3)			
Utah	 Salt Lake-Utah county line and I-15 Santaquin 	Utah Highway 114 and I 15 interchange in Provo	19.0 (30.4)			
Wasatch	Salt Lake-Utah county line and I-15	Heber City	41.9 (67.0)			

Table 4.

Year 2020 gravel sources and centers of consumption in six counties in northern Utah, assuming current sources remain in operation.

County	Gravel Source	Center of Consumption	Distance, miles (km)
Davis	 Salt Lake-Davis county line and I-15 Intersection of I 84 and U.S. Highway 89 	I-15, U.S. Highway 89 junction in Farmington	8.9 (14.2)
Salt Lake	 Salt Lake-Davis county line and I-15 Salt Lake-Utah county line and I-15 	7200 South and State Street	17.1 (27.4)
Summit	 Salt Lake-Davis county line and I-15 Mouth of Big Cottonwood Canyon 	Mayflower exit on U.S. Highway 40	39.9 (63.8)
Tooele	Tooele City	Mills Junction	8.3 (13.3)
Utah	 Salt Lake-Utah county line and I-15 Santaquin 	Utah Highway 52 and I-15 interchange in Orem	14.9 (23.8)
Wasatch	Salt Lake-Utah county line and I-15	Heber City	41.9 (67.0)

Table 5. Year 2020 gravel sources and centers of consumption in six counties in northern Utah, assuming gravel operations are moved.						
County	Gravel Source	Center of Consumption	Distance, miles (km)			
Davis	1. Stansbury Mountains	I-15, U.S. Highway 89 junction in Farmington	59.7 (95.5)			
Salt Lake	 Utah-Tooele county line and Utah Highway 72 (Five Mile Pass) Stansbury Mountains 	7200 South and State Street	51.9 (83.0)			
Summit	 Utah-Tooele county line and Utah Highway 72 (Five Mile Pass) Tooele City 	Mayflower exit on US 40	80.1 (128.2)			
Tooele	Stansbury Mountains	Mills Junction	13.0 (20.8)			
Utah	Utah-Tooele county line and Utah Highway 72 (Five Mile Pass)	Utah Highway 52 and I-15 interchange in Orem	33.7 (53.9)			
Wasatch	Utah-Tooele county line and Utah Highway 72 (Five Mile Pass)	Heber City	52.4 (83.8)			

Park City area in Summit County is growing rapidly; therefore, the current center of consumption was assumed to be the I-80-U.S. Highway 40 interchange near Park City. Because extensive real estate development is planned along the eastern shore of Jordanelle Reservoir farther to the east, the future center of consumption was chosen to be the Mayflower exit on U.S. Highway 40 near the reservoir. In Utah County the current center of consumption was assumed to be the center of Provo City and the I-15- Utah Highway 114 exit that leads into downtown Provo. Because several cities have recently been incorporated in northern Utah County, the future center of consumption was moved northward to the I-15-Utah Highway 52 interchange in Orem.

Economic Effect of Moving Gravel Sources

Locating gravel operations from high-grade deposits along the Wasatch Front westward to the Oquirrh and Stansbury Mountains will have a significant economic impact. By the year 2020, relocating gravel production for the six counties to Tooele County and western Utah County could double the price of gravel due to additional transportation costs alone. The model output for the base case described above is presented in table 6. The total estimated cost of relocating gravel sources for the six subject counties to the Oquirrh and Stansbury Mountains over the next 20 years is nearly one billion dollars (discounted at 5 percent). The majority of this

Table 6. Model output for the base case described in text (\$ x 1,000) for years 2000 through 2020.								
Year	Extra Trucking Costs	Discounted Trucking Costs	Extra Asphalt Costs	Discounted Asphalt Costs	Extra Cement Costs	Discounted Cement Costs	Total Extra Costs	Discounted Total Extra Costs
2000	5,151	4,906	634	604	477	455	6,263	5,965
2001	10,576	9,593	1,303	1,182	980	889	12,859	11,664
2002	16,346	14,120	2,012	1,738	1,514	1,308	19,871	17,166
2003	22,175	18,243	2,735	2,250	2,058	1,693	26,968	22,187
2004	28,386	22,241	3,505	2,746	2,637	2,066	34,528	27,053
2005	34,868	26,019	4,308	3,214	3,241	2,418	42,416	31,652
2006	41,620	29,579	5,144	3,656	3,870	2,750	50,634	35,985
2007	48,631	32,915	6,013	4,070	4,524	3,062	59,168	40,047
2008	55,917	36,045	6,916	4,458	5,203	3,354	68,036	43,856
2009	63,469	38,965	7,852	4,820	5,907	3,627	77,228	47,411
2010	71,503	41,806	8,847	5,173	6,656	3,892	87,006	50,871
2011	79,386	44,205	9,822	5,469	7,390	4,115	96,599	53,790
2012	87,757	46,540	10,857	5,758	8,169	4,332	106,784	56,630
2013	96,415	48,696	11,927	6,024	8,974	4,532	117,315	59,252
2014	105,338	50,670	13,030	6,268	9,803	4,716	128,172	61,653
2015	114,548	52,476	14,168	6,491	10,660	4,883	139,376	63,850
2016	124,038	54,117	15,342	6,694	11,543	5,036	150,923	65,847
2017	133,769	55,584	16,551	6,877	12,452	5,174	162,772	67,635
2018	143,770	56,895	17,794	7,042	13,388	5,298	174,952	69,234
2019	154,024	58,050	19,072	7,188	14,350	5,408	187,446	70,646
2020	164,558	59,067	20,386	7,317	15,338	5,506	200,282	71,890
Total % of Total	\$1,602,246 82%	\$800,731 82%	\$198,218 10%	\$99,038 10%	\$149,135 8%	\$74,515 8%	\$1,949,599 100%	\$974,284 100%

cost (82 percent) is due to increased transportation costs as a result of longer haul distances.

These calculations indicate the cost of gravel production if it were moved westward, not the market price for the consumer. The market price is dependent upon the elasticities of supply and demand curves. If the demand curve is sufficiently inelastic (where the increased cost does not significantly decrease demand), then most of the cost increase will be passed on to the consumer. However, should demand be significantly impacted, gravel producer's operating margins will drop to a point where production will meet the decreased level of demand.

Plotting the future value of sand and gravel production in Utah, with and without additional trucking costs, (figure 4), indicates that trucking costs alone will significantly increase the price of gravel and therefore, the cost of related construction in northern Utah. The linear projection of present data indicates that by year 2020, the value of gravel produced in Utah could reach \$139.9 million. However, when the cost of additional trucking is considered, the value of gravel production in the year 2020 increases to \$300 million, an increase of 117 percent. Interestingly, the major increase in trucking cost is related to transporting gravel over longer distances into Davis, Salt Lake, and Utah Counties. The larger quantities of gravel required in these counties is more significant in determining cost than is the longer haul distances to counties farther east. Approximately 60 percent of the extra trucking cost is attributed to Salt Lake County, with 24 percent and 13 percent of the additional cost being attributed to Davis and Utah Counties, respectively. Summit County is responsible for only 2 percent of the additional trucking costs, despite longer haul distances into Summit County from the Oquirrh Mountains. Tooele and Wasatch Counties are each responsible for less than 1 percent, as a result of their lower populations.

Lower quality gravels located in the Oquirrh and Stansbury Mountains will also have an effect on construction economics. These gravels will require approximately 1 percent more liquid asphalt and \$1.20 more lime per ton (\$1.32 per mt) of aggregate to manufacture asphalt suitable for road construction. Also, these gravels are not as well sorted as Wasatch Front deposits, requiring additional screening to separate them into respective size fractions. This cost is estimated to be approximately \$1.50 per ton (\$1.65 per mt). The total cost of this extra processing and additional additives is estimated to be approximately \$4.20 per ton (\$4.60 per mt) of manufactured asphalt, and that an additional cost of \$1.58 per ton (\$1.74 per mt) will be required to manufacture concrete (Case, T., Associated General Contractors of Utah, oral communication, 1999). The total cost over 20 years is estimated to be \$100 million. These gravels will also require additional cement to manufacture concrete. This amount is estimated to be one-half a bag (47 lbs) of cement per cubic vard (28 kg of cement per m³) of concrete. The total cost of this extra cement is estimated to be \$75 million over the next 20 years.



Figure 4. Effect of additional transportation costs on the value of gravel produced in northern Utah from year 2000 through 2020 as a result of moving to new gravel sources.

The rate at which gravel operations are forced to move from the Wasatch Front to the Oquirrh and Stansbury Mountains will also have a major effect on costs over the next 20 years (figure 5). If all Wasatch Front gravel operations are forced to close within the next five years, the total cost over the next 20 years is estimated to be \$1.8 billion, discounted at 5 percent. Extending the time to close Wasatch Front gravel operations to 20 years decreases the cost to \$1.0 billion, a relative decrease of 45 percent. Extending the time to close Wasatch Front gravel operations to a 50-year period decreases the total cost to \$409 million; 23 percent of the cost if only five years are allowed to move to new gravel sources. The discount rate used to value future costs has a significant effect on determining the total cost of moving to new sources of gravel (figure 4). If one assumes that new sources of gravel are located over a 20-year period, the total cost over that time period will be \$1.4 billion if future costs are discounted at 2.5 percent. The total cost drops to \$334 million if a discount rate of 15 percent is used over that same time period.

The discount rate is a function of two items, a required rate of return, and expected inflation. Furthermore, the rate of return and inflation undoubtedly will vary over the next 20 years. This makes identifying a proper discount rate to use



Figure 5. Effect of time and discount rate to move gravel operations on total extra costs over the next 50 years.

in evaluating future cash flows difficult. A survey conducted in 1984 of Departments of Transportation for 45 states, the District of Columbia, and three Canadian provinces found discount rates from 4 percent to 10 percent being used to evaluate highway construction projects (Peterson, 1985). Grant, Ireson, and Leavenworth (1982), recommended using a discount rate of 7 percent. However, their data was published in 1982, when inflation and interest rates were higher than at present. Based on several decades of data, the Portland Cement Association found that discount rates of 1 to 2.5 percent are commonly used after accounting for inflation (Peterson, 1985). Given the current inflation rate of approximately 2 percent would result in a nominal discount rate of 3 to 4.5 percent. Therefore, using a 5 percent discount rate for the base case appears to be reasonable. Should the inflation rate increase, the discount rate should also increase.

CONCLUSIONS AND RECOMMENDATIONS

Relocating Wasatch Front gravel operations westward to the Oquirrh and Stansbury Mountains over the next 20 years has the potential to cost the northern Utah construction industry as much as \$1 billion. The majority of this cost is due to additional transportation costs due to increased haul distances. The remainder of the cost is due to additional processing required to manufacture asphalt and concrete from lower quality gravels in the Oquirrh and Stansbury Mountains.

Gravel operators should consider selectively moving general construction aggregate production to the western mountain ranges, while continuing to produce asphalt and concrete aggregate from higher quality gravels along the Wasatch Front.

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BERYLLIUM DEPOSITS AT SPOR MOUNTAIN, UTAH

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ABSTRACT

The world-famous beryllium deposits at Spor Mountain, northwest of Delta, Utah, are the principal resource of beryllium in the United States. Beryllium metal, beryllium-metal alloys, and beryllium oxide ceramics have a long history of specialty applications. Beryllium is used in X-ray windows, nuclear reactors, and a wide variety of industrial and electronic products.

The Spor Mountain deposits are located on the western rim of the Thomas caldera, one of at least three volcanic depressions that subsided during voluminous eruption of rhyolitic ash-flow tuff in early Oligocene time. Beginning in early Miocene time, the caldera rim and its volcanic fill were cut extensively by basin-and-range faults. Basin-and-range faulting was accompanied by local eruption of high-silica rhyolite. High-silica topaz rhyolites at Spor Mountain (21 Ma) and Topaz Mountain (6 to 7 Ma) are especially rich in fluorine and lithophile trace elements such as beryllium. Topaz rhyolite of the Miocene Spor Mountain Formation, or its magma, was the source of the Spor Mountain beryllium deposits.

At Spor Mountain, deposits of beryllium, as submicroscopic bertrandite, $Be_4Si_2O_7(OH)_2$, occur in rhyolite tuff beneath flows and domes of topaz rhyolite. The beryllium deposits also contain minor disseminated fluorite, lithium, uranium, and anomalous traces of other lithophile elements. The host tuff, originally composed of glass, zeolite, and abundant clasts of carbonate rock, has been altered to clay and potassium feldspar. Fluorite, quartz, and opal replaced carbonate clasts in the tuff. Beryllium was deposited with fluorite in altered clasts and in the matrix of altered tuff.

Fluorspar and uranium deposits are spatially and genetically associated with the beryllium deposits at Spor Mountain. Fluorspar deposits at Spor Mountain occur mostly in breccia pipes. Some fluorspar pipes contain uranium, thought to be dispersed in the structure of fluorite. Secondary uranium minerals are dispersed throughout the tuff that hosts beryllium deposits and comprise lenses of oregrade uranium at the Yellow Chief mine.

APPLICATIONS, RESOURCES, AND PRODUCTION

Beryllium metal, beryllium-metal alloys, and beryllium oxide ceramics have a long history of specialty applications (Mulligan, 1968; Griffitts, 1973; Cunningham, 1997; Brush Wellman, Inc., 1998). Beryllium metal has a small nuclear cross section, light weight, and a high melting point. Beryllium-copper alloy is an excellent conductor of heat and electricity. Beryllium oxide is a heat dissipating electrical insulator. Beryllium metal is used in windows in X-ray tubes and as neutron moderators and reflectors in nuclear reactors. Beryllium alloys (copper and aluminum) are used in a wide variety of industrial and aerospace applications requiring exceptional strength, light weight, and durability. Berylliumcopper alloys and beryllium oxide are used in electronic components that must withstand high temperatures.

Beryllium deposits at Spor Mountain, in the Thomas Range of western Utah, are the principal resource of beryllium in the United States. The Spor Mountain mining district contains the world's largest economic deposits of beryllium, estimated at the time of discovery in 1959-60 to be 3.5 to 5 million short tons (st) (3.2-4.5 million metric tons [mt]) of ore averaging 0.6-0.7 percent BeO; sufficient to last 25 to 50 years at the then-current rate of U.S. consumption (Williams, 1963). Mining by open-pit methods began in 1968 and through 1984, approximately one million st (0.9 million mt) of ore had been mined and processed by Brush Wellman (Davis, 1984). In 1998, Brush Wellman reported ore reserves of 7.747 million st (7.028 million mt) averaging 0.719 percent BeO (0.259 percent Be) (Brush Wellman, Inc., 1998). In addition to beryllium, the district produced approximately 350,000 st (318,000 mt) of metallurgical grade fluorspar (>60 percent CaF₂) during the years 1944 through 1980 (Bullock, 1981), and prior to 1963 more than 100,000 st (91,000 mt) of uranium ore averaging 0.20 to 0.23 percent U₃O₈ (all from the Yellow Chief mine) (Bowyer, 1963). Some uranium has also been produced as a byproduct of processing beryllium ore (Brush Wellman, Inc., no date).

GEOLOGY

The geology of the Spor Mountain mining district has been studied by many geologists from the U.S. Geological Survey, industry, and academia. A slide show that summarizes the geologic setting of the beryllium deposits, history of volcanism and mineralization, major controls of mineralization, and probable processes of mineralization and alteration is available on the World Wide Web (Lindsey, 1998).

The Spor Mountain district is situated on the western margin of the Thomas caldera, one of at least three volcanic subsidence structures formed during Oligocene time (Shawe, 1972). These structures lie in an east-west trending belt of igneous rocks and mineral deposits, called the "beryllium belt of western Utah" (Cohenour, 1963), or the "Deep Creek-Tintic belt" (Hilpert and Roberts, 1964), which also includes other metal deposits outside the Spor Mountain district. Strong aeromagnetic anomalies, reflecting the presence of igneous stocks and thick accumulations of volcanic rocks in calderas, also delineate parts of the mineral belt (Bankey and others, 1998; Zietz and others, 1976).

Spor Mountain consists of a west-tilted fault block of mostly carbonate rocks of early Ordovician to Devonian age (figure 1) (Staatz and Osterwald, 1959; Staatz and Carr, 1964). Thrusts of the Sevier orogeny displaced the Paleozoic rocks of Spor Mountain during Cretaceous time. Around the foot of Spor Mountain, Paleozoic carbonate rocks are unconformably overlain by volcanic rocks of Eocene to Miocene age (figure 2) (Lindsey, 1979; 1982). The Thomas caldera subsided in Oligocene time and was filled with ash-flow tuff. The western margin of the caldera, marked by a narrow zone of faults and landslide breccias, is located at the east side of Spor Mountain. Beginning in early Miocene time, normal faulting cut both Paleozoic rocks and Tertiary volcanic rocks, producing the fault-block structure and topography typical of basin-and- range systems. All of the faults were potential pathways for mineralizing fluids.

All of the mineral deposits at Spor Mountain formed during topaz rhyolite volcanism, beginning at 21 Ma. Topaz rhyolite is distinctive in that it contains high silica (typically, 75 to 80 percent SiO₂) and fluorine (as much as 1 percent or more, in fluorite and topaz), and it contains anomalous trace amounts of lithophile elements, including beryllium and uranium. Two formations of topaz rhyolite and associated tuff have been mapped (Lindsey, 1979): (1) the Miocene Spor Mountain Formation (21 Ma), and (2) the Miocene Topaz Mountain Rhyolite (6 to 7 Ma). The Spor Mountain Formation is restricted to the vicinity of Spor Mountain, where it is extensively mineralized and cut by basin-and-range faults (figure 2). The Topaz Mountain Rhyolite makes up most of the Thomas Range, east of Spor Mountain. Topaz Mountain



Figure 1. Generalized geologic map of Spor Mountain, Utah, showing Paleozoic rocks, major faults, and mineral deposits (modified from Staatz and Carr, 1964: Shawe, 1968: Bullock, 1981; and Davis, 1984). Cross section A-A' is shown in figure 2.



Figure 2. Geologic cross section showing structure and stratigraphy of area of beryllium mining at Spor Mountain (section A-A' located on figure 1; from Lindsey, 1979).

Rhyolite is not faulted or mineralized for the most part, although it contains weak geochemical anomalies of fluorine and beryllium that probably emanated from the Spor Mountain district.

Tuff and flows of topaz rhyolite were formed by two contrasting styles of eruption (figure 3) (Burt and Sheridan, 1981). Initial eruption was explosive, producing coarsely stratified tuff ranging from fine ash to coarse pumice. Fragments of pre-rhyolite volcanic and carbonate rocks were also erupted with ash and pumice. Tuff of the Spor Mountain Formation (called informally the "beryllium tuff member") contains abundant fragments of Paleozoic carbonate rocks, which were important in localizing fluorite and beryllium deposition. Explosive eruption of tuff was followed by quiet eruption of thick, viscous rhyolite domes and flows. Rhyolite flows formed a caprock that protected the soft stratified tuff from erosion and channeled mineralizing fluids and ground water into the tuff. Margins of the rhyolite cooled quickly, forming vitrophyre and flow breccia. Locally, heat from the cooling rhyolite fused the top of the underlying tuff. In the Thomas Range, multiple episodes of explosive and quiet eruptions deposited layers of overlapping tuff and rhyolite that comprise the Topaz Mountain Rhyolite.

Beryllium Deposits

In much of the Spor Mountain mining district, beryllium is concentrated in the upper part of the beryllium tuff member of the Spor Mountain Formation. At the Taurus and North End mines, however, beryllium ore was found in more than one level in the tuff (Davis, 1984). Beryllium ore bodies are tabular, typically 5 to 10 feet (1.5-3 m) thick, and extend as much as 2 miles (4 km) along strike (figure 1) (Griffitts, 1964; Shawe, 1968). In detail, the ore bodies are complex and offset by small faults. Basin-and-range faults, having hundreds of feet of offset, tilt the ore bodies 10 to 30 degrees west (figure 2). The downdip minable extent of these ore bodies, which can be as much as 1,000 feet (300 m), is limited by an overburden of hard topaz rhyolite. The host tuff unconformably overlies older rocks and fills northeasttrending paleovalleys (Griffitts, 1964; Davis, 1984). The continuous extent of the tuff indicates that it probably covered most topographic features.

The ore body at the Roadside beryllium mine (figures 1 and 2), which has been studied more than any other Spor Mountain beryllium deposit (Griffitts and Rader, 1963; Shawe, 1968; Lindsey, Ganow, and Mountjoy, 1973), is thought to be typical. The host tuff is altered to smectite and potassium feldspar; the most intensely altered tuff is associated with the beryllium ore. As much as 5 to 10 percent fluorite, derived from alteration of carbonate clasts, accompanies beryllium. Lithium-bearing clay (Shawe, Mountjoy, and Duke, 1964), manganese-oxide minerals, and uranium minerals are found in



EXPLANATION



Figure 3. Idealized cross section showing rhyolite vents and ore deposits at Spor Mountain prior to erosion (modified from Burt and Sheridan, 1981).

the ore and adjacent altered tuff. Other constituents include quartz, cristobalite, opal and, in weakly mineralized host tuff, zeolite, glass, calcite, and dolomite.

The tuff surrounding beryllium ore contains distinct alteration zones and geochemical anomalies (figure 4) (Park, 1968; Lindsey, Ganow, and Mountjoy, 1973). Varying degrees of alteration of carbonate clasts in tuff define three zones (from top down): fluorite (with beryllium ore), calcite, and dolomite (unaltered clasts). The calcite zone mostly underlies ore and is accompanied by magnesium-rich trioctahedral smectite and anomalous traces of lithium (up to 1,000 Lithium occurs in trioctahedral smectite, formed ppm). when magnesium was leached from dolomite clasts by mineralizing fluids. Anomalous amounts of manganese and uranium (up to 200 ppm) broadly accompany beryllium ore but are more dispersed than beryllium. Manganese occurs as secondary (?) oxide minerals in veinlets, pores, and rinds on altered clasts. Among manganese oxide minerals at Spor Mountain, pyrolusite and cryptomelane are common; psilomelane, chalcophanite, and todorokite (?) have also been identified. Some uranium occurs in uraniferous opal veinlets, but most is in yellow secondary uranium minerals including beta-uranophane.

Alteration zones preserved in nodules (originally dolomite clasts) in mineralized tuff reflect the overall downward zonation of alteration in the beryllium tuff member of the Spor Mountain Formation (Lindsey, Ganow, and Mountjoy, 1973). Commonly called "beryllium nodules," individual altered clasts exhibit colorful zones of (from outside in) purple to white fluorite and opal, quartz, and calcite. Quartz and calcite zones vary widely in color, but are commonly gray, white, or some shade of brown. Spectrochemical analyses of individual mineral zones reveal more than 1 percent beryllium concentrated in fluorite-rich zones. Other trace elements, such as lithium and uranium, are likewise concentrated in fluorite. The only known beryllium mineral in the Spor Mountain deposits is bertrandite, $Be_4Si_2O_7(OH)_2$ (Griffitts, 1964). Bertrandite at Spor Mountain is submicroscopic, and is best identified by X-ray diffraction of concentrates. Bertrandite concentrates can be readily prepared by dissolving beryllium-rich fluorite nodules in a hot solution of concentrated, acidified AlCl₃ (Stevens and others, 1962). Bertrandite also occurs in the matrix of tuff, but is more difficult to isolate for identification.

Fluorspar and Uranium Deposits

Fluorspar and uranium deposits are spatially and genetically associated with the beryllium deposits at Spor Mountain. Fluorspar deposits at Spor Mountain occur mostly as replacements of carbonate rock in breccia pipes (figure 3) (Staatz and Osterwald, 1959; Thurston and others, 1954). Pipes occur singly or in groups along faults and at fault intersections in Paleozoic rocks at Spor Mountain. Small plugs of topaz rhyolite intrude a few of the pipes. Fluorite forms veins, boxworks, and earthy masses (Bullock, 1981); fluorite veins traverse pipes. Clay and silica are common gangue minerals in pipes. Borders of pipes are transitional into brecciated carbonate wallrock. Uranium, thought to be dispersed in the structure of fluorite, occurs in some fluorspar pipes; anomalous concentrations of beryllium are not known.

Secondary uranium minerals comprise tabular lenses of ore-grade uranium at the Yellow Chief mine (Bowyer, 1963). The host rock is a lens of tuffaceous sandstone and conglomerate that directly underlies the beryllium tuff member. From observation of drill cuttings, the host unit can be traced in the subsurface south of the mine. The unit is conformable to the overlying beryllium tuff and was mapped with the latter (Lindsey, 1979). Ore lenses are typically 30 feet (9 m) across and 2 to 6 feet (0.6 to 1.8 m) thick. The principal ore



Figure 4. Vertical profiles showing typical zones of alteration and elemental concentrations associated with beryllium deposits in tuff at Spor Mountain (generalized from Griffitts and Rader, 1963; Park, 1968; Lindsey and others, 1973; and Lindsey, 1982). PPM, parts per million; PCT, percent.

mineral at the Yellow Chief mine was beta-uranophane, but weeksite was the principal uranium mineral in a small ore lens left exposed near the top of the pit when mining ceased (Lindsey, 1982). No reductant or roll-like structure has been observed. No mineral alteration or concentration of other elements, such as fluorine and beryllium, is present in the Yellow Chief deposit.

Origin of the Spor Mountain Deposits

Mineralization by both hydrothermal and meteoric fluids (composed mostly of water) has been proposed to explain the origin of mineral deposits at Spor Mountain. As proposed, hydrothermal mineralization involves hot fluids ascending from a heat source, such as magma or a cooling pluton, through a plumbing system of vents, faults, and porous tuff (Staatz and Griffitts, 1961; Shawe, 1968; Lindsey and others, 1973). Fluorine and beryllium were expelled from cooling magma, or leached from a concealed pluton or country rock, and deposited as fluorite and bertrandite during cooling and reaction with carbonate rock in breccia pipes and tuff. Mineralization by meteoric fluids, perhaps heated by rhyolite lava, was proposed as an alternative to hydrothermal mineralization (Burt and Sheridan, 1981). Descending fluids leached fluorine and beryllium from cooling rhyolite and deposited fluorite and bertrandite in tuff and carbonate rocks directly beneath rhyolite.

The two alternative proposals for mineralization at Spor Mountain are not mutually exclusive. Convection systems of meteoric fluids, with or without a magmatic component, can be driven through faults and tuff by heat from the geothermal gradient or from cooling rhyolite. Such systems are often called "hydrothermal," even though the source of hydrothermal water is mostly or entirely meteoric and not from magma. Additionally, ore deposits can be redistributed by cool ground water after initial formation. Such supergene redistribution is undoubtedly responsible for concentrations of oxidized secondary minerals, including those containing manganese and uranium.

In summary, volcanism, hydrothermal activity, and ground-water alteration probably acted together to form the deposits of beryllium, fluorspar, and uranium at Spor Mountain (figure 3). Explosive eruptions through carbonate rocks deposited glassy tuff and breccia containing carbonate clasts. Eruptions of tuff were followed by quiet extrusion of topaz rhyolite magma. Warm fluorine- and metal-rich fluids, circulating through vents, faults, and tuff, altered glass and carbonate clasts in tuff to clay, feldspar, and fluorite. Declining temperature and pressure of fluids helped precipitate fluorite and silica minerals, and break down metal-fluoride complexes. With the decline of fluoride activity, beryllium precipitated as bertrandite, and uranium precipitated in the structures of fluorite and opal. Subsequent alteration of tuff and mineralized rock by ground water released uranium for reprecipitation as yellow, secondary uranium minerals.

ACKNOWLEDGMENTS

I thank Brush Wellman, Inc. for access to mines and prospects in the 1970s, and for providing the latest company annual report and brochures on mining operations. D.R. Shawe and C.J. Nutt, U.S. Geological Survey, and L.J. Davis, consultant, reviewed early versions of this manuscript and provided suggestions for its improvement.

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INDUSTRIAL ROCK AND MINERAL RESOURCES AND DEVELOPMENTS IN UTAH

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ABSTRACT

Utah produces a wide variety of industrial rock and mineral commodities, valued in 1998 at \$534 million (28 percent of the total non-fuel mineral production of Utah). Major commodities produced in 1998 include: halite; potash and magnesium chloride; Portland cement; sand and gravel; carbonates including lime, limestone, and dolomite; phosphate; crushed stone; clays; perlite; gypsum; and sulfur and sulfuric acid. Commodities produced in lesser amounts include: diatomite; pumice; silica; lightweight aggregate; gemstones, ornamental stone, and mineral and fossil specimens; byproduct sulfur and sulfuric acid; silica; and building stone.

The years 1993 through 1998 were a period of steady growth in industrial rock and mineral production. However, some commodities have grown much more rapidly than others. The robust western U.S. economy has stimulated production of construction-related commodities like sand and gravel, raw materials for Portland cement, lime, and building stone, resulting in exploration for raw materials, development of new quarries, and expansion of existing plants. Noteworthy specific developments include: (1) opening of new aggregate operations and buyouts of small aggregate operations by large national and international firms, (2) expansion of a lime operation and two cement plants, and (3) development of several new gypsum mines.

The future of the industrial minerals industry in Utah looks promising despite a more restrictive regulatory environment and a growing anti-development attitude among its citizens. While Utah has become less pro-development than it was prior to the 1990s, it is still moderate compared to strongly anti-development states, so companies have some motivation to choose Utah in their strategic mineral development plans. As long as the western states' economies continue to grow, Utah's industrial minerals industry should thrive.

INTRODUCTION

Due to the breadth of the topic and the lack of information on some segments of Utah's industrial minerals industry, it is impossible to provide a balanced discussion of all commodities and all mining operations. It is particularly difficult to provide an up-to-date summary of company developments as many smaller operators produce intermittently and mining properties change hands frequently. A detailed discussion is limited to mining operations that were judged to be most significant. For example, building stone quarries and sand and gravel pits are not discussed in detail and are not plotted on figure 1. Humate, gilsonite, and tar sand production are also not included in this report since they are not classified as industrial minerals. For information on these commodities refer to Bon and Gloyn (1999).

The commodities discussed in this report are arranged in alphabetical order. Table 1 lists 1997 and 1998 commodity production and estimated values. Quarry and pit locations are shown on figure 1. Annual mine production included in the following text is from unpublished file data of the Utah Division of Oil, Gas and Mining if no other source is cited. This report supercedes earlier published Utah Geological Survey reports on Utah's industrial minerals (Tripp, 1985, 1991, 1992, 1997).

COMMODITY OVERVIEW

Although Utah's economy has diversified in recent years, mineral production, including industrial rocks and minerals, remains an important segment of the state's economy. Minerals-industry products were valued at \$1.86 billion in 1998; \$534 million of this amount (about \$270 per Utah resident) came from industrial rock and mineral production (Bon and Gloyn, 1999). The value of industrial rock and mineral production has risen steadily from 1993 through 1998, a time when production of many other energy, and base- and precious-metal commodities has declined. The increase in value of industrial rock and mineral production in Utah is shown by the following: 1993 - \$410 million, 1994 -\$428 million, 1995 - \$429 million, 1996 - \$433 million, 1997-\$533 million, and 1998 - \$534 million. Industrial mineral commodities with the highest values in 1998 are listed in alphabetical order in table 1.

BUILDING STONE

Utah companies quarry quartzite, sandstone, limestone (Tripp, 1993), and granite. Several companies produce quartzite flagstone and ashlar in northern Box Elder County from the Proterozoic Elba Quartzite and Quartzite of Yost, and the Cambrian Quartzite of Clarks Basin (Tripp, 1994). Quartzite from Box Elder County has been produced since the 1950s, but the market has begun to grow recently with

Box Eider Cache Rich AGG - Lightweight aggregate HAL - Halite LIM - Lime (Ca/Mg) LST - Limestone BRI - Brine CEM - Cement rock North Sh ore Ltd. Pa (PLT, BRI) CL - Chlorine MG - Magnesium PER - Perlite PHOS - Phosphate PLT - Plant CLY1 - Shale/clay CLY2 - Bentonite e Brick Co. (CLY1) DIT - Diatomite d POT - Potash SIL - Silica DOL - Dolomite GEM - Gemstone sh Grove Cement Co. (CLY1) STN1 - Crushed stone GYP - Gypsum MC Kalium Ogden Corp. (POT, HAL, PLT) O- Interpace Industries, Inc. (PLT) Ø C 30 60 Miles ø Morgan Union Pacific (STN1) 0 40 80 Kilometers **4**∩ Q Magcorp (PLT, MG, CL) Daggett Co. (CLY2) •0 Daggett Holnam, Inc. (PLT,CEM, SIL) Tooele (STN1) Summit Wilkinson Construction (STN1) Paving and Construction Co., Inc. (STN1) nd Hullinger (SIL) -91 Holnam, Inc (LST) Cargiil Salt, Inc. (PLT, HAL) 10 0 Utelite Corp. (AGG, PLT) DG&T Co. (LST) 0. . (STN1) of Arizona, Inc. (PLT, LIM) Duct nterstate Brick Co. (PLT) ational, Inc. (PLT, HAL) Co. (PHOS) **Ashley Creek Phosph** eilly Industries, Inc. (PLT, POT s. Inc. (CLY1) SF Phi Ltd. (PLT. PHOS Valley Asphalt Co. (STN1) ø Calcite (LST) 0 Cad 00 Skull Valley Diaton ie (DIT) Brick Co. (CLY1) IME Co ction Inc. (STN1) Interstate Brick Co. (CLY1) Θ Sta r Paving and Co . (STN1) Valley Asphalt Co. (STN1) Juab t Services, Inc. (LST) Utah erv industrial Resources Co. (LST) Ash Grove Cement Co. (CLY1) Carbon 0 G Ash Grove Cement Co. (SiL) B.E.G Resources LLC. (LST) Ash Grove Cement Co. (PLT) T.J Peck and Se Inc. (GYP) Millard ECDC Environ ntal LC. (CLY2) O-H.E Dav Uintal Grand Emery Co. (GYP) Sannete n Clay Co. (CLY2) Red Dome, Inc. (STN1) Redmond Minerals, Inc. (PLT, CLY2, HAL) nont Western U.S., Inc. (LIM) Western Clay Co. (LST) Georgia Pacific Corp. GYP) ø nont Western U.S., Inc. (PLT) Inc. (GYP) nd K Gyp U.S. Gypsum Co. (PLT, βYP) orgia Pacific Corp. PLT, GYP) ⊙- U.S. Gypsum Co. (GYP) ⊙---- Georgia Pacific Corp. (GYP) tern Clay Co. (CLY2) Moab Salt, Inc. (PLT, HAL, POT) Basin Perlite Co. (PER) Sevie đ 0 ock Co. (STN1) 🛛 🗝 aradise Manae int Corp. (CLY1) Grand Co. (CLY2) • ø Basin Perlite Co. (PLT) 0 one Mining, Inc. (GEM) Θ Beave Piute Cotter Corp. (LST) Garfield All Gypsum Corp. (GYP) Ъ Iron Washingt San Juan 55

Figure 1. Major Utah industrial mineral pits, quarries, and selected developments.

 Table 1.

 Quantities (in short tons (st) with metric tons (mt) in parentheses) of industrial minerals produced in Utah and their estimated values (modified from Tripp and Bon, 1999; data from Balazik, 1997; Kostick, 1997; Miller, 1997; van Oss, 1997; Tanner, 1998; Tepordei, 1999; and Virta, 1997).

	1997			1998		
	Quantity		Value	Qu	Quantity	
Commodity	(:	x10 ³)	(\$ x 10 ³)	(x 10 ³)		(\$ x 10 ³)
bentonite	50	(45)	1,080	69	(63)	1,638
common clay	330	(299)	4,510	225	(204)	1,428
crushed stone	6,600	(6,000)	27,000	13,000	(11,800)	54,300
gemstones			221			
gypsum	390	(354)	2,124	400	(363)	3,180
expanded shale				180	(163)	
halite	1,840	(1,670)	69,000	1,700	(1,500)	45,000
lime	1,400	(1,300)	7,900	1,000	(910)	40,870
phosphate	2,500	(2,300)		3,000	(2,700)	
Portland cement	1,500	(1,400)	125,000	1,500	(1,400)	120,400
potash	660	(600)	113,370	430	(390)	74,000
sand and gravel	36,000	(33,000)	110,000	44,900	(40,700)	125,000

increased national and international demand, a strong western U.S. economy, and improved technology for producing tiles from quartzite blocks. Tan and red, flaggy to thick-bedded sandstone is quarried from the Jurassic Nugget Sandstone in Summit Counties, mostly for local consumption, particularly in the rapidly growing Park City area. Red and tan sandstone blocks are also guarried from the Triassic Moenkopi Formation in western Wayne County. Gray and tan sandstone is extracted from the Uinta and Green River Formations in southern Duchesne County. Small amounts of white, oolitic limestone from the Tertiary Green River Formation are quarried in south-central Sanpete County. The historic Temple granite quarry, a few miles southeast of Salt Lake City in Little Cottonwood Canyon, was reopened in 1997 for extraction of quartz monzonite blocks which were shipped to the Idaho Travertine Company for sawing into veneer stone for the new Church of Jesus Christ of Latter-Day Saints Conference Center. An estimated 12,000 st (11,000 mt) of stone were excavated to complete the project.

CLAYS

Utah has an assortment of sedimentary and hydrothermal clays including bentonite, bloating clay, common clay, Fuller's earth, halloysite, and kaolinite. The two largest clay producers in Utah are Interstate Brick Company and Interpace Industries, Inc., both of which blend common clays from several quarries to produce a variety of brick. Redmond Minerals, Inc. produces bentonite from southern Sanpete County for use in construction and in well-drilling fluids. Western Clay Company produces bentonite and Fuller's earth from northern Sevier County and from their Last Chance pit, in southwestern Emery County, for use in construction. The Last Chance pit produced 6,382 st (5,788 mt) of bentonite in 1998. ECDC Environmental, L.C. produced and stockpiled large quantities of clay from northern Emery County in 1996, but has not produced since then; they do, however, plan to mine 100,000 st (91,000 mt) in calendar year 2000. ECDC mines clay for construction of waste-containment cells at their massive landfill site in eastern Carbon County. Grand County mines bentonite from their Spanish Valley Clay pit in northern San Juan County to line water canals. Daggett County mined 1,470 yd³ (1,120 m³) of clay in northern Daggett County for use in construction. Ash Grove Cement Company continued mining clay from their County Canyon pit, in eastern Juab County, for use at their nearby Leamington cement plant in eastern Juab County (see Portland cement section of this report).

An important new market for clay is as a source of highalumina, low-alkali material for cement production at two cement plants. The Ash Grove Cement plant in Inkom, Idaho continued to evaluate their Grouse Creek clay pit in western Box Elder County as a source of alumina in the manufacture of low-alkali-reactivity Portland cement. Ash Grove produced 4,616 st (4,187 mt) of clay in 1997 and none in 1998, but plans to start producing 40,000 short tons per year (stpy) (36,000 metric tons per year [mtpy]) over the next ten years beginning in 1999. Holnam, Inc. purchased kaolin from Paradise Management Corporation's Koosharem mine in northern Piute County as a source of alumina for their cement plant in central Morgan County.

CRUSHED STONE

Utah has nearly unlimited sources of high-quality rock throughout the state suitable for crushed stone. The importance of this resource will increase as sand and gravel deposits in urban areas are depleted or made inaccessible by residential development, and as material specifications become more stringent. Production of crushed stone for aggregate has created a regulatory debate in Utah. U.S. Aggregates, Inc.'s (Monroc, Inc. division) and Oldcastle's (Staker Paving and Construction Co., Inc. division) stone quarries in northern Salt Lake County produced sand and gravel for many years, but both companies recently exhausted their sand and gravel reserves and began mining and crushing bedrock at their pits. Sand and gravel production does not require reclamation permitting in Utah, and when Monroc switched to crushing stone, they claimed that they were still exempt from permitting. This has been very controversial in part due to the highly visible Monroc and Staker pits that are located close to major transportation corridors.

Twin Mountain Rock Company, a subsidiary of Peter Kiewit and Sons, opened a new railroad ballast quarry in central Beaver County in 1997. The quarry produces from a Tertiary quartz porphyry. In 1998, the quarry produced 221,700 st (201,100 mt) of ballast. Reserves are estimated to be sufficient to last 50 years at an annual production rate of 400,000 to 600,000 stpy (360,000 to 550,000 mtpy) (Utah Division of Oil, Gas and Mining unpublished files, 2000).

In 1997, Valley Asphalt Company, a subsidiary of U.S. Aggregate, opened two crushed stone pits; the Lehi pit in northern Utah County and the Ekins East pit in southern Utah County. The Lehi pit is in the Mississippian Great Blue Limestone and produced about 911,000 st (826,000 mt) in 1998, its first year of production. The Ekins East pit is in the Mississippian Deseret Limestone. The Ekins East pit produced about 293,000 st (266,000 mt) in 1998.

Most of the 300,000 st (280,000 mt) of limestone produced by IME Construction, Inc. at the Larsen Limestone mine (see limestone section of this report) in central Utah County was sold as crushed stone for construction, although smaller amounts were sold for flue gas desulfurization and for flux at the Kennecott copper smelter in Salt Lake County (Mark Hardman, verbal communication to Roger Bon, March 23, 2000).

Wilkinson Construction opened the Metz Hollow pit in central Morgan County in 1997. In 1998, Wilkinson produced approximately 32,000 st (29,000 mt) of stone for aggregate and planned to produce a similar amount in 1999.

Harper Contracting Inc. continued operating the Parley's Canyon quarry in eastern Salt Lake County. In 1998, Harper produced 284,961 st (258,515 mt) of crushed Jurassic Twin Creek Limestone for use in construction.

Red Dome, Inc. continued production of volcanic cinders in southeastern Millard County. The company produced 24,370 st (22,103 mt) of cinders from October 1994 to September 1995. Much of this material was sold for landscape rock mulch.

Union Pacific Railroad Company occasionally quarries crushed stone from their Lakeside quarry in southern Box Elder County. The quarry is located in the Mississippian Great Blue Limestone on the west end of the Great Salt Lake railroad causeway. Much of the material mined has been used for construction and maintenance of the railroad causeway.

DIATOMITE

Skull Valley Diatomite produced 200 st (180 mt) of diatomite in 1998 from Lake Bonneville sediments in southeastern Tooele County. The deposit is reported to be about 30 feet (9 m) thick. The material was shipped to Holnam, Inc. (Utah Division of Oil, Gas and Mining, unpublished file information, 2000), presumably for use as a pozzolanic additive.

EXPANDED SHALE

Utelite Corporation mines the organic-rich, argillaceous Cretaceous Frontier Formation from western Summit County (figure 2). The mined material is expanded (in four rotary kilns, figure 3) into a lightweight product which is used as aggregate in concrete roofing tiles, concrete blocks, structural concrete, and for miscellaneous uses such as horticulture, highway construction, and loose fill. Utelite mined 180,000 st (160,000 mt) of shale in 1998.

GEMSTONES, ORNAMENTAL STONE, AND MINERAL AND FOSSIL SPECIMENS

Utah has long produced semi-precious gemstones, decorative stone, and mineral and fossil specimens on a small scale. Gemstone companies sporadically produce blue celestite, topaz, amethyst, and red beryl. Decorative stone production includes small amounts of banded rhyolite, marble, onyx, alabaster, scoria, obsidian, black- and white-banded dolomite, travertine and tufa, sandstone and tuffaceous picture stone, aragonite, and opal. Utah companies also mine the following fossil and mineral specimens: septarian nodules, trilobites, azurite, bixbyite, calcite, garnet, geodes, hematite, malachite, selenite, and variscite.

Utah red beryl has the potential to develop into a more significant commodity. Gemstone Mining Inc. is currently evaluating the Violet claims, in central Beaver County, which produce a very unusual gem-quality red beryl that has been sold either unprepared or faceted by a Millard County family. Kennecott Exploration Company drilled the property in 1996 and delineated a substantial resource, but decided not to pursue further development. The beryl occurs in clay along fractures in devitrified topaz rhyolite of Tertiary age. The reason that the beryl may be present at the Violet claims and not in similar rocks elsewhere is due to the localized incursion of abundant surface water into still-hot rhyolite (Keith and others, 1994; Christiansen and others, 1996).



Figure 2. Mining of organic-rich shale of the Cretaceous Frontier Formation by Utelite Corp. in western Summit County (view is to the southwest, photo taken July 2000).



Figure 3. Utelite Corporation's expanded shale plant in western Summit County, Rockport Reservoir is in the background (view is to the northeast, photo taken July 2000).

GYPSUM

Utah has one of the largest gypsum resources in the United States. Withington (1964) estimated reserves of 2 billion st (1.8 billion mt) averaging more than 85 percent gypsum in beds a minimum of 4 feet (1.2 m) thick within 30 feet (9 m) of the ground surface. Whereas numerous geological formations contain gypsum, the Pennsylvanian Paradox Formation of the Hermosa Group, the Jurassic Arapien Shale, the Jurassic Summerville Formation, and the Jurassic Carmel Formation contain most of the resource. Most of the production (table 1) is used in the manufacture of wallboard, but some is used for Portland cement retarder, agricultural gypsum, wallboard joint compound, plaster, and fireproof cores for doors.

Georgia Pacific Corporation mined gypsum from the Carmel Formation, at their Eagle Canyon pit in central Emery County, to supply their Sigurd wallboard plant (Georgia Pacific, 2000), in west-central Sevier County. The Eagle Canyon pit produced 120,442 st (109,239 mt) in 1999. Georgia Pacific acquired the Hebe gypsum property, in southwest Emery County, from Western Clay in August 1998, and produced 18,129 st (16,443 mt) from this site in 1999.

U.S. Gypsum Company mines gypsum from the Jurassic Arapien Shale at their Jumbo Jensen quarry near their Sigurd plant in east-central Sevier County. The plant produces wallboard, plaster, and wallboard joint compound. The Jumbo Jensen quarry produced 145,047 st (131,621 mt) of gypsum in 1998. U.S. Gypsum also opened their new Kimball Draw gypsum mine in southwest Emery County which produced 239 st (217 mt) in 1999.

T.J. Peck and Sons, Inc. mines gypsum from the Arapien Shale at their Nephi gypsum quarry in eastern Juab County. The gypsum is marketed to Holnam, Inc.'s cement plant at Inkom, Idaho, and to Ash Grove's cement plant in eastern Juab County.

H.E. Davis and Sons, Inc. mines gypsum from the Arapien Shale at its Henry 1 and 2 property in southeastern Juab County for shipment to Holnam's cement plant in Morgan County. In 1998, the mine produced 32,000 st (29,000 mt) of gypsum. Nephi Sandstone Company mines gypsum from their Cedar Springs pit in the Jurassic Arapien Shale near Levan. Nephi Sandstone Corp. mined 491 st (445 mt) of gypsum in 1998.

The All Gypsum Corporation opened their Dry Creek mine, in Iron County, and produced 97 st (88 mt) of gypsum in 1998. The Dry Creek mine has a history of small production; last documented production was in 1924.

HALITE

Significant halite resources occur at seven locations in Utah (figure 4): (1) in surface brines of Great Salt Lake, (2) in salt beds and subsurface brines of the Pennsylvanian Paradox For-

mation of the Hermosa Group in the Paradox Basin, (3) in subsurface brines in Quaternary sediments of the Great Salt Lake desert, (4) in salt beds of the Jurassic Arapien Shale of Sevier and Sanpete Counties, (5) in subsurface brines in Quaternary sediments of Sevier Lake, (6) in Tertiary salt domes of northern Millard County, and (7) in salt beds of the Jurassic Preuss Sandstone of northeastern Utah.

Great Salt Lake

Great Salt Lake has long been an important producer of halite by solar evaporation of surface brines in shallow harvest ponds. Production from Great Salt Lake accounted for the bulk of the 1.7 million st (1.5 million mt) of salt produced in Utah in 1998 (Tripp and Bon, 1999). The lake consists of two distinct brine bodies, the north and the south parts of the lake which are separated by the Union Pacific railroad causeway. In November 1999, the south part of the lake had a brine density of 1.057 g/cm³, and was becoming less salty since it receives fresh water from the two main rivers entering Great Salt Lake. The north part of the lake had a brine density of 1.206 g/cm3 in November 1999 (J.W. Gwynn, verbal communication, 1999). The lake brine contains commercial concentrations of sodium, potassium, and magnesium salts, but is not anomalously rich in other salable commodities such as lithium, bromine, and boron (Sturm, 1980). Three companies currently produce halite from Great Salt Lake: IMC Salt Co. (in western Weber County), and Morton International, Inc. (figure 5) and Cargill Salt, Inc. (both in northeast Tooele County). IMC Salt has a plant capacity of about 1.5 million stpy (1.4 million mtpy) (IMC Global, 2000).

There have been numerous business changes in the Great Salt Lake salt industry over the past several years. Cargill purchased their plant from AKZO Nobel Salt, Inc. in April 1997. In December 1997, IMC Global Inc. acquired Harris Chemical Group, Inc. including its subsidiaries Great Salt Lake Minerals (GSL) and North American Salt (the two subsidiaries shared some facilities). GSL was renamed IMC



Figure 4. Salt resources of Utah (modified from Elston and Shoemaker, 1963; Hite, 1964; Parker, 1964; and Dyni, 1996).

Kalium Ogden Corp. and North American Salt was renamed IMC Salt Co. Morton International, Inc. sold their evaporation ponds and plant on the south end of the Great Salt Lake to Kennecott Utah Copper Co. in 1991 and moved a few miles west to the salt facility formerly owned by North American Salt (J.W. Gwynn, in press). Kennecott needed Morton's property for expansion of their tailings pond. On June 21, 1999, Morton International, Inc. merged with, and became a subsidiary of, Rohm and Haas.

Other Halite Deposits

The other halite deposits in Utah contain large resources, but have produced relatively small amounts of halite compared to Great Salt Lake. In the Paradox Basin in southern Grand County, Moab Salt, Inc. (acquired in 1995 by Potash Corporation of Saskatchewan as part of the purchase of Texasgulf, Inc.) recovers halite as a by-product of potash mining. Moab Salt solution mines evaporite salt beds of the Paradox Formation (salt cycle five), and processes

the resulting brine by solar evaporation. Moab Salt produces three grades of halite for animal feed, hide processing, water softening, and ice control (Potash Corporation of Saskatchewan, 2000). Their average daily halite production is about 2,200 st (2,000 mt).

Reilly Industries, Inc.'s potash plant in the Great Salt Lake Desert in western Tooele County has produced large amounts of halite as a by-product of potash production. Most of the harvested halite remains in the evaporation ponds where it precipitated during a preliminary step in potash recovery; only small quantities of the halite have been shipped to market.

In southern Sanpete County, Redmond Minerals, Inc. mines rock salt underground from a diapir of the Arapien Shale (figure 4) (Pratt and others, 1965). The salt diapir is approximately 1,000 feet across, 1,000 feet thick, and could be more than 5 miles long (300 m by 300 m by 9 km). Additional thick salt layers have been penetrated in nearby drill holes (Willis, 1991). The rock salt is primarily sold for livestock salt and as a health-food table salt (Durtschi, 1999).

Crystal Peak Minerals attempted to produce halite from subsurface brines of the Sevier Lake playa (figure 4) in south-central Millard County (Gwynn, 1990), but the operation was suspended in 1993 due to lack of a market. In northern Millard County, oil and gas drilling at the Argonaut Energy No.1 Federal well revealed the presence of a salt dome (figure 4) in Tertiary rocks 2,550 feet (760 m) below the surface. The salt section in this well is more than 5,000 feet (1,500 m) thick and is believed to extend roughly five miles (8 km) in an east-west direction (Mitchell, 1979). The northsouth extent of the deposit is not known, and the deposit has not been developed. In Summit and Rich Counties, the Preuss Sandstone (figure 4) contains a large amount of salt in the subsurface. More than 2,000 feet (600 m) of salt occurs in northernmost Summit County, although this thickness probably reflects salt flowage and the effects of Sevier-age thrusting (Lamerson, 1982). Preuss salt has not been mined in Utah, but has been produced in small quantities in Idaho (Mansfield, 1927).

LIME, LIMESTONE, AND DOLOMITE

Cambrian to Mississippian geologic formations are the source of most of Utah's carbonate production. Calcite veins and oolitic sands of Great Salt Lake are other sources of present or past production. Twelve operators in Utah produce a wide variety of carbonate products.

(1) Graymont Western U.S., Inc. (formerly Continental Lime, Inc.), in central Millard County, produces about 900,000 stpy (820,000 mtpy) of high-calcium quicklime in four rotary kilns from its Cricket Mountain plant. The Cricket Mountain plant opened in July 1980, with one 500 stpd (450 mtpd) rotary kiln, but added a second kiln in 1987, a third kiln in 1992, and a fourth 1,200 stpd (1,090 mtpd) kiln in February 1998 (Graymont Western U.S., Inc., 1999). Limestone from the Cambrian Dome Formation is mined and crushed at Graymont's Poison Mountain pit, and trucked 6.5 miles (10.4 km) east to their plant on the Bloom railroad siding of the Union Pacific Railroad. Graymont is currently developing the Flatiron pit in the Cambrian Dome Limestone about 0.75 miles (1.4 km) northwest of their Poison Mountain pit. The Flatiron pit will soon be their main source of limestone (the Poison Mountain pit is nearly mined out). Graymont is also evaluating their extensive limestone resources north and south of the Poison Mountain pit. The company will also begin producing dolomitic lime from the newly opened B.B. Claims pit which is 1.2 miles (2 km) east of the Poison Mountain pit (Vic Kastner, verbal communication, 2000). The B.B. Claims pit is in the Cambrian Limestone of the Cricket Mountains (Hintze, 1984).

(2) Chemical Lime of Arizona, Inc. has the capacity to produce roughly 90,000 stpy (82,000 mtpy) of dolomitic quicklime and hydrated lime (Type S) from the Ordovician Fish Haven Dolomite at their Grantsville facility (figure 6) in northeastern Tooele County (Chemical Lime Company, 2000). Coal is their primary fuel, augmented by a tire burner connected to their rotary kiln. In 1995, Chemical Lime purchased the old Utah Marblehead Lime plant at Delle in northern Tooele County from U.S. Pollution Control, but are



Figure 5. Solar salt harvesting equipment at Morton International, Inc.'s solar evapo-

ration ponds on the south end of the Great Salt Lake, Utah (photo taken May 1999).



Figure 6. Chemical Lime of Arizona's dolomitic lime plant located at the north end of the Stansbury Range, Utah. The plant's tire burner is in the foreground (photo taken May 1999).

not currently operating it. The Delle facility originally processed Ordovician Fish Haven Dolomite into deadburned dolomite for manufacture of refractories used in the steel industry.

(3) Geneva Steel of Utah quarried dolomite and limestone at their Keigley quarry in southwest Utah County, from a Cambrian carbonate section, for use as flux at their nearby steel mill. Geneva also shipped limestone powder to the coal mines of Central Utah for rock dust and sold crushed stone for aggregate (Hawes, 1992). In 1999, Geneva sold the Keigley quarry to Staker Paving and Construction Co. (a division of the international aggregate firm Oldcastle, Inc.). In a classified advertisement (Rock Products, 1999) Geneva provided the following resource information for the Keigley quarry: 1,500 acre (600 ha) area, 15 million st (14 million mt) reject aggregate, 100 million st (90 million mt) limestone reserves, and 35 million st (32 million mt) dolomite reserves. Geneva stated that their crushed aggregate meets Department of Transportation specifications for bituminous aggregate.

(4) Cotter Corporation mines roughly 25,000 stpy (23,000 mtpy) of Pennsylvanian Hermosa Group limestone at its Papoose quarry in northern San Juan County. The limestone is trucked 65 miles (105 km) to Nucla, Colorado where it is used for flue-gas desulfurization in a small coal-fired electric power plant (Reed, 1996).

(5) Emery Industrial Resources Company began producing limestone from their Cherry Hill Park mine, in southeast Utah County for coal mine rock dust in 1993. Emery mined about 29,000 st (26,000 mt) of limestone in 1998 from the Tertiary Flagstaff Limestone.

(6) Rancho Equipment Services intermittently mines limestone from the Ordovician Pogonip Group at its Topaz Valley mine in central Juab County. Rancho hasn't mined limestone since 1995; they have been shipping material from their stockpile, but they had produced an average of 52,000 st (47,000 mt) per year from 1990 through 1995. One of their main customers has been the Intermountain Power Project electric plant, in northern Millard County, which requires about 200,000 stpy (181,000 mtpy) of limestone for flue-gas desulfurization.

(7) Western Clay Company mines limestone from their Redmond limestone quarry in the Tertiary Flagstaff Limestone of northern Sevier County for use as coal-mine rock dust and crushed stone. In 1998, they produced about 23,520 st (21,330 mt) of limestone.

(8) Magnesium Corporation of America (MagCorp) uses oolitic sands from the shores of Great Salt Lake, in northeast Tooele County, as a stack-gas neutralizing agent in their process for making magnesium metal and chlorine. MagCorp mined 50,000 st (45,000 mt) of oolites between May and September 1998.

(9) Cedarstrom Calcite produced 4,352 st (3,947 mt) of vein calcite in 1998 from the Mississippian Deseret Limestone and the Humbug Formation. The calcite from their underground mine in western Utah County is used primarily for poultry grit.

(10) IME Construction, Inc., produces limestone from the Mississippian Deseret Limestone from their pit in western Utah County. IME processed 300,000 st (270,000 mt) of lime-

stone in 1998, most of which was sold for road base, railroad ballast, and for other construction uses. Some higher calcium carbonate material in the pit was selectively mined for use in flue-gas desulfurization and for use as flux at Kennecott.

(11) Deseret Generation and Transmission Co. (DG&T Co.) opened a limestone quarry in 1999 in Mississippian Madison Limestone to provide limestone for flue-gas desulfurization at their Bonanza power plant in east-central Uintah County. The quarry, located in northern Uintah County, will initially produce about 30,000 stpy (27,000 mtpy) of limestone, some of which will be sold as crushed stone for construction purposes (Brad Exton, verbal communication, 2000).

(12) B.E.G. Resources mines and crushes a Holocene travertine from a pit in southeast Juab County. It produced 18,000 st (16,000 mt) in 1997. Some of the product was shipped to the Intermountain Power Project electric power plant near Delta, Utah for use in flue-gas desulfurization (Tom Munson, DOGM, verbal communication, 1999).

NON-HALITE SALTS

Four localities in Utah contain large quantities of potassium and magnesium salts, and sodium sulfate: Great Salt Lake, Great Salt Lake Desert, Paradox Basin, and Sevier Lake. In addition, there are large alunite deposits in southwestern Utah that are potential sources of both potash and aluminum. Finally, the Uinta Basin contains bedded sodium carbonate and sodium-carbonate-rich brines (figure 4).

Great Salt Lake

Three Great Salt Lake operations produce salts other than halite: Magcorp, IMC Kalium Ogden Corp. (IMC), and North Shore Ltd. Partnership. Magcorp concentrates magnesium chloride brine through solar evaporation for conversion to magnesium metal and chlorine gas. Magcorp's plant (figure 7) has a capacity of 42,000 st (38,000 mt) of metallic magnesium (Clifford, 2000).



Figure 7. MagCorp's Rowley magnesium plant on the west side of the Great Salt Lake, Utah (photo taken May 1999).

IMC produces potassium sulfate (potash) and magnesium chloride (crystal and flake form). In 1997, IMC produced 435,000 st (395,000 mt) of potassium sulfate (KCl equivalent) (Bon and Gloyn, 1998). IMC's 1997 magnesium chloride production capacity was 117,000 stpy (106,000 mtpy) (Kramer, 1997). Potassium sulfate is primarily used in plant fertilizer. Magnesium chloride is used for dust control on dirt roads, as an oil-well drilling fluid additive, a dessicant, a fire-retardant coating, an animal and plant nutritional supplement, and for a wide variety of other industrial and chemical processes (IMC Global Inc., 2000).

Another interesting brine operation on Great Salt Lake is North Shore Ltd. Partnership, in northern Box Elder County. In 1998, the company concentrated 15.85 acre-feet (0.02 hectare-m) of lake brine through solar evaporation to produce a trace element nutritional supplement.

The potash resource of Great Salt Lake is estimated to be 100 million st (91 million mt) of K_2O equivalent (Adams and Hite, 1983). An additional saline resource, buried at shallow depth within the Quaternary sediments in the center of Great Salt Lake, consists of a bed of mirabilite (a hydrated sodium sulfate) which reaches a maximum thickness of about 32 feet (10 m). Construction crews discovered the mirabilite (figure 4) while building the original wooden railroad trestle across Great Salt Lake in 1903 (Hite, 1964); this resource has never been developed.

Great Salt Lake Desert

Reilly Industries, Inc.'s Bonneville potash plant produces standard-grade and coarse-grade potassium chloride (potash) and magnesium chloride brine (Reilly Industries, Inc., 2000) from three subsurface aquifers of the Bonneville Salt Flats in western Tooele County (figure 4). The shallowest aquifer, generally less than 20 feet (6 m) deep, provides most of the brine which is gravity drained through canals toward the plant. Brine "elevators" raise the brine from the canals to the solar evaporation ponds. A froth flotation circuit separates the valuable sylvite from the sylvinite (a

sylvite/halite salt mixture) harvested from the solar ponds. Less concentrated brine from a deep aquifer is produced from wells as deep as 2,051 feet (625 m). Wells as deep as 200 feet (61 m), in an alluvial-fan aquifer to the north of the Bonneville plant, provide brackish water used in the plant for processing sylvite (Bingham, 1980). The Bonneville plant has a capacity of 50,000 stpy (45,000 mtpy) (MgO equivalent) (Kramer, 1997). The potash resource of the Great Salt Lake Desert is estimated to be 10 million short tons (9 million mt) of K_2O equivalent (Adams and Hite, 1983). Potash is used for plant fertilizer, as a flux in metal smelting, and as an ingredient in oil well drilling fluid.

Paradox Basin

Bedded sylvite, carnallite, and associated subsurface brines underlie a large part of the Paradox Basin in southeast Utah (figure 4). The potash resource occurs within 18 of 29 evaporite cycles in the Pennsylvanian Paradox Forma-

tion of the Hermosa Group; eleven of these cycles contain significant amounts of potash (Hite, 1961). The potash resource of the Paradox Basin is estimated to be 280 million st (254 million mt) K_2O equivalent (Adams and Hite, 1983). Moab Salt, Inc. produces about 1,490 stpd (1,350 mtpd) of potash (Potash Corporation of Saskatchewan, 2000) by solution mining the old workings of their former underground mine in southern Grand County (Phillips, 1975). Moab Salt produces potash from an 11-foot-thick (3 m) sylvite bed in the fifth evaporite cycle down from the top of the evaporite sequence. This bed occurs at depths of less than 4,000 feet (1,200 m) (Hite, 1964). Process water for the operation comes from the Colorado River. Moab Salt produces two grades of potash for domestic, industrial, and oil-field markets.

Sevier Lake

Sevier Lake, in south-central Millard County (figure 4), dry through most of historical time, contains subsurface brines comparable to those of Great Salt Lake (Gwynn, 1986). However, Sevier Lake brines have a higher sulfateto-chloride ratio and a lower magnesium content than Great Salt Lake brines (Whelan, 1969). Crystal Peak Mineral Corporation built salt ponds and a plant near Sevier Lake, but was unable to develop a profitable operation. This inactive property is now held by Salada Minerals, LLC.

Alunite Deposits

The large alunite deposits of southwestern Utah (figure 4) represent an unconventional potash and aluminum resource. These deposits are the largest of their type in the United States. The White Mountain replacement deposit contains an estimated 232 million st (210 million mt) of ore containing 33 percent alunite, and an additional 402 million st (365 million mt) of ore containing 28 percent alunite (Hall, 1978). A consortium of companies planned to produce aluminum and potash from this deposit in the 1970s, but the project economics were unfavorable. Minor amounts of potash were produced from the Marysvale vein and replacement deposits of Piute and Sevier Counties during World War I and World War II.

Uinta Basin Sodium Carbonate Deposits

Halite and sodium carbonate minerals occur in the subsurface in the Tertiary Green River Formation at two sites in the Uinta Basin (figure 4), the Duchesne deposit and the Bird's-nest aquifer. At the Duchesne deposit, core taken at depths ranging from 4,165 to 4,252 feet (1,269 to 1,296 m) contained three beds of mixed halite and wegscheiderite totaling 20 feet (6 m) thick and six other beds of mixed sodium carbonate minerals (trona, nahcolite, wegscheiderite, and eitelite) ranging in thickness from 0.3 to 1.5 feet (0.1 m to 0.5 m) (Dyni, 1996). The Bird's-nest aquifer contains sodium carbonate brine over a minimum 250-square-mile (650 km²) area (T. 8 to 11 S., R. 22 to 25 E.) in the southeastern Uinta Basin (Dyni, 1996).

PERLITE

The Pearl Queen Perlite Corporation commenced perlite processing in February 1998, with the completion of a new 100,000 stpy (91,000 mtpy) mill on a railroad siding in Milford, Utah. Pearl Queen reopened the North Pearl Queen mine which last produced in 1966. The North Pearl Queen deposit of northeast Beaver County covers a 5,900-foot by 2,000-foot (1,800 m by 600 m) area, and ranges in thickness from 16 to100 feet (5 to 30 m), averaging 80 feet (25 m). The ore is hosted by a 0.78-m.y.-old, obsidian-rich, rhyolite flow. The rhyolite is vertically zoned with pumiceous and shardy perlite on the surface in sequence with a granular perlite, then classical "onion skin" perlite. The majority of the ore has a fine granular texture. The mine was producing at an annual rate of 48,000 st (44,000 mt) in August 1999. Pearl Queen has delineated a total resource of 25 million st (23 million mt) with 4 million st (3.6 million mt) of proven reserves.

In December 1999, Basin Perlite Company (an affiliate of Resource Capital Fund, Denver, Colorado) purchased the operation from Pearl Queen (Gatten, 2000). The Basin Perlite plant supplies perlite to U.S. Gypsum and other Midwest ceiling tile and construction businesses, and supplies the horticultural and foundry markets (North American Mineral News, 1999).

PHOSPHATE

Most of the phosphate resources in Utah are contained in Permian rocks; a smaller resource is contained in Mississippian rocks (Gere, 1964). The phosphatic shales of the intertongued Park City and Phosphoria Formations of Permian age are the source of most of the phosphate production in Utah. Presently, the only commercial operation is SF Phosphates Ltd.'s Little Brush Creek mine in northern Uintah County. SF Phosphates Ltd., a partnership between Farmland Industries, Inc. of Kansas City, Missouri and J.R. Simplot Company of Boise, Idaho, purchased this operation from Chevron Chemicals in 1992. In 1998, SF Phosphates mined 3 million st (2.7 million mt) of ore (Bon and Gloyn, 1999) to produce about 1.2 million st (1.1 million mt) of concentrate. The company transports its concentrates northward across the Uinta Mountains through a 90-mile-long (145 km) underground slurry pipeline to their Rock Springs, Wyoming fertilizer plant for treatment with sulfuric acid. The sulfuric acid is a by-product from the oil and gas fields of the area (Woody, 1986).

Another phosphate mine has recently been proposed by Universal Chemical and Minerals Corporation. The proposed operation would mine 1 million st (0.9 million mt) of ore from the Meade Peak Phosphatic shale Member Formation on Ashley Creek Phosphates Company's property in northern Uintah County and transport a phosphate-rich solution to a proposed dicalcium phosphate plant in east central Uintah County. The plant would yield about 400,000 stpy (360,000 mtpy) of dicalcium phosphate. The plan also calls for construction of a rail connection to a main line at Wamsutter, Wyoming or Craig or Rangley, Colorado (Woolf, 1999). The dicalcium phosphate would initially be sold for use as a mineral supplement in livestock and poultry feed. Additional future products could include phosphoric acid and a range of plant fertilizers (Russ Fotheringham, verbal communication, 2000).

Mississippian phosphatic shales of the Delle Member of the Deseret Limestone and the Little Flat Formation contain smaller phosphate resources that have not been exploited.

PORTLAND CEMENT

Utah contains vast amounts of the raw materials used in the production of Portland cement, including high-calcium limestone, natural cement rock, high-silica quartzite and sandstone, clay and shale, iron ore, industrial by-product iron, and gypsum. There are two producers of Portland cement in Utah: Holnam, Inc. in central Morgan County and Ash Grove Cement Company in eastern Juab County.

Holnam, Inc. uses limestone from the Jurassic Twin Creek Limestone (figure 8), a natural cement rock which averages 42 percent CaO, at its 700,000 stpy (635,000 mtpy), dry-process Devil's Slide plant. The new plant (figure 9), completed in November 1997, replaces their post World War II era 350,000 stpy (317,000 mtpy), wet-process plant (Holnam, Inc., 1999). Other materials utilized include: (1) highcalcium limestone from their Poverty Point pit in the Mississippian Great Blue Limestone in northeast Tooele County, (2) silica from the Triassic-Jurassic Nugget Sandstone from a pit near their plant, (3) gypsum from the Jurassic Arapien Shale in eastern Juab County (six percent of the finished cement is gypsum), and (4) by-product iron from Kennecott Copper Corporation in western Salt Lake County. The Poverty Point pit produced 60,000 st (54,000 mt) of limestone in 1997 (Holnam, Inc., 1999). Calcining and clinker formation occurs in a single 150-foot-long (47 m) rotary kiln.



Figure 8. Loading blasted Twin Creek Limestone ore at Holnam's Devil's Slide pit, in Morgan County, Utah. The capacity of the shovel is about 20 st (18 mt) and the trucks used are either 50 st (45 mt) or 100 st (90 mt) (photo taken July 2000).

cement: limestone from the Cambrian Dome Formation from a quarry adjacent to their plant site; shale from the Mississippian Long Trail Shale Member of the Great Blue Limestone at their County Canyon quarry; and silica from the Permian Diamond Creek Sandstone at the company's Nielson quarry. The County Canyon and Nielson quarries are located within a few miles of Ash Grove's plant in eastern Juab County. The County Canyon quarry produced 105,156 st (95,375 mt) of shale in 1998. Ash Grove obtains iron from slag from Kennecott's copper smelter and from mill scale from Nucor's steel recycling plant in eastern Box Elder County. Gypsum, used for retarding the setting time of the cement, is obtained from the Jurassic Arapien Shale at the T.J. Peck quarry in eastern Juab County. To supplement coal as a primary fuel, Ash Grove burns a large number of whole tires. The company increased their plant capacity from 650,000 stpy

(590,000 mtpy) to 825,000 stpy (749,000 mtpy) in the spring of 1996.



Figure 9. The five-stage preheater/flash calciner tower at Holnam's Devil's Slide cement plant in Morgan County, Utah (photo taken July 2000).

Fuel used at the Morgan County plant is primarily coal (with natural gas as a backup fuel). The plant also burns a small amount of shredded tires, and cubed paper and plastic manufacturing waste from the Kimberley Clark diaper plant in Ogden.

Ash Grove's 825,000 stpy (749,000 mtpy) dry-process, coal-fired cement plant uses the following materials to make

SAND AND GRAVEL

The bulk of sand and gravel produced in Utah comes from Pleistocene Lake Bonneville shoreline deposits along the Wasatch Front urban corridor from Provo in the south to Brigham City in the north. There are four major sand- and gravel-bearing Lake Bonneville benches or deposits that mark relatively long-lived, stable shorelines of the lake. The two highest benches, the Bonneville and Provo benches, provide most of the sand and gravel in the state. The Bonneville bench was deposited at an elevation of 5,090 feet (1,551 m) above mean sea level (Currey and others, 1984), nearly 900 feet (270 m) above the current elevation of Great Salt Lake. The Provo bench was deposited at an elevation of 4,740 feet (1,440 m) above mean sea level (Currey and others, 1984). For additional information of these deposits see Jim Bliss' article, this publication.

The locations of the active pits are not shown on figure 1 due to their large number, but a list of the pits and their locations is available through the U.S. Mine Safety and Health Administration office in Denver, Colorado, and through the U.S. Geological Survey in Reston, Virginia. In 1997, statewide sand and gravel production totaled 36,566,070 st (33,165,000 mt), that was valued at \$99.3 million (Tanner, 1999). Most of the production is for construction sand and gravel, but several companies also produce small amounts of industrial sand.

The 1990s was a period of consolidation for the sand and gravel industry, with small and medium-sized, locally-owned companies being acquired by large national and international companies. For example: (1) U.S. Aggregates, Inc. acquired Cox Rock Products, Monroc Inc., Valley Asphalt, Inc., and Western Rock Products Corp. (U.S. Aggregates, Inc., 1999); (2) CRH plc's Oldcastle Materials Group acquired Staker Paving and Construction Company and Geneva Steel's Keigley quarry; and (3) Hanson Building Materials America acquired Pioneer USA and their Metro West Ready Mix operation (Drake, 2000). Silica from the Devonian Stansbury Formation is mined by McFarland and Hullinger in northeastern Tooele County and sold to Kennecott as a copper-smelting flux. The company mined 83,846 st (76,000 mt) of metallurgical grade (+92% silica) quartzite in 1997. The size of the reserve is not known, but is considered to be very large.

SULFUR AND SULFURIC ACID

Although small, natural sulfur deposits such as Sulphurdale in northeastern Beaver County have produced in the past (Mount, 1964), all of the current sulfur and sulfuric acid production in Utah is a byproduct from industrial processes. Kennecott Utah Copper Company, located in eastern Salt Lake County, recovers about 1 million stpy (0.9 million mtpy) of sulfuric acid from smelting copper ore (Elise Erler, Kennecott Utah Copper Company, verbal communication, April 2000). Geneva Steel's northern Utah County mill produces about 5 stpd (4.5 mtpd) of elemental sulfur from desulfurization of coke oven emissions; they have produced this byproduct since the fall of 1993 (Geneva Steel, 1997). Three petroleum refineries in North Salt Lake recover the following amounts of elemental sulfur: Chevron - 13 stpd (12 mtpd) (Jim Palmieri, verbal communication, March 2000), Amoco - 6 stpd (5 mtpd) (Mike Grim, verbal communication, March 2000), and Flying J - 3 stpd (2.7 mtpd) (Jeff Utley, verbal communication, March 2000). Phillips also produced a small amount of sulfur (Mary Applegate, verbal communication, March 2000). Most of the produced sulfuric acid and sulfur is sold to the fertilizer and chemical industries.

COMMODITIES PRESENT BUT NOT PRODUCED

Commodities present in significant quantities in Utah, but not currently produced in significant quantities include: barite, magnesite, fluorspar, pumice, titanium, zeolites (Mayes and Tripp, 1991), and zirconium. A good reference which describes these resources is found in Hilpert (1964).

THE FUTURE OF INDUSTRIAL ROCKS AND MINERALS IN UTAH

The future for mining Utah's industrial rock and mineral deposits is uncertain, despite favorable geology, because the regulatory environment is becoming increasingly restrictive and public sentiment is increasingly anti-mining. The large percentage of federal land in Utah makes mining development vulnerable to federal conservation initiatives like the U.S. Bureau of Land Management's re-inventory of lands for wilderness designation, and the U.S. Forest Service's recent roadless area designation proposal.

Development of new sand and gravel operations in Utah will face many obstacles. The sand and gravel development scenario for Washington County illustrates some of the challenges for future development. Washington County is not blessed with abundant sand and gravel, and urbanization, environmental concerns, and land-use restrictions are making it difficult to ensure a future supply of high-quality aggregate in the county (Blackett and Tripp, 1998). The same situation exists in Salt Lake County and other counties with high population densities. Increased haul distances will inevitably make aggregate, and therefore construction costs, more expensive in the Salt Lake City area (Isaacson, 1999 and this publication).

Relatively good news for future mine development in Utah is that regulatory barriers to development are perceived to be even more severe in most other mining states. A survey of mining companies (Fraser Institute, 1999) ranked Utah 5th among 17 U.S. mining states on the Policy Potential Index. The Policy Potential Index ranks the state's response to proposed mining operations. A high score (approaching 100) indicates a setting friendly to mining development. A low score (approaching 0) indicates a setting hostile to mining development. Scores for the top five states follow: Nevada ranked #1 with 86 points, Arizona ranked #2 with 75, Texas was #3 with 71, Wyoming was #4 with 63, and Utah was #5 with 61.

ACKNOWLEDGMENTS

The Utah Division of Oil, Gas and Mining provided essential information for this report on current activities of industrial mineral companies. Reviews by J. Wallace Gwynn, Roger L. Bon, and Michael Hylland improved the quality of this paper.

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HISTORY OF STATE OWNERSHIP, RESOURCE DEVELOP-MENT, AND MANAGEMENT OF GREAT SALT LAKE

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ABSTRACT

Utah statute defines sovereign lands as "those lands lying below the ordinary high water mark of navigable bodies of water at the date of statehood, and owned by the state by virtue of its sovereignty." The lands within the bed of Great Salt Lake (GSL) are, by this definition, sovereign lands, acquired at statehood in 1896 in accordance with the "equal footing" doctrine, granting each state control and ownership of navigable waters and the lands underneath those waters within its borders. Under public trust doctrine, the state, as trustee for the people, bears responsibility for preserving and protecting the right of the public to use of the waters for navigation, commerce, fishing, recreation, and wildlife habitat.

Also by statute, sovereign lands are defined as "state lands," to be managed by "multiple use sustained-yield principles." The Division of Forestry, Fire and State Lands is given management authority for sovereign lands and, as manager, has responsibility to prepare comprehensive plans, initiate studies of the lake and its resources, implement comprehensive plans through state and local entities, and coordinate the activities of various divisions within the Department of Natural Resources (DNR). The Division of Forestry, Fire and State Lands also has responsibility for management of mineral leasing on sovereign lands. The many resources on the lake--water, minerals, wildlife, recreation, archeological and historical values--are managed by as many state agencies which occasionally creates conflicts.

The brines of GSL contain several ions that crystalize into valuable minerals during evaporation. The major ions in the lake are, in order of relative abundance, chloride, sodium, sulfate, magnesium, and potassium. Mineral products which are currently extracted from lake brines are sodium chloride, magnesium chloride brine which can be sold as flake magnesium chloride or further processed into magnesium and chlorine gas, and potassium sulfate. Mineral products which have potential for extraction include gypsum, sodium sulfate, and trace amounts of lithium, boron, and bromine.

The GSL contained an estimated 4.3 billion short tons (st) (3.9 billion metric tons [mt]) of dissolved salts in 1998. Utah Geological Survey (UGS) estimates of the dissolved salt content in GSL have fluctuated from 4.0 to 5.5 billion st (3.6 to 5.0 billion mt) due to the dynamic conditions in the lake as salts are precipitated and redissolved, and due to the diversion of brines from GSL, such as the West Desert Pumping Project. The lake has four areas of varying salinity, separated by dikes or other man-made structures: north arm and Stansbury Bay brines at near saturation (25 to 27 percent total dissolved solids [TDS]); the main body of the south arm with concentrations ranging from 7 to 15 percent TDS as lake elevations fluctuate; the waters in Farmington Bay at approximately 3 to 5 percent TDS; and Bear River Bay at <1 to 7 percent TDS. The percent TDS in Bear River Bay fluctuates with lake level, and changes in Bear River inflow. The transfer of salts from the south arm to the north arm has raised questions about the viability of the mineral and brine shrimp industries. The UGS and the U.S. Geological Survey (USGS) continue to monitor salinities at designated sites on the lake to document changing lake salinity. A recurrent theme is that placement of dikes and diversions can have significant and rapid impacts on various conditions in the lake.

Hydrocarbon resources on the lake are significant, but presently undeveloped. The hydrocarbons are low gravity (4 to 9 degree API) and tar-like, contain high nitrogen concentrations, and up to 12 percent sulfur. The unusual characteristics of the oil have been the subject of studies by chemists at Weber State University and Université Louis Pasteur de Strasbourg. However, these resources are difficult, and at present, uneconomic to extract using current technology because of the nature of the hydrocarbons, and production in "an offshore, highly saline environment."

Oolitic sand deposits make up many of the beaches and shorelines around the lake. Because of their high calcium carbonate content, oolites have been used by Magnesium Corporation of America (MagCorp) and its predecessors for acid neutralization and dike construction. Oolites are also used in very minor amounts in flower drying. The Utah Division of Oil, Gas and Mining reports up to 130,000 st (118,000 mt) mined annually by MagCorp from U.S. Bureau of Land Management (BLM) lands adjacent to GSL.

Currently, there are twelve producing mineral leases which generated slightly more than \$1,000,000 in royalties during calendar year 1998. IMC Kalium Ogden Corp. (IMC Kalium) produces potassium sulfate and magnesium chloride from brines concentrated through solar evaporation in Bear River Bay and Clyman Bay. By-product sodium chloride is transferred to IMC Salt, which packages and sells the salt. MagCorp produces magnesium metal from brines concentrated in Stansbury Bay. Cargill Salt produces sodium chloride from brines provided by MagCorp under a lease agreement. Morton Salt produces salt at the southeast end of Stansbury Island. Lastly, North Shore Limited produces con-
centrated brines for use in dietary and mineral/vitamin supplements near Spring Bay in the north arm of the lake.

Producers of magnesium, potash, and salt from GSL contribute significantly to the value of metals and industrial minerals in Utah. Together these companies contribute approximately \$240 million in gross value, or 18 percent of the value of the state's nonfuel mineral production. Most of this production is exported.

INTRODUCTION

The U.S. government acquired lands that are now Utah from Mexico through treaty following cessation of war with Mexico on February 2, 1848, six months after the arrival of the first Mormon pioneers into Salt Lake Valley. Congress created the Utah Territory from those lands on February 21, 1855. As a territory, these lands were managed for disposal by the General Land Office which sold or granted lands for railroads, Native American allotments and reservations, forest lands designation, homesteading and mineral entries, and land grants to the territorial government.

The area had been explored by American, French, and British fur trappers starting in 1829. Captain John Charles Fremont led an exploration, authorized by the U.S. Congress in 1843, of the Great Basin, including GSL. In 1849-50, Captain Howard Stansbury, as part of the U.S. Army Corps of Topographical Engineers, was in charge of a "trigonometrical and nautical survey" of GSL.

Captain Stansbury's observations in his accounts of the survey range between fascination with the vastness of the lake and disappointment in its desolation. He gives this account soon after his arrival at Bear River Bay on October 22, 1849:

"Morning clear and calm. The Salt Lake, which lay about half a mile to the eastward, was covered by immense flocks of wild geese and ducks, among which many swans were seen, being distinguishable by their size and the whiteness of their plumage. I had seen large flocks of these birds before, in various parts of our country, and especially upon the Potomac, but never did I behold anything like the immense numbers here congregated together. Thousands of acres, as far as the eye could reach, seemed literally covered with them, presenting a scene of busy, animated cheerfulness, in most graceful contrast with the dreary, silent solitude by which we were immediately surrounded" (Stansbury, 1852).

His observations from Promontory Point that evening describe his ambivalence about GSL:

"The evening was mild and bland, and the scene around us one of exciting interest. At our feet and on each side lay the waters of the Great Salt Lake, which we had so long and so ardently desired to see. They were clear and calm and stretched to the south and west...On the west appeared several dark spots, resembling..islands, but the dreamy haze hovering over this still and solitary sea threw its dim, uncertain veil over the more distant features of the landscape...The stillness of the grave seemed to pervade both air and water; and, excepting here and there a solitary wild-duck floating motionless on the bosom of the lake, not a living thing was to be seen. The night proved perfectly serene, and a young moon shed its tremulous light upon a sea of profound, unbroken silence....The bleak and naked shores, without a single tree to relieve the eye, presented a scene so different from what I had pictured in my imagination of the beauties of this far-famed spot, that my disappointment was extreme" (Stansbury, 1852).

HISTORY OF STATE OWNERSHIP OF GREAT SALT LAKE

What Are Sovereign Lands?

At statehood, the state was not only granted school trust lands (four sections out of every township) for support of its schools and institutions, but also sovereign lands (lands under navigable waters). These sovereign lands were to be managed by the states for public trust purposes such as navigation, commerce, and fisheries. In southwestern states, there has been slow recognition of management responsibilities for sovereign lands, where water for diversion and irrigation were far more important than preserving a waterway for these public trust purposes. The first chapter of "The Great Salt Lake," describes the attitudes toward this lake: "Lake of paradoxes, in a country where water is life itself and land has little value without it, Great Salt Lake is an ironical joke of nature--water that is itself more desert than a desert" (Morgan, 1947).

Utah statute defines sovereign lands as "those lands lying below the ordinary high water mark of navigable bodies of water at the date of statehood and owned by the state by virtue of its sovereignty" (Utah Code Ann., Section 65A-1-1(5)). The lands within the bed of GSL are by this definition sovereign lands, acquired at statehood in 1896 in accordance with the "equal footing" doctrine granting each state control and ownership of navigable waters and the lands underneath those waters within its borders. These lands are managed according to the doctrine of public trust, a system of court-interpreted common law dating back to the sixth century Roman law as codified in Institutes and Digests of Justinian (Coastal States Organization, 1997).

The BLM and its predecessor the General Land Office were responsible for surveying the public domain so that land could be conveyed into various ownerships. Unappropriated lands remained under the management of the federal government. The BLM's 1973 Manual of Surveying Instructions notes: "Beds of navigable bodies of water are not public domain and are not subject to survey and disposal by the United States. Sovereignty is in the individual states. Under the laws of the United States the navigable waters have always been and shall forever remain common highways" (U.S. Bureau of Land Management, 1973).

Public trust principles guide the management of sovereign lands. This doctrine has evolved over several centuries. Black's Law Dictionary (1990) defines public trust doctrine in terms of the state's responsibility, as trustee for the people, to preserve and protect the submerged or submersible lands for public use in navigation, fishing, and recreation. There have been rulings by the courts which expand the definition of public trust uses on submerged lands to mean protection of visual, wildlife, and open-space values for the benefit of all the state's citizens. Coastal States Organization (1997) asserts the public trust doctrine "provides that public trust lands, waters, and living resources in a State are held by the State in trust for the benefit of all of the people, and establishes the right of the public to fully enjoy public trust lands, waters, and living resources for a wide variety of recognized public uses." The living resources (for example, the fish and aquatic plant and animal life) inhabiting these lands is also subject to the Public Trust Doctrine (Coastal States Organization, 1997).

Utah Statutes Defining Sovereign Lands and Public Trust

Each state, through its constitution and statutes, determines how the multiple resources within sovereign lands are to be managed for the public trust. There exists what the Coastal States Organization (1997) refers to as a "pyramid of authority over navigable waters." "At the top, and operating within the narrow scope of 'improvements to navigation' is the federal navigational servitude. Next is the State authority, as trustee, to manage its trust lands, waters, and resources for the benefit of the public's various trust uses, including the authority to reasonably regulate riparian rights, or to deny them altogether. Finally, "riparian owners have certain rights ... " In this context, the 'federal navigational servitude' is defined as the "dominant servitude over navigable waters. 'The right of the United States in the navigable waters within the several States is, however, limited to the control thereof for the purposes of navigation'" (Coastal States Organization, 1997).

Utah's constitution does not address sovereign or public trust lands directly but rather defines the use of public lands as follows in Article XX, Section 1:

"All lands of the State that have been, or may thereafter be granted to the State by Congress, and all lands acquired by gift, grant, or devise, from any person or corporation, or that may otherwise be acquired, are hereby accepted, and, except as provided in Section 2 of this article, are declared to be public lands of the State; and shall be held in trust for the people, to be disposed of as may be provided by law, for the respective purposes for which they have been or may be granted, donated, devised, or otherwise acquired" (Utah Constitution, Article XX, Section 1, 1896).

By statute, sovereign lands are defined as "state lands," to be managed by "multiple-use sustained yield principles" (Utah Code Ann., Section 65A-2-1). 'Multiple use' is defined as "management of various surface and subsurface resources in a manner that will best meet the needs of the people of this state"(Utah Code Ann., Section 65A-1-1(3)). 'Sustained yield' is defined as "the achievement and maintenance of high level annual or periodic output of the various renewable resources of land without impairment of the productivity of the land" (Utah Code Ann., Section 65A-1-1(7)).

The Division of Forestry, Fire and State Lands (DFF&SL) has been given management authority for sovereign lands and, as manager, "may exchange, sell, or lease sovereign lands but only in the quantities and for the purposes as serve the public interest" (Utah Code Ann., Section 65A-10-1). Sales and exchanges have been few in number compared to other dispositions. Utah statute further defines powers and duties for management of sovereign lands within GSL. These duties include preparing comprehensive plans, initiating studies of the lake and its resources, defining the lake's flood plain, determining the need for public works and utilities, implementing comprehensive plans through state and local entities, coordinating the activities of various divisions within the DNR, and encouraging the continued activity of the GSL technical team.

Just as public trust doctrine has evolved over several centuries and has been interpreted by the laws and customs of several governments, the management directives for sovereign lands in Utah have also changed over the years since statehood. Nevertheless, a common thread is that, from statehood, the Utah State Land Board (Land Board) was intended to be a "conservation organization, empowered to protect vital watersheds" in its management of timber and rangelands (Smith, 1960).

Management and disposition of minerals initially was a low priority relative to agricultural uses and water rights on, or adjacent to, sovereign lands. The Land Board legislation in 1917 allowed the sale of submerged lands but only if lakes or waterways were dewatered "to reclaim the bed thereof for agricultural purposes..." (Utah State Legislature, 1917, Chapter 114). By 1925, submerged lands could also be sold if riparian landowners had made valuable improvements below the water's edge, but with mineral rights to be reserved to the state (Utah State Legislature, 1925, Chapter 31). In 1929, the Utah Legislature granted use of some sovereign land in Bear River Bay to the United States for use as a migratory bird refuge. In 1931, the Land Board was authorized to make surveys of lands for flood control. This charge to DFF&SL is still in effect, although flood control activities were given to the State Engineer in 1936 (Smith, 1960).

Development of Management Principles for Sovereign Land

In 1933, legislation was added to the Utah Code which began to define public trust goals for the state's sovereign lands. This legislation allowed sovereign lands to be sold for "public or quasi public use or service" (Utah State Legislature, 1933) as long as such sales did not interfere with navigation. In 1956, sovereign land near Little Mountain in Weber County was sold to Marquardt Aircraft Company, presumably for national defense purposes. In 1957, land was sold to Weber Basin Water Conservancy District; Willard Bay Reservoir now covers this land. In 1973 and 1982, parcels were sold to the town of Perry for its sewage lagoons. Both of these sales include reversionary interest clauses through which title reverts to the state if the land is not used for a public purpose. In 1984 and 1991, land exchanges were consummated to resolve ownership disputes in Farmington Bay and Bear River Bay.

The 1982 sale to the town of Perry was the last sale of sovereign land. The administrative rule for the sale of land has since lapsed. Any future sale proposal will be closely scrutinized from a public trust perspective, and rulemaking will be required. Rules are in place for leases, exchanges, and other dispositions.

With exception of the Bear River Migratory Bird Refuge and state waterfowl management areas, most early non-mineral development on the bed of GSL occurred during the heyday of recreational resort development. Much of this development took place before there was an administrative framework for sovereign land management, and probably with some confusion over the nature of riparian rights or the lack thereof. It was not until the late 1950s that the Land Board required formal applications to request special-use leases for the kinds of development that had occurred earlier.

The earliest lease applications were for a boat harbor, public resorts, a fresh-water, artificial lake, and the use of mill tailings in land reclamation. Some of these proposed projects were studied, but not constructed. Others flourished briefly, but eventually succumbed to the changing level of GSL, fires, or the changing recreational pursuits of an increasingly mobile society. Today, the only remaining early developments are the GSL Boat Harbor, owned by the Utah Division of Parks and Recreation, and the privately owned Saltair Resort.

U.S. Supreme Court Decision

In the early 1960s, as interest grew in non-salt minerals in the lake, BLM served notice on the Land Board that it intended to survey a boundary line along the GSL to separate state and federal ownership, and that it would locate such boundary line at an elevation of 4201.8 feet (1,280.7 m) above mean sea level (m.s.l.), which was the same elevation as the water level on January 4, 1896, when Utah obtained statehood. Utah objected because it believed that the State owned the lake, the watercovered bed, and the shore lands located within the surveyed meander line as officially surveyed and approved by the U.S. Government during the 18 surveys performed from 1855 through 1966 (Dewsnup and Jensen, 1980). The lake level was at many different elevations during that 111year period.

In 1976, after nearly 15 years of congressional and legal proceedings, the U.S. Supreme Court ruled to affirm "in Utah, ownership of all lands, brines, and other minerals within the waters of the lake and within the bed and all shore lands located within the official surveyed meander line as duly surveyed prior to or in accordance with Section 1 of the Act of June 3, 1966, 80 Stat. 192." (Utah vs. United States, 1975). The Supreme Court's final decree did not address the title to lands within the Bear River Refuge, the Weber Basin Federal Reclamation Project, and the Hill Air Force Range as bounded by the water's edge June 15, 1967.

Ownership of Islands in Great Salt Lake

Utah considers unsurveyed islands as

being sovereign lands while surveyed islands are owned by the "upland" land owner. Surveyed islands in the lake are Antelope, Fremont, and Carrington Islands (see figure 1). Unsurveyed islands are Gunnison/Cub, Dolphin, Egg, Goose, Hat, and Badger Islands. At the time of the U.S. Supreme Court decision, significant parts of Gunnison/Cub and Hat Islands were in private ownership. Following legislation passed in 1977, lands in private ownership on Gunnison/Cub and Hat Islands were purchased by the state and subsequently designated as wildlife management areas for the protection of the American White Pelican.

MANAGEMENT OF GREAT SALT LAKE RESOURCES

The lake's many resources; water, minerals, wildlife, recreation, archeological, and historical values, are managed by several state agencies. Examples of conflicts involving one or more state agency include: conflicts in water require-





ments among mineral operations and wildlife; conflicts between recreational use (for example, access, water use, and visual impacts) and issuance of mineral leases; conflicts between recreational use and wildlife use, especially during breeding and nesting seasons; disturbances or hazards to wildlife by mineral development or commercial activities, especially in areas owned by the Division of Wildlife Resources (DWR) or authorized for use as wildlife management areas, fishing waters, and recreational activities by Utah Code Ann., Section 23-21-5.

Several islands have been acquired by state agencies to be dedicated to wildlife management or recreational use. The DWR purchased Gunnison/Cub and Hat Islands, and the Division of Parks and Recreation purchased Antelope Island. In addition, the Land Board withdrew areas around Hat and Dolphin Islands from mineral leasing (Utah State Land Board minutes, 1976) and dedicated sovereign lands below Harold Crane Wildlife Management Area (WMA) to wildlife use (Utah State Land Board minutes, 1982). Table 1 lists these areas and figure1 shows their location on GSL.

Current Management of Sovereign Lands

In 1988, the management direction for sovereign lands was changed by the state legislature to ".....sell or lease sovereign lands but only in the quantities and for the purposes as serve the public interest and do not interfere with the public trust." (Utah Code Ann., Section 65A-10-1). 'Public trust assets' were defined as lands and resources, including sovereign lands, administered by the division that are not part of the school or institutional trust lands. Specific management responsibilities are set forth in statute for sovereign lands within GSL. Statute allows the state as represented by DFF&SL to exchange, sell or lease sovereign lands, to set aside sovereign lands for recreational purposes, and instructs DFF&SL to "develop plans for the resolution of disputes over the location of sovereign land boundaries." In addition, DFF&SL may enter into agreement with state agencies and private parties to establish boundaries (Utah Code Ann., Section 65A-10 3(1-2)).

The DFF&SL was created in 1994 with the responsibility for management and planning of all mineral resource development on sovereign lands, in addition to responsibilities for comprehensive planning and coordination of activities of public and private entities. Management of many of these resources has been delegated to other natural resource agencies; recreation and boating to the Division of Parks and Recreation; the various aspects of water resources to the Divisions of Water Resources, Water Quality, and Water Rights; and wildlife to the DWR.

Planning Efforts for Great Salt Lake

Sovereign lands within GSL are the largest contiguous area (approximately 1.35 million acres (0.547 million ha) within the surveyed meander line) to be managed by the state of Utah. These "lands" are part of a hypersaline lake rich in mineral resources, wildlife ("ornithologically the most impressive salt lake on the continent"- Jehl, 1994), recreational values, and vast expanses of view and water. Management plans were prepared for GSL in 1976 and 1987, however, planning for mineral resources was not fully incorporated into those plans because mineral leasing was administered by the Division of State Lands and Forestry while planning and coordination was done by the Division of Great Salt Lake (1976 to1979) and then by DNR (1980 to1988).

Three levels of planning satisfy the statutory requirement for the management of sovereign lands. The basic level of planning is a site-specific plan prepared in response to an application for a particular land use in a specific location. This usually requires preparation of a record of decision. The next level is resource management planning, such as the 1996 Mineral Leasing Plan for Great Salt Lake. The broadest level of planning is a comprehensive management plan, such as the Great Salt Lake Planning Project initiated in 1997 and completed in 2000.

The DFF&SL, with the approval of the executive director of DNR and the governor, may set aside sovereign land for public or recreational use. Management authority for those lands may be delegated to any state agency. In 1977,

Table 1.

Lands in the vicinity of Great Salt Lake owned or managed by other state agencies. The column "Year" is the year that the Land Board delegated management responsibility.

Agency	Area	Acres	Year
Division of Wildlife Resources	Locomotive Springs	17,937	1931
		2,657	Additional acreage proposed
Division of Wildlife Resources	Public Shooting Gnds	13,063	1923
Division of Wildlife Resources	Harold Crane	8,593	1963
Division of Wildlife Resources	Ogden Bay	18,395	1937
Division of Wildlife Resources	Howard Slough	3,300	1958
Division of Wildlife Resources	Layton-Kaysville	25,000	1975
Division of Wildlife Resources	Farmington Bay	10,772	1935
Division of Wildlife Resources	Bird (Hat) Island)	22	1977
Division of Wildlife Resources	Gunnison Island	163	1977
Division of Wildlife Resources	Dolphin Island	624	1977
Division of Wildlife Resources	West Bear River Bay	>5	Proposed for public access
Division of Parks and Recreation	Antelope Island	28,022	1969/1981
Division of Parks and Recreation	South Shore	5,874	1977

the Land Board exercised this authority for the creation of Great Salt Lake State Park and delegated management authority to the Division of Parks and Recreation. The sovereign land included in this action extended one mile (1.6 km) lakeward from the Meander Line, generally between the Goggin Drain and Black Rock. The state park existed until 1997 when a partial recission of the delegation of management authority was executed to return management authority for most of the sovereign land to DFF&SL. This was done after the Division of Parks and Recreation reconsidered the suitability of the land as a state park and decided it was not suitable park land. This decision was based, in part, on the difficulty of dealing with the fluctuating level of GSL - the same difficulty encountered by resort owners decades earlier. In what was the state park, the Division of Parks and Recreation retained management authority for only the Great Salt Lake Marina. A similar delegation of management authority was executed for sovereign land around Antelope Island State Park in 1985. The Division of Parks and Recreation manages an irregular boundary, generally extending one mile (1.6 km) lakeward, around the island.

The DFF&SL has established general statewide sovereign land classifications through administrative rule:

Class 1. Lands managed to protect existing resource development uses,

- Class 2. Lands managed to protect potential resource development options,
- Class 3. Lands managed as open for consideration of any use,
- Class 4. Lands managed for resource inventory and analysis,
- Class 5. Lands managed to protect potential resource preservation options, and
- Class 6. Lands managed to protect existing resource preservation uses.

These classifications were applied to GSL in 1995, and were reviewed under the current (2000) Great Salt Lake Planning Project. Lands under these classifications will change over time in response to changes in public demand, and changes in legislative and administrative policy.

In addition to the classification of lands, several easement corridors have been created to expedite commerce on sovereign lands within GSL. The main north-south easement corridor is along the east side of the lake, primarily for utility lines. The main east-west corridors are the two Union Pacific Railroad causeways. Major easements in the future will be directed to these corridors to attempt to lessen the cumulative impacts on sovereign lands.

Section 23-21-5 Lands

The Utah Legislature has authorized the DWR to use all or parts of 39 townships of GSL for the creation, operation, maintenance, and management of wildlife areas, fishing waters, and other recreational activities (Utah Code Ann., Section 23-21-5). This geographic area covers Bear River Bay, Ogden Bay, Farmington Bay, portions of the south shore area, and the north end of Spring Bay. This statutory authorization is interpreted as establishing wildlife management and wildlife-related recreation as the primary intended land uses, except for areas identified for other uses through a planning process. Land uses with significant adverse impacts on wildlife and recreation values may be prohibited, even though mitigation strategies are available. Within this area, the DWR established the Harold Crane WMA, Howard Slough WMA, Ogden Bay WMA, Farmington Bay WMA, and Locomotive Springs WMA (figure1).

Use of this area for wildlife is influenced by the level of GSL. At high lake levels, WMA dikes may be overtopped and fresh water impoundments lost to salt water inundation. At low lake levels, expansive mud flats are exposed lakeward of the WMA dikes. Wildlife species using the area changes accordingly. Extensive non-wildlife developments such as IMC Kalium's evaporation ponds have been permitted. The record is not clear on the extent of consultation with the DWR when mineral leases were issued in the early 1960s, but by the late 1960s it is clear that the Land Board was concerned that consultation should occur before additional mineral leasing. IMC Kalium and the DWR and DFF&SL have recently cooperated as opportunities arise to relocate undeveloped lease acreage to relatively less sensitive areas of GSL, primarily its west side.

Mineral Leasing Plan for Great Salt Lake

The DFF&SLs' focus in the past has been on management and leasing of minerals and rights-of-way on sovereign lands. With regard to mineral extraction, DFF&SL has several directives under Utah Code, Section 65A-10-18. These directives are:

- Encourage development of the lake in a manner which will preserve the lake;
- Encourage availability of brines to lake extraction industries;
- (3) Protect wildlife and recreation facilities;
- (4) Promote the development of lake brines, minerals, chemicals, and petro-chemicals to aid the state's economy;
- (5) Encourage the use of appropriate areas for the extraction of brines, minerals, chemicals, and petro-chemicals; and
- (6) Encourage the development of an integrated industrial complex.

MINERAL AND ENERGY RESOURCES

Captain Howard Stansbury's accounts of his exploration of GSL, when the lake elevation was around 4,201 feet (1,281 m), make many references to the very saline character of the lake. The chemical analyses of the lake in the appendices of his report described lake brines as "perfectly clear, and had a specific gravity of 1.170, water being 1.00." Dissolved solids were reported as 22.42 percent, and sodium chloride as 20.196 percent (Stansbury, 1852). Stansbury describes his attempts to preserve meat at Black Rock:

"Before leaving Black Rock, I made an experiment upon the properties of the water of the lake for preserving meat. A large piece of fresh beef was suspended by a cord and immersed in the lake for rather more than twelve hours, when it was found to be tolerably well corned."

The method worked so well that the survey party preserved all their beef with lake brines. In fact, the brine had to be diluted with fresh water to avoid the meat from becoming "what the sailors call 'salt junk' "(Stansbury, 1852).

Besides the salt in the lake, Stansbury also noted other mineral resources in the course of his year-long survey, including the asphalt seeps at Rozel Point, and the presence of oolitic sands. At the beaches west of Rozel Point, he describes the sands under a magnifying glass as "rounded globules, chiefly of calcareous rocks, worn doubtless by attrition into their present form, not an angular particle being found among them. It is variegated by different and brilliant colors... A piece of bitumen was found buried in the sand, which had adhered to it when softened by the sun, and completely frosted it over, so that it very much resembled one of the small chocolate lozenges of the shops, covered with miniature sugar plums" (Stansbury, 1852).

Mineral Resources in Brines

The brines of GSL contain several ions that crystallize into valuable minerals during the evaporative process. The major ions in the lake are, in order of relative abundance, chloride, sodium, sulfate, magnesium, and potassium. The composition of GSL water is similar to the oceans although GSL brines are significantly more concentrated. Compared with other inland seas, GSL is high in sulfates, which aids in the production of schoenite (a hydrated potassium, magnesium sulfate). Schoenite is, in turn, a key ingredient used in producing potassium sulfate from high magnesium/potassium harvest salts.

Mineral products currently extracted from lake brines are sodium chloride, magnesium chloride brines (and from that, magnesium metal and chlorine gas), and potassium sulfate. Production of sodium sulfate (salt cake) recently ceased due to declining demand and competition with sodium sulfate produced as a waste product in the manufacture of nylon and other products.

Mineral products which have the potential for commercial production include gypsum, and, in trace amounts, lithium, boron and bromine. Of these, the extraction of lithium has attracted the most interest. MagCorp concentrates lithium in their electrolytic cells, but does not produce lithium chloride for sale at present. The company also extracts boron as part of the brine preparation, but discards it as a waste product. Lithium Corporation of America, predecessor to IMC Kalium, investigated the production of lithium and bromine, but did not pursue the idea.

Salt Resources

An estimated 4.3 billion st (3.9 billion mt) of dissolved salts were contained in GSL in 1998. UGS estimates of dissolved solids in GSL have fluctuated from 4.0 to 5.5 billion st (3.6 to 5.0 billion mt) (J.W. Gwynn, Utah Geological Survey, personal communication, 1999) due to the dynamic conditions in the lake as salts are precipitated and redissolved, and to the diversions of brines from GSL, such as the West Desert Pumping Project. About 2.0 million st (1.8 million mt) of dissolved solids flow into the lake each year from surface runoff. Flow-volume, weighted average calculations of these dissolved solids indicate the following chemical composition: sodium 23 percent; chloride-36.4 percent; bicarbonate-25.4 percent; sulfate-5.3 percent; calcium- 5.08 percent; magnesium-2.9 percent; and potassium-1.6 percent. Most of the bicarbonate, calcium, and sulfate will precipitate onto the lake bed as calcite and gypsum. The composition of dissolved solids in streams flowing into the lake is somewhat influenced by agricultural, municipal, and industrial use of tributary waters. Salts are also deposited in the lake by wind and ground water but there are no estimates of the composition and amounts from these sources (J.W. Gwynn, unpublished data, 1998).

Brine Concentration

Brine concentration and the precipitation of salts are dependent upon a number of factors. These factors include water elevation and fresh water flow into the lake, construction of causeways and other diking systems, pumping of lake brines for flood control, and seasonal variations in temperature. Precipitation of salts, whether on the lake bed, in the Newfoundland Evaporation Basin, or in solar evaporation ponds, removes salts from the lake water. Salts on the lakebed have historically precipitated from, and redissolved into, the lake brine system in response to changing lake levels. Mirabilite (sodium sulfate with ten waters of hydration) precipitates out during winter months and is redissolved as the water warms during the summer.

Impacts of Causeway, Diking, and Diversion Operations

Variations in brine concentrations throughout the lake are directly influenced by the causeway and other diking systems. Continuous monitoring of brine concentrations began in 1966, seven years after the construction of the northern Union Pacific causeway. Prior to that time, there is little information about brine concentrations beyond occasional historical references. These early records indicate the lake was a relatively homogenous saline body of water with somewhat higher concentrations of brine on the western side of the lake due to smaller inflows of fresh water and higher rates of evaporation. After construction of the northern Union Pacific causeway, the lake was divided into two bodies of water. There was limited interchange of brines through two culverts in the causeway and through the causeway itself; over time, however, the two arms developed distinct physical and chemical characteristics. In addition to higher concentrations along the west side of the lake, the north arm of the lake had concentrations nearly twice the concentrations of the south arm. The south arm was stratified into a shallow, less concentrated layer (to a depth of 23 feet [7 m]) and a deep layer (below 23 feet [7 m]) of dense, fetid brine (due to hydrogen sulfide and considerable organic matter) at the center of the lake. Concentrations of these deep brines were approximately two times that of the upper layer.

Flood management during the high water years of the early to mid-1980s had significant impacts on lake salinity. When the 300-foot (91 meter) breach on the western end of the northern Union Pacific causeway was opened, a very large volume of dilute south arm brine flowed through the opening at the surface into the north arm of the lake, and a large volume of more dense north arm brine moved through the same opening into the depths of the south arm as return flow. As a result, the north arm of the lake became temporarily stratified. By mid-1991, due to wave action, the north arm of the lake became totally mixed from top to bottom and all signs of stratification were gone. Due to the general lowering of the lake level from 1990 through 1995, the denser brine from the north arm stopped flowing through the breach to the south arm in 1990, when the brine depth at the breach decreased to approximately four feet (1.2 m). As the lake rose from 1996 through most of 1998, brines flowed through the breach from south to north, resulting in the transfer of large volumes of salt to the north arm. In the fall of 1998, as the elevation of the two arms of the lake were within a foot of each other, there was some flow of dense north arm brines into the south arm. There is significant concern that the settling of the existing causeway fill and the addition of extra fill along the length of the causeway has reduced the return flow from the north arm through the causeway fill.

Diking elsewhere in the lake, at the north end of Antelope Island and Stansbury Bay, causes differences in salinity. Farmington Bay is more dilute than the rest of the south arm of the lake while Stansbury Bay has concentrations approaching those of the north arm. As a

result, the lake has four areas of salinity induced by diking or other man-made structures (figure 2):

- (1) North arm and Stansbury Bay brines are at, or near, saturation (25 to 27 percent),
- (2) The main body of the south arm has concentrations ranging from 7 to 15 percent as lake elevations fluctuate,
- (3) The waters in Farmington Bay are at approximately 3 to 5 percent, and
- (4) Bear River Bay, which fluctuates with the lake level and Bear River inflow, varies between fresh water and salinities from 7 to 10 percent. In comparison, the salinity of seawater ranges from 3 to 5 percent.

The transfer of salts from the south arm to the north arm gave rise to charges that the ability of south arm mineral industries to extract salts from brines is impaired and that the viability of brine shrimp, which thrive in a salinity range of 13 to 19 percent, is threatened. To help resolve these issues, the UGS continues to monitor salinities at designated sites on the lake.

Natural Factors in Brine Concentrations

Salinity is also affected by natural factors. Water inflow and evaporation rates are the most important influences, natural or man-caused. In the south arm, the relationship between water elevation and salinity is an inverse one; as the lake goes up due to increased inflows, precipitation, and decreased rates of evaporation, the salinity goes down. In the north arm, for the period 1966 through 1983, salinity remained at or near saturation regardless of the north arm elevation. This was because evaporation was greater than the diluting effect of the south arm brines that flowed from south to north. There appears to be variation in salinity in the north arm, with higher concentrations to the north and west, due to inflows at the causeway breach and because of counterclockwise currents in the lake. During the high water years of 1983 to1987, the salinity of the north arm decreased. The brines in the north arm again became concentrated enough to precipitate salts in the summers of 1995, 1996, and 1997, but were below the saturation point in 1998 (J.W. Gwynn, unpublished data, 1998). According to IMC Kalium's observations, precipitation of salts occurs mostly in the shallow areas in the north and west sides of the north arm.

Salt Resource Consumption and Loss in Great Salt Lake

Salts have been extracted in significant amounts, and at an increasing rate since 1965. In that year, salt companies produced about 0.3 million st (0.27 million mt) of sodium chloride. By 1994, production from GSL was over 2 million st (1.8 million mt) of sodium chloride and approximately 0.3



Figure 2. Areas of salinity levels within Great Salt Lake.

million st (0.27 million mt) of other salts. To produce salable tons of potassium, and magnesium salts, many more tons of salt (sodium chloride) are deposited in concentration ponds as waste. Some of these salts are returned to the lake if sufficient fresh water is available to flush the salts from the ponds.

A far more significant depletion of the resource was the loss of approximately 12 percent of the lake's dissolved salts as a result of the pumping of brines into the Newfoundland Evaporation Basin west of GSL. Even so, geologists and industry representatives estimate it will take at least 200 years to deplete 10 percent of the lake's remaining sodium chloride at current rates of extraction (or 1,000 years to deplete the sodium chloride in the lake to the point that further extraction is not economic), not accounting for the annual replenishment of salts from surface and ground water inflows. Some ions, notably the sulfate, magnesium, and potassium, are more limited in supply than sodium and chloride ions but their production cannot be separated from the production of salt. The DFF&SL has not monitored the amounts of salts which are deposited into evaporation ponds and how much of these salts are flushed back into GSL. This data could provide insight into the long- term resources contained in the lake.

Waste Salts

Industries extracting magnesium or potassium salts produce substantially more salts than they process for sale. Significant amounts of sodium chloride are used to form floors for the harvesting ponds. Remaining, unwanted salts either accumulate on the bed of the evaporation ponds, as happens in the Stansbury Bay portion of MagCorp's operations and in IMC Kalium's west pond, or are partially flushed with fresh water from the ponds each season, as is the case with IMC Kalium's ponds in Bear River Bay. At both these locations, significant amounts of sodium chloride are harvested by other salt companies under agreements with the original lessees. The returned salts are altered in chemical composition from lake brines because target ions have been removed. Millions of tons of salts are precipitated out annually in Stansbury Basin and Clyman Bay, or are used in harvesting ponds in all salt operations, and therefore not returned to lake brines. Some of these salts are harvested and sold, some are flushed back into the lake, and others remain on pond floors.

The accumulation of waste salts on pond floors becomes a significant problem for producers. So that production of target chemical salts can continue, higher and higher dikes must be built or considerable sums must be spent for the removal of these waste salts. Removal of salts into areas of lower salinity (as in Bear River Bay) can create environmental problems.

Salt Extraction Requirements

The most important factor in the salt extraction process is the original concentration of lake brines. The lower the concentration of brines, the greater the evaporation pond area required for a given volume of produced salt, or alternatively, a limitation on the amount of salt which can be produced. Similarly, those companies extracting potassium, sulfate, or magnesium ions require much larger ponding areas than companies extracting salt because those ions are far less abundant in lake brines.

Evaporation ponds require large areas with suitable soil conditions, access to transportation and utilities, availability of fresh water to flush excess salts from evaporation ponds, and a location conducive to high evaporation rates. These conditions place the greatest constraints for new or expanded operations on the lake. Currently, there are over 100,000 acres (40,000 ha) in evaporation ponds around GSL. Potential ponding sites that are currently unleased include Rozel Bay, Spring Bay, the northwest portion of Gunnison Bay, and the mudflats along the south shore between Stansbury Island and Lake Point.

Lakebed Deposits

Sodium chloride precipitates on the lake bed as salinity increases in the north arm and in Stansbury Bay. If the north arm of the lake stabilizes at or near the saturation point for sodium chloride, as happened for the period from 1966 to 1983, these lakebed deposits will accumulate.

Sodium sulfate (mirabilite) also precipitates on the lake bed during winter months in response to cooler temperatures and higher salinity. Mirabilite deposits are found at the southwestern tip of Promontory Point and throughout the lake during winter months if brines become cold and concentrated enough to precipitate. A substantial portion of these deposits redissolve as temperatures warm again. "Permanent" deposits probably occur around much of the perimeter of the lake. These are mirabilite-cemented sands which were probably formed by mirabilite being blown upon the beaches, dissolving, then resolidifying, cementing the sands at depth (Wilson and Wideman, 1957). These cemented sands have been found at Saltair and the south shore marina, where they had to be blasted to deepen the marina, and in other areas around the lake. There is also a very thick layer of mirabilite westward from the southern tip of Promontory Point (Eardley, 1962). The potential for mineral extraction of these deposits is small due their low value, limited or declining markets, and high extraction costs.

Hydrocarbon Resources

Hydrocarbon resources underlying the lake are significant, but presently undeveloped. The hydrocarbons are low gravity (4 to 9 degree API) and tar-like. They contain high nitrogen concentrations and up to 12 percent sulfur. The UGS reports: "The oil is chemically similar to ichtyol, a rare substance used for medicinal purposes, and thus has the potential to be an extremely valuable commodity. Higher molecular weight fractions, when added to oil, are known to increase the lubricity of the oil" (Chidsey, 1995). The unusual characteristics of the oil have been the subject of studies by chemists at Weber State University and Université Louis Pasteur de Strasbourg. However, these resources are expensive to process and, at present, uneconomic to extract using current technology because of the nature of the hydrocarbons and production in "an offshore, highly saline environment" (Kendall, 1993).

Two oil fields have been discovered on GSL, Rozel Point and West Rozel. The Rozel Point field is located in T. 8 N., R. 7 W., Salt Lake Base Line, along the north shore of the lake. West Rozel field is located in T. 8 N., R. 8. W., three miles (5 km) from the shoreline of the Rozel Point field. The estimated area of the Rozel Point field is about ten acres (4 ha). The field has a low reserve estimate because of the poor reservoir seal. Small amounts of hydrocarbons or asphaltum have been recovered from natural seeps and shallow wells at Rozel Point since the turn of the century. Earliest use was as a lubricant. More recent uses have been to resurface roads and for impregnating tire cords (Chidsey, 1995). In the early 1960s, several wells were drilled on a one-acre (0.5 hectare) spacing order from the Division of Oil, Gas and Mining (DOGM). One 40 acre (16.2 hectare) lease in this field expires in 2002.

The West Rozel field was discovered as a part of Amoco Exploration Company's exploration program on GSL in the late 1970s. Thirteen "offshore" wells were drilled between June 1978 and December 1980, resulting in the discovery of the West Rozel field, and with oil shows reported in eight wells. Two development wells were drilled at West Rozel, identifying a field covering 2,300 acres (930 ha) with heavy oil similar to that at Rozel Point. Reserve estimates for the field are high, in contrast to Rozel Point, with a primary recovery of 1 to 10 million barrels (0.16 to 1.6 million m3) of oil. However, Amoco did not develop the field "because of the high water cut and the high cost of operating an 'offshore' field" (Bortz, 1987). The unusual character of the oil also contributed to this decision. This field is considered by UGS to have "low development potential" because the oil cannot be economically produced. Changing technology may make the field viable. Oil characteristics and reserve estimates for the West Rozel and Rozel Point fields are summarized in table 2.

Condemnation proceedings against Anschutz Ranch to establish a purchase price for Antelope Island documented the low potential for oil and gas in the vicinity of the island (Howard Ritzma, personal communication, 1995). No wells have been drilled and there is no exploration activity, but there are two oil, gas, and hydrocarbon leases off Sea Gull Point on Antelope Island. These leases cover 1,411 acres (571.3 ha) and expire in 2002.

World-wide, there appears to be low prospects for tar sands development and even less for "super" heavy oil extraction under such difficult conditions. Only Canada and Venezuela, with lead time, infrastructure, and experience, have been successful in developing their heavy oil and tar sands industries (Howard Ritzma, personal communication, 1995).

Other Mineral Resources

Oolitic sand deposits make up many of the beaches along the shoreline around the lake, with higher concentrations along northwestern Antelope Island, the east side of Spring Bay, the western side of Stansbury Island, and on Carrington Island. Because of their high calcium carbonate content, oolites have been used by MagCorp, and its predecessors, for acid neutralization and dike construction. Oolites are also used in very minor amounts in flower drying. Until recently, the DOGM reported up to 130,000 st (118,000 mt) mined annually by MagCorp on BLM lands adjacent to GSL.

HISTORY OF MINERAL LEASING ON GREAT SALT LAKE

Sodium Chloride Leases

Sodium chloride is the mineral with the longest history of successful extraction on GSL. Native Americans and early explorers extracted small amounts of salt. Permanent salt production facilities began in 1850, using boilers to evaporate salt. In 1888, Inland Salt Company developed a process called fractional crystallization, which used a series of evaporation ponds to produce salt free of contaminating chlorides and sulfates of magnesium, calcium, and potassium. Inland Salt Company was the predecessor of a succession of salt companies which dominated the salt industry in Utah. Inland Salt Company was bought by Morton Salt in 1923, and Morton continued to dominate the salt market until the 1950s, operating from sites near Saltair and Burmester. In a highly competitive market, several salt companies came and went as the waters of the lake fell and then rose, and as industrial markets for salt followed the rise and fall of silver mining (Clark and Helgren, 1980).

Leases for the extraction of salt and other minerals have

Field	Oil Characteristics		Reserve Estimates	
West Rozel	Gravity	4° API	Proved area, 500 acres	
	Color	Dark Brown	Primary Recovery, 1-10 mmbc	
	Sulfur	12.5%		
	Pour Point	75%		
	Viscosity	3000-4000cp@140°F		
Rozel Point	Gravity	5° API	Proved area, 10 acres	
	Color	Black, tar-like	Primary Recovery, 2,665 bo	
	Sulfur	12%		

been issued by the Land Board for various products "under the waters of Great Salt Lake" since 1919, after authority for management of sovereign lands was given to the Land Board. Leased minerals included sodium sulfate, salt, magnesium, and oil and gas, sometimes all in one lease. In 1935, the legislature made reservation of coal and other minerals on state lands mandatory and "reserved from sale, except on a rental and royalty basis..."(Utah State Legislature, 1935).

In 1940, despite this long history of leasing, Deseret Land and Livestock filed for a diversion from GSL under the state's water appropriation laws for the purpose of extracting salt. Deseret claimed the state did not own the salts contained in brines and that no royalty or lease agreement was needed. In 1941, the legislature added a section to Utah statute which included "salts and other minerals in the waters of navigable lakes and streams" as minerals to be managed by the Land Board. A 1946 Utah Supreme Court decision affirmed state ownership of minerals in the waters of the lake. Royalty terms on these leases were variously 35 cents and 50 cents per st (38 cents to 55 cents per mt), but this rate was disputed by Deseret Land and Livestock Company and Morton Salt, in particular. After eight years of negotiation with the Land Board, Morton negotiated a 15-year lease to extract sodium chloride from brines, and the lease did not provide any acreage within the meander line. The royalty rate was 10 cents per st (11 cents per mt). These lease terms were subsequently offered to all producers and new lessees on the lake. Many lessees negotiated mineral leases in connection with royalty agreements which allowed sovereign lands to be used for evaporation ponds or for the lessee to extract salt precipitated on the bed of the lake. As the royalty agreements reached the end of their terms in the late 1960s, the Land Board added language which allowed leases to be held by production. Royalty rates were left at 10 cents per st (11 cents per mt).

In 1997, more than 40 years after the 10 cents per st (11 cents per mt) rate was agreed to by the Land Board, DFF&SL enacted new rules to increase the royalty rate to 50 cents per st (55 cents per mt), that will be phased in over a five to ten year period, depending on each salt producer's circumstances. After the royalty rate reaches 50 cents per st (55 cents per mt) for all producers, it will be adjusted annually for inflation by an index tied to the Producer Price Index for industrial commodities.

Non-Halite Salt Leases

During the 1960s, the Land Board entered into agreements with three companies, two interested in extracting magnesium chloride to be refined into magnesium (H-K, Inc. and Bonneville-on-the-Hill, now MagCorp), and the third interested in lithium and potassium products (Lithium Corporation, now IMC Kalium). These agreements had 49 year terms and an ad valorem royalty rate beginning at 1.5 percent applied against "dry" products and escalating to 5 percent over a 25 year period. The magnesium chloride producer was granted an exclusive right to produce that product from 1961 to 1969. At the end of that period, salt lessees were offered an opportunity to convert their royalty agreements, which allowed the extraction of sodium chloride only, to an agreement which allowed extraction of all minerals, including magnesium chloride, contained in brines. Also at the end of that period, a royalty rate for magnesium was added to the royalty schedule beginning at 0.1259 percent and escalating to 0.4196 percent. This rate was meant to produce equivalent royalty revenues when applied to the value of magnesium metal that the 1.5 percent to 5 percent rate would have generated if applied against the value of anhydrous magnesium chloride. However, the new schedule fell significantly short of accomplishing this goal. All royalty agreements contained a provision which entitled lessees to the lowest royalty rate granted to any other lessee on the lake. This provision was applied primarily to royalties on sodium chloride in those agreements which contain that clause.

Lessees under these royalty agreements began production in the mid 1970s. Ten years later, as GSL was approaching its historic high elevation of 4,211.60 feet (1,283.7 m) above m.s.l., and most producers on the lake were experiencing major damage to their dikes, the Land Board granted both companies royalty relief by starting the clock at year one of the royalty schedule.

An Attorney General's Opinion dated June 9, 1966, in response to a request for an opinion by the Director of State Lands, stated that "salt and salt derivative leases on the bed of GSL would be subject to the simultaneous filing provisions of the statute" if the lands were under a lease which was terminated by board action or released from a withdrawal from mineral leasing (State Land Board minutes, 1966). However, salt leases on GSL have never been offered as part of a simultaneous filing.

Current Salt Operations

Although the two non-halite salt companies (MagCorp and IMC Kalium) have maintained their leases since the 1960s, sodium chloride leases have dwindled from 8 to10 small operations on the lake during the 1940s, to three significant operations. Following the high lake levels in the mid-1980s, Morton Salt Company relinquished its original royalty agreement negotiated with the Land Board in 1954, to assume control of a site southeast of Stansbury Island, formerly operated by American Salt Company. SolAire Salt (now owned by Cargill Salt) relinquished its operations near Lake Point, the original lease site for Deseret Livestock Company and its many successors, and now operates from a royalty agreement by acquiring concentrated brines from MagCorp. American Salt (now IMC Salt) moved its operations to Bear River Bay and operates on a sublease agreement, purchasing crude salt from IMC Kalium. Mineral extraction from GSL brines currently provides the largest source of mineral royalties on sovereign lands with between 1.5 and 2.0 million st (1.4 million and 1.8 million mt) of sodium chloride and close to 300,000 st (272,000 mt) of other minerals salts extracted each year.

Currently, there are 12 producing mineral leases totaling 164,950 acres (66,780 ha) that generated slightly more than \$1,300,000 in royalties during calendar year 1999. IMC Kalium produces potassium sulfate and magnesium chloride from 89,257 leased acres (36,069 ha) in Bear River Bay and Clyman Bay. Sodium chloride, produced as a byproduct, is transferred to IMC Salt, which packages and sells the salt. MagCorp produces magnesium metal from its 75,610 leased acres (30,611 ha) in Stansbury Bay. Cargill Salt Company produces sodium chloride from brines provided by MagCorp

under a lease agreement with DFF&SL. Morton Salt Company produces salt on ponds above the meander line with an 83 acre (33.6 ha) lease which serves as a right of way to GSL brines from the southeast end of Stansbury Island. Finally, North Shore Limited Partnership produces high magnesium brines for use in dietary and mineral/vitamin supplements. Lake brine is brought from the lake through a canal, located on a state right of way, onto its ponds on private lands near Spring Bay in the north arm of the lake. Lessees, acres, producing status, and expiration dates for active leases on GSL are summarized in table 3.

Oil, Gas, and Hydrocarbon Leases and Development

Interest in oil and gas leasing on the bed of GSL is long standing. Leases have been issued with the standard 10 year primary term and 12 percent royalty rate. Natural seeps at Rozel Point have attracted oil industry interests since the turn of the century, and the area has been under nearly continuous lease with a number of different lessees.

At present there is a single 40 acre (16.2 ha) lease covering the majority of wells in the Rozel Point area. Despite a long history of leasing and some efforts to stimulate production by electric heaters and steam injection, there has been minimal production and no payment of royalties. Including adjacent private land, the Rozel Point site has abandoned wells, the remains of drilling and production piping, buildings, tanks, abandoned vehicles, tires and other debris, and seeps spontaneously ooze oil, especially on warm days. All wells except one were drilled before the implementation of DOGM's current regulations. Several abandoned wells were capped in 1996, in cooperation with DOGM, UGS, Environmental Protection Agency, and the U.S. Fish and Wildlife Service.

In 1972, the Land Board held public hearings regarding plans for large-scale drilling on the lake in response to lease applications for oil and gas exploration by Marvin Wolf in 1972 for approximately 180,000 acres (73,000 ha) along the east shore of the lake and by Amoco Production Company for over 600,000 acres (240,000 ha) in the main body of the lake. Ultimately, drilling rules were approved by DOGM and a lease form was approved by the Division of State Lands in the summer of 1973. Both DOGM rules, and leases issued by the Land Board, placed timing and location restrictions on drilling unless permission to drill was granted by both the Board of Oil, Gas and Mining and the Land Board. Leases were issued to Amoco in 1973. At that time the Land Board decided to take no action on the Marvin Wolf lease applications along the east shore because of concerns about "the ecology factor."

From 1973 to 1985, Amoco Production Company conducted its exploration program drilling 13 exploration wells and two development wells. Amoco established five units on the lake, the most promising of which was the West Rozel unit in T. 8 N., R. 8 W., Salt Lake Base Line. All units were abandoned in the early 1980s, and leases were terminated in 1985. In 1978, the Land Board reversed its original decision to lease lands along the east shore and issued leases which were ultimately acquired by Phillips Petroleum, Sun Exploration, and other oil and gas companies. Most of these leases were relinquished in 1986.

SIGNIFICANCE OF MINERALS EXTRACTED FROM GREAT SALT LAKE

Producers of magnesium, potash, and salt from GSL have contributed significantly to the growth in metals and

Table 3. Current mineral, oil, gas, and hydrocarbon leases on Great Salt Lake. Data from Division of Forestry, Fire and State Lands lease files.					
Lease No.	Lessee	Lease Type	Acres	Lease Status	Expiration Date
ML 9300-SV	Morton	Chemical Salts	83	Producing	Held by production
ML 18779-SV	Magnesium Corp.	Chemical Salts	75,610	Producing	Held by production
ML 19024-SV	IMC Kalium	Chemical Salts	10,413	Producing	Held by production
ML 19059-SV	IMC Kalium	Chemical Salts	1,282	Producing	Held by production
ML 21708-SV	IMC Kalium	Chemical Salts	20,860	Producing	Held by production
ML 22782-SV	IMC Kalium	Chemical Salts	7,580	Producing	Held by production
ML 23023-SV	IMC Kalium	Lakebed Salts	14,381	No production	Past primary term
ML 24631-SV	IMC Kalium	Chemical Salts	1,911	No production	Termination of Royalty Agreement
ML 25859-SV	IMC Kalium	Chemical Salts	10,583	Producing	Held by production
ML 29864-SV	William J. Coleman	Chemical Salts	0	No Production	12/31/2003
ML 43388-SV	IMC Kalium	Chemical Salts	709	Producing	Held by production
ML 44455-SV	Nova Natural Res.	Oil Gas & Hydro.	640	No Production	8/31/1999
ML 44456-SV	Nova Natural Res.	Oil Gas & Hydro.	960	No Production	8/31/1999
ML 44607-SV	IMC Kalium	Chemical Salts	37,830	Producing	Held by production
ML 45646-SV	Kenneth Pixley	Oil Gas & Hydro.	49	No Production	6/30/2002
ML 45741-SV	Coleman Morton	Oil Gas & Hydro.	765	No Production	9/30/2002
ML 45772-SV	Coleman Morton	Oil Gas & Hydro.	647	No Production	12/31/2002
200-00001	North Shore Limited	Chemical Salts	0	Producing	Held by production
200-00002	Cargill Salt	Salt	0	Producing	Held by production

industrial minerals production in Utah. Production of magnesium and potash began in the early 1970s and by 1980 had reached over 25,000 st (23,000 mt) of magnesium metal and nearly 100,000 st (90,000 mt) of potassium oxide equivalent. There was a lapse in production during the lake's high-water years for all products followed by a second surge in production to current levels. Production of salt also increased significantly during this same twenty-year period. Together these companies contribute approximately \$240,000,000 in gross value, or 18 percent of the value of the state's non fuel mineral production. Most of this production

is exported. These companies together employ more than 1,000 people; approximately 250 by salt producers, 550 in magnesium production, and 220 in the production of potassium sulfate and magnesium chloride.

The importance of the mining industry in Utah has declined as a percent of the state's gross product, falling from 6.3 percent in 1965 to 3.2 percent in 1996. However, this statistic alone understates the importance and continued growth in the mining sector, especially for non fuel mineral products (metals and industrial minerals). In constant dollars, the value of industrial minerals and metals has more than tripled from 1980 through 1996 according to the U.S. Bureau of Economic Analysis' estimate of gross state product (Utah Office of Planning and Budget, 2000). The state's economy has instead become increasingly diverse so that mining plays a much smaller role than in the past. In addition, the value of industrial minerals may be significantly under reported in these estimates, possibly because much of the value of industrial minerals is attributed to the manufacture of end products rather than mining of the raw material. The UGS, for example, reports the value of industrial minerals in 1998 as \$533 million, while the value

of non metallic minerals is reported in gross state product estimates as only \$30 million (Utah Office of Planning and Budget, 2000).

MARKETS FOR MINERALS EXTRACTED FROM GREAT SALT LAKE

Halite

In 1998, approximately 1.6 million st (1.4 million mt) of salable solar salt were produced from GSL (Division of Forestry, Fire and State Lands, unpublished data, 1998). Most of the solar salt production from GSL (75 to 80 percent) is exported, primarily to other Rocky Mountain and Midwest states where it is used for agriculture, water conditioning, industrial/chemical use, and highway deicing. Most of the salt not exported is used for highway deicing.

The USGS's 1999 Minerals Yearbook reports 1997 prices of \$16.21 per st (\$17.83 per mt) for dry bulk solar salt (Kostick, 2000a). The USGS's 1999 Mineral Commodity Survey for salt reports an average 1998 price for all solar salt of \$29 per st (\$32 per mt) (Kostick, 2000b). The Salt Institute reports 1997 average salt prices of \$52 per st (\$57 per mt) for agricultural uses and \$91 per st (\$100 per mt) for water conditioning. Since 1981, these prices for solar salt

have increased by approximately 4 percent per year. In contrast, prices for vacuum pan and rock salt have increased at rates of 2 to 3 percent per year (Kostick, 2000a).

Bulk solar salt can be produced for prices ranging from \$7 to \$10 per st (\$8 to \$11 per mt) so Utah producers appear to be in a competitive position to maintain markets in the Midwest. Total sales revenues from solar salt production on GSL range between \$30 to \$50 million per year (Division of Forestry, Fire and State Lands, unpublished data, 1998).

Solar Salt Production



Figure 3. Comparison of solar salt production from Great Salt Lake (GSL) to total U.S. solar salt production and to solar salt production from other U.S. states from 1984 through 1998. Data from Kostick, D.S., 2000a.

Solar salt produced from GSL represents a significant, and increasing, share of total domestic solar salt production. Figure 3 shows this relationship over the past 15 years. The remainder of solar salt produced in the U.S. is primarily from California with some production from New Mexico.

Solar salt competes in regional markets with rock salt and vacuum pan salt for chemical and industrial, water conditioning, and agricultural uses. Nationwide, the consumption of rock salt is four times that of solar salt. However, in markets other than road salt (primarily rock salt) and food processing (primarily vacuum pan salt), the three types of salt are in closer competition. Table 4 shows the historic pattern of consumption for Utah solar salt where its uses compete with vacuum pan and rock salt. These include chemical, industrial, water treatment, and agricultural end uses, but exclude uses of salt for deicing and food processing. Since 1987, solar salt consumption has grown annually by about 6 percent while rates of growth in consumption of vacuum pan and rock salt have grown at a much lower rate. USGS data show that markets for most salt products are regional, but the market for road salt is local. In Pacific Coast states (California, Oregon, and Washington), consumption of rock salt is negligible while consumption of solar salt, stable for several years at 1.2 million st (1.1 million mt), has recently increased to about 1.5 million st (1.4 million mt) (figure 4). California produces solar salt but Pacific Coast states import between 0.5 and 1.0 million st (0.45 million and 0.9 million mt) of

Table 4.							
Annual production of halite by type of recovery process (in							
thousands of metric tons), 1987 through 1997. Competing end							
uses used in this table are: chemical, industrial, water treatment,							
and agricultural. Data from Kostick, D.S., 2000a.							
Year	Solar	Vacuum	Rock	Total	% Solar		
1987	2,188	2,347	3,949	8,484	25.79		
1988	2,674	2,446	4,173	9,293	28.77		
1989	2,781	2,881	4,415	10,077	27.60		
1990	3,028	2,926	4,438	10,392	29.14		
1991	2,956	2,704	3,941	9,601	30.79		
1992	2,904	2,584	4,170	9,658	30.07		
1993	3,309	2,529	4,482	10,320	32.06		
1994	3,220	2,530	4,682	10,432	30.87		
1995	3,460	2,446	4,031	9,937	34.82		
1996	3,840	2,439	4,360	10,639	36.09		
1997	3,779	2,239	4,037	10,055	37.58		
, , , , ,							

Consumption of Solar Salt by Region Market Areas for Utah Salt, 1987-1998



Figure 4. Growth in solar salt consumption in regional markets for chemical, industrial, water treatment, and agricultural end uses from 1987 through 1997. Data from Kostick, D.S., 2000a.

solar salt each year. Imports of solar salt have recently declined from a previously stable level of 1 million st (0.9 million mt). In the past, Pacific Coast states were a difficult market for Utah solar salt to penetrate. However, solar salt from Utah may be finding its way to these markets due to increases in consumption and a decline in exports of solar salt by California.

Solar salt consumption in Rocky Mountain states (Utah, Colorado, Nevada, Wyoming, Idaho, and Montana) is just over 1 million st (0.9 million mt) per year. Consumption of solar salt shows some growth in these states for uses such as road salt, where demand is stable, or chemical uses, where demand could decline.

In Midwestern states (Illinois, Indiana, Iowa, Kansas, Minnesota, Nebraska, North Dakota, South Dakota, and Wisconsin), solar salt markets have grown from 0.43 million st (0.38 million mt) to 0.9 million st (0.8 million mt) in the past nine years. As with the Pacific Coast markets, these markets have been difficult to penetrate. Despite this, as figure 5 illustrates, production of Utah solar salt closely parallels the consumption of solar salt in Midwestern and Rocky Mountain states, where combined consumption of solar salt has grown from over 1 million st (0.9 million mt) to almost 2 million st (1.8 million mt). Since the only other major sources of solar salt for these areas would be from Oklahoma, the Great Lakes region, or Mexico, via the Mississippi River, the data suggest Utah producers are making steady inroads into Midwestern markets.

In summary, the production data since 1987 indicate:

- Utah solar salt companies produce a significant and increasing share (40 to 55 percent) of solar salt produced domestically.
- Solar salt competes closely with rock salt and vacuum pan salt for end uses such as chemical/industrial, water treatment, and agriculture; solar salt is the dominant source for agricultural and industrial uses.
- In total, consumption of salt for these uses is not growing steadily, but solar salt consumption is increasing at a stable and significant rate (approximately 6 percent/year), while rock salt shows uneven growth, and vacuum pan salt shows a decline in tons sold. Likewise, prices for solar salt have increased more rapidly than those for vacuum pan and rock salt.

Markets for solar salt in Pacific Coast states have grown in the past five years, while imports of solar salt have declined.

Solar salt consumption is increasing in Midwestern and Rocky Mountain states at a level which parallels Utah solar salt production; Midwestern markets consume 40 to 45 percent of Utah's production and have the highest rate of growth in tons consumed.

Based on these observations, DFF&SL expects the production of solar salt to increase at an average of 3 percent per year for the next several years. Fluctuations in production can be expected due to weather, lake levels, and precipitation.

Potash (Potassium Sulfate)

IMC Kalium produces potassium sulfate and magnesium chloride brines from its facilities at Bear River Bay. The company has the capacity to produce 0.34 million st (0.3 million mt) of potassium sulfate from its 37,000 acres (15,000 ha) of evaporation ponds in Bear River Bay and Clyman Bay (on GSL's west side) (Odgen Standard-Examiner, 1992). IMC Kalium also produces magnesium chloride brines as a by-product and sells salt to a related company, IMC Salt, to process and market.

Potassium sulfate is preferred for most agricultural applications because the sulfate base is better for plants than the chloride in muriate of potash (KCl). However, because of its much higher cost to produce, and resulting higher selling price, potassium sulfate is used primarily as a specialty fertilizer for certain crops. In 1997, the K_2O equivalent price for potassium sulfate was \$350 per st (\$385 per mt). In comparison, the K_2O equivalent price for muriate of potash was about \$130 per st (\$140 per mt). Prices for potassium sulfate have fluctuated somewhat since 1991, when K_2O equivalent sold for \$289 per st (\$318 per mt) of K_2O equivalent. Over

Salt Production Trends vs. Consumption 1987-1998



Figure 5. Comparison of Utah solar salt production to solar salt consumption in the Rocky Mountain/Midwest regions from 1987 to 1998. Data from Kostick, D.S., 2000a.

all, prices for potassium sulfate have increased about 3 percent per year.

About 20 to 25 percent of all potassium fertilizer produced in the U.S. is potassium sulfate. Potassium sulfate comprises 30 percent of all potash shipped to overseas markets such as the Pacific Rim and South America. The tobacco producing states also buy significant quantities of potassium sulfate (Searls, 1999).

The U.S. potash industry operates in the shadow of Canadian producers. Canadian potash reserves and production are far greater than those in the U.S., producing close to 10 million st (9 million mt) of K_2O equivalent, compared to U.S. production of 1.5 million st (1.4 million mt) per year. Markets for potassium sulfate are much smaller, because of the high price of the product. However, U.S. production of potassium sulfate is more competitive with foreign producers, principally in Canada and Germany. While the U.S. is dependent on imports to satisfy agricultural grades of potassium chloride, U.S. producers of potassium sulfate supply most U.S. consumption and export most of their remaining production to other countries. Total U.S. potassium sulfate production is approximately 0.3 million st (0.27 million mt) of K₂O equivalent.

IMC Kalium, which purchased Great Salt Lake Minerals Corporation from Harris Chemical in 1998, is now the sole producer of potassium sulfate in the U.S. In North America, IMC Kalium is in competition with only one other producer, Potash Corporation of Saskatchewan. IMC Kalium's plant on GSL enjoys the advantage of a unique resource in lake brines which are rich in sulfate ions as well as potassium. Other producers must manufacture potassium sulfate from potassium chloride; IMC Kalium extracts potassium minerals from the lake brines from which potassium sulfate is produced through a leaching process. IMC also supplements production by combining excess sulfate ions with potassium chloride to convert it to potassium sulfate.

Markets for potassium sulfate, although small, grew from 0.25 million st (0.22 million mt) to more than 0.3 million st (0.27 million mt) from 1991 to 1995. Production will likely be stable at these levels and IMC Kalium will continue to be a major supplier.

Magnesium Chloride

IMC Kalium also produces magnesium chloride brines. Its annual production capacity is reported to be 0.12 million st (0.11 million mt) of MgO equivalent, or about 10 percent of U.S. production capacity; however, its actual production of magnesium chloride brines is far below this capacity. Much of this brine is sold for dust control for \$50 per st (\$55 per mt) or less. IMC Kalium sells magnesium chloride hexahydrate as well. Because of the additional processing, this product sells for close to \$300 per st (\$330 per mt), and is used as a chemical intermediate or in refractories (Kramer, 1999).

Magnesium Metal

MagCorp produces magnesium chloride brines from its operations on Stansbury Bay and Knolls ponds. The company refines these brines and produces magnesium metal through an electro-winning process. The plant has a capacity of 45,000 st (41,000 mt) per year of magnesium metal, which is half of U.S. magnesium metal production capacity, and approximately 10 percent of current world capacity. Until November 1998, there were two other U.S. producers, Northwest Alloys which produces magnesium from dolomite in Washington, and Dow Chemical which produced magnesium from seawater in Texas. In November 1998, Dow Chemical closed its 71,000 st (65,000 mt) per year capacity plant due, in part, to damage sustained from a lightning strike in June of that year and damage from floods during Hurricane Francis in September. Northwest Alloys is the only other U.S. producer with an annual production similar to MagCorp. MagCorp is undergoing an electrolytical cell upgrade which will temporarily lower its production capacity for the next two years.

U.S. magnesium metal production in 1997 was at 86 percent of plant capacity, down from close to 100 percent capacity in 1995 and 1996. These high levels of production were in response to high price levels, which peaked in 1995 at \$2.09 per lb (\$4.60 per kg) and dropped to \$1.55 per lb (\$3.41 per kg) in 1998 (Kramer, 1999). Of the minerals extracted from GSL, only magnesium metal has this price volatility.

In contrast to salt (sodium chloride), but similar to potassium sulfate, magnesium metal enjoys both a national and international market. MagCorp faces great competition from other domestic and foreign producers. In addition, much of the demand for magnesium metal is met by secondary sources through recycling of magnesium products. The U.S. produces the largest tonnages of both primary and secondary magnesium, but with new applications in the automotive industry, new production capacity is being brought on line in Canada, Australia, Israel, China, and possibly the Congo. These additions will have a significant impact on a relatively small industry. World-wide magnesium production is approximately 0.4 million st (0.36 million mt) per year, but is one or two orders of magnitude less than aluminum, at 4.0 million st (3.6 million mt) per year, or steel, at 100 million st (90 million mt) per year. Magnesium is used as an alloying agent for these metals, as well as competing with aluminum in diecasting applications for the automotive industry (Kramer, 1999).

The U.S. magnesium industry has been concerned enough about foreign imports of magnesium in recent years to file anti-dumping investigations against magnesium producers in Canada and the Ukraine. As a result of these investigations, antidumping duties were set at varying rates against a Canadian firm from 1991 through 1995, and against imports from the Ukraine, although, this latter decision is under appeal before the Court of International Trade (Kramer, 1999).

Because of the competitiveness and secrecy associated with each company's production processes, there has been little opportunity for technology transfer within the industry and production costs have remained high (Howard-Smith, 1998). The cost of producing magnesium for a new producer in Tasmania and Australia range between \$0.65 and \$0.90 per pound (\$1.43 and \$1.98 per kg) (Kramer, 1999).

ACKNOWLEDGMENT

Dr. J. Wallace Gwynn of the Utah Geological Survey contributed most of the data and history for the section on mineral resources of GSL. His contributions to and review of that section are greatly appreciated.

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GYPSUM RESOURCES AND DEVELOPMENT ON THE WIND RIVER INDIAN RESERVATION, WYOMING

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ABSTRACT

The Eastern Shoshone and Northern Arapaho tribes of the Wind River Indian Reservation, Wyoming are interested in developing their industrial mineral resources. The U.S. Bureau of Indian Affairs (BIA), Division of Energy and Mineral Resources (DEMR) is assisting the tribes in evaluating the potential of their industrial mineral prospects for development.

Gypsum occurs on both sides of the Owl Creek Mountains in the basal portion of the Jurassic Gypsum Springs Formation. The gypsum resources that are being evaluated crop out along the northern flank of the Owl Creek Mountains in the Sweetwater basin, a small topographic sub-basin of the Big Horn Basin. From October 1998, to April 1999, DEMR personnel mapped, sampled, and drilled the southcentral butte within the Sweetwater basin. Samples were analyzed for free and combined water, and major mineral oxides to determine gypsum purity. Gypsum purity averaged 93.6 percent for surface samples and 95.1 percent for drill core samples. The basal portion of the Gypsum Springs For-

mation is comprised of several beds of gypsum up to 9 feet (2.7 m) thick separated by 0.5 to 2.0 foot (0.15 to 0.61 m) thick lenses of siltstone and limestone. Overall gypsum in the formation ranges from 35 to 90 feet (11 to 27 m) in thickness. A resource of approximately 7 million short tons (st) (6.4 million metric tons [mt]) has been identified.

INTRODUCTION

Project Background

The Eastern Shoshone and Northern Arapaho tribes of the Wind River Indian Reservation are interested in developing their industrial minerals. In the Summer of 1997, the tribes requested technical assistance from the BIA's DEMR in the evaluation of their gypsum resources. The tribes requested that DEMR conduct a drilling program to evaluate the Sweetwater basin gypsum resources on the north slope of the Owl Creek Mountains. The area is approximately 10 miles (16 km) west of the town of Thermopolis. Previous work included mapping and collecting surface samples from the Sweetwater basin gypsum deposits. The drilling program was conducted in April 1999. Five holes were drilled, one by rotary air drilling and the remaining four by diamond core drilling. A total of 195 feet (59.4 m) of core was recovered from the four core holes.

DEMR personnel assisted tribal personnel in presenting a display of their industrial mineral resources at the 1997 and 1998 Northwest Mining Association Annual Conferences in Spokane, Washington and the 35th Forum on the Geology of Industrial Minerals in Salt Lake City, Utah.

General Setting

The Wind River Indian Reservation, in west-central Wyoming, contains about 3,500 square miles (9,000 km2) of land. The reservation stretches from the northern part of the Owl Creek Mountains south to the crest of the Wind River Mountains (figure 1). To the east, it begins just west of the town of Shoshone and extends westward to the town of Du-



Figure 1. Location map of the Wind River Indian Reservation, Wyoming (modified after Gersic and Worthington, 1984).

bois. There are approximately 2,500 Shoshone and ap-proximately 5,000 Arapaho living on the reservation.

MINERAL DEVELOPMENT ON TRIBAL LANDS

Tribal Government

The Eastern Shoshone and Northern Arapaho tribes jointly govern the Wind River Indian Reservation. Each tribe has its own General Council that meets about three times a year. Each General Council is composed of all adult members of the tribe and operates similar to a town meeting. The General Council of each tribe has delegated certain powers to its Business Council, but retains most major decisionmaking authority. Each Business Council is comprised of six members from which a chairman is elected. Together, these twelve members comprise the Joint Business Council (JBC) of the Shoshone and Arapaho tribes. The JBC is directly responsible for the day to day activities on jointly owned resources and joint programs of the tribes.

The tribal headquarters for the Northern Arapaho tribe is in Ethete; the headquarters for the Eastern Shoshone tribe is in Fort Washakie. The JBC of the Shoshone and Arapaho tribes regularly meets Monday and Wednesday of each week in Fort Washakie. Other meetings may be scheduled by special request.

Mineral Agreements

In December, 1982 Congress enacted Public Law 97-382, the "Indian Mineral Development Act." The Act greatly expanded the types of agreements that Native American tribes could enter into for development of their energy and mineral resources. Mineral agreements involving Indian lands enjoy exclusive economic privileges. The Indian Mineral Development Act of 1982 (IMDA) allows negotiable forms of agreement, resulting in many unique possibilities. The act also revised the process by which these agreements are evaluated in fulfilling the trust responsibilities of the Secretary of the Interior. The BIA provides assistance to tribes entering into mineral lease agreements and determines whether the agreements meet the necessary criteria for departmental approval.

The IMDA, in addition to providing tribes the opportunity to actively participate in mineral development, eliminated the shortcomings of previous mineral leasing acts by making the forms of agreements, terms, and acreage negotiable. The IMDA does not prescribe what form the agreement must take, how the parties will participate, whether there is a carried interest, a working interest, or both, what the term will be, how many acres will be involved, what employment and/or contracting opportunities may be negotiated, how the products will be disposed of (sold or taken in-kind), or some combination thereof. In other words, all terms and conditions of an agreement are negotiable. Consequently, each agreement is unique and all elements contained in an agreement must be evaluated by the Secretary of the Interior to determine if the agreement provides the best economic return to the tribe for the contemplated development.

The Secretary of the Interior must either approve or disapprove any completed agreement within 180 days of its submittal. Since the National Environmental Policy Act (NEPA) must also be satisfied, initial approval covers only the economic terms of the agreement and is conditioned on full compliance with NEPA requirements before land disturbance activities are initiated.

BIA Processing of Mineral Agreements

The DEMR evaluates agreements to make a "best interest" determination related to potential economic return to the Native American mineral owner. Determinations related to environmental, social, and cultural effects on the tribe are made by BIA personnel at Area and Agency offices. The DEMR reviews where lands under the proposed agreement are located, considers geologic and geographic features within the area, and comments on any concerns that may result from this review. These concerns may result from proximity to private residences or communities, other commercial developments, water resources, or alternative land uses.

If the approving official at the BIA's Agency or Area office feels the proposed agreement is deficient in the requirements necessary for approval or the tribe/developer disagree with the BIA, the agreement must be forwarded to the BIA's Central Office in Washington, D.C. for review. If the Central Office sustains the findings of the Agency or Area office and the Assistant Secretary for Indian Affairs does not approve the agreement, any further recourse must be decided in a U.S. District Court.

Commonly, tribes request the DEMR to provide assistance, either at the outset or early in the negotiation of a minerals agreement. Generally, this expedites the approval process because problem areas in a proposed agreement can be identified early and corrected before the final document is submitted for approval by the Secretary of Interior.

Regulatory Authority

The following Code of Federal Regulations (CFR) apply to the leasing of solid minerals on tribal and allotted Native American Trust lands: (1) 25 CFR 211, Leasing of Tribal Lands for Mineral Development; (2) 25 CFR 212, Leasing of Allotted Lands for Mineral Development; and (3) 25 CFR 225, Oil and Gas, Geothermal, and Solid Mineral Agreements.

Joint Business Council Contact

The JBC feels it is in the best interest of their people to fully develop their industrial mineral resources in an efficient, economic, and environmentally sound method. The JBC along with staff of the Wind River Tax Commission, the Shoshone Oil and Gas Commission, and tribal attorneys will evaluate all mineral development proposals within thirty days of submittal. The JBC will then act on the recommendation of the staff and attorneys within thirty days of their recommendation. The address of the Joint Business Council of the Shoshone and Arapaho tribes is c/o Wind River Tax Commission, P.O. Box 830, Fort Washakie, Wyoming, 82514.

GENERAL GEOLOGY

The Wind River Indian Reservation lies within the western half of the Wind River Basin. The reservation is flanked on the southwest by the Wind River Range and on the north by the Owl Creek and Absaroka Mountains. The northeast corner of the reservation lies in the southernmost part of the Big Horn Basin. The Wind River and Big Horn Basins are large, complex structural as well as topographic basins (figure 2). The margins of each basin are delineated by complexly folded and faulted Precambrian, Paleozoic, and Mesozoic rocks that are exposed in the bounding mountain ranges and uplifts. The interiors of the basins contain less disturbed Cenozoic rocks. Gypsum-bearing rocks outcrop primarily along the basin margins, on the slopes of the Wind River and Owl Creek Ranges.

Gypsum-bearing formations crop out for a distance of more than 100 miles (1,600 km) along the northeast flank of the Wind River Range, along both flanks of the Owl Creek Mountains, and along the flanks of the Lander-Hudson, Sage Creek, Maverick Springs, and Circle Ridge anticlines (figure 3). Large quantities of gypsum reportedly occur in the Triassic Chugwater and Dinwoody Formations, but the Jurassic Gypsum Springs Formation contains the most extensive and potentially valuable gypsum resources in the area. On the reservation, the basal portion of the Gypsum Springs Formation consists of a massive gypsum bed which ranges from 35 to 90 feet (11 to 27 m) in thickness. This massive bed contains thin lenses of red siltstone and limestone.

PROJECT METHODS

Personnel from DEMR condensed existing National

Indian Energy and Mineral Resource (NIEMR) database information about the tribe's gypsum resources into a report, complete with geologic maps, sample location maps, and references. This report was sent to Wind River tribal and BIA Area personnel; tribal personnel then distributed the report to private industry.

In the summer of 1998, DEMR personnel performed field verification of geology described in existing U.S. Bureau of Mines reports (Harrer, 1955; Bolmer and Briggs, 1965; Seeland and Brauch, 1975; Pressler, 1979; Gersic and Worthington, 1984; Gersic and Nononi, 1985), and conducted a mapping and surface sampling program of several gypsum deposits on the north flank of the Owl Creek Mountains. DEMR personnel collected digital orthophotoquads and integrated these into ArcView and ArcInfo to assist in mapping and modeling the deposits.

Because industrial minerals are sensitive to economic factors such as shipping distances, the study area for this project was limited to the Sweetwater basin due to its proximity to the railhead in Thermopolis (figure 3).

In October 1998, a detailed field study of the Sweetwater basin was performed which included mapping and sampling the gypsum occurrences (figure 4). Thirty-eight samples were collected and analyzed. Following this analysis, DEMR personnel submitted a proposal for further evaluation of the Sweetwater basin gypsum deposit via a drilling program. Tribal approval was granted and drilling began in April 1999. DEMR personnel recovered 195 feet (59.4 m) of core from four wells and analyzed 45 representative core samples.

Surface samples were collected by removing any loose dirt or topsoil in order to collect a clean sample. At least three pounds (1.4 kg) of sample were taken at each location to ensure a representative sample. During the month of



Figure 2. Geologic map of the Wind River Indian Reservation, Wyoming (modified after Bolmer and Briggs, 1965).



Figure 3. Areas of gypsum outcrop on the Wind River Indian Reservation, Wyoming (modified after Bolmer and Briggs, 1965).



Figure 4. Gypsum resource study area in the Sweetwater basin, Wind River Indian Reservation, Wyoming.

October 1998, 38 samples were collected from nine trenches around a butte in the south-central part of the Sweetwater basin (figure 4).

Five holes were drilled on top of the butte, one by rotary air drilling and the remaining four by diamond core drilling. One inch- (25 mm) to five inch- (127 mm) long samples were selected approximately every 3.5 feet (1.1 m) of representative sections of drill core. Forty-five samples were collected and analyzed. Gypsum samples were analyzed for free and combined water, and for the elements aluminum, calcium, chromium, iron, potassium, magnesium, manganese, sodium, phosphorous, sulfur, silica, and titanium. The results were then recalculated according to ASTM Test C 471-96 (ASTM, 1997).

PROJECT RESULTS AND FUTURE PLANS

Gypsum Resources

The study delineated a large resource of high-purity gypsum. Typically, gypsum is mined above a cutoff grade of 85 percent purity. The average grade of gypsum in the Sweetwater basin area exceeds this cutoff. Currently, there is a large demand for gypsum due to the strength of the construction industry, and the three gypsum mines in Wyoming operated at capacity in 1998 (Zeise, 1999).

No resource tonnage was calculated, but DEMR personnel estimate a geological resource of approximately seven million st (6.4 million mt) of gypsum within the study area. Outcrops of gypsum also occur both east and west of this deposit within Sweetwater basin.

Gypsum Quality

Within the Sweetwater basin, the gypsum is fractured on the surface and contains red silt from the siltstone layers above it. Drilling revealed several clean gypsum beds up to nine feet (3 m) thick separated by distinct lenses of limestone and red siltstone ranging from 0.5 to 2.0 feet (0.15 to 0.61 m) in thickness.

Samples collected from surface sampling and drilling were analyzed for free and combined water, and major oxides. From the October 1998 surface sampling program, all but one sample had a total gypsum content of 90.7 percent or higher (figure 5), with an average gypsum content of 95.5 percent. From the drill samples collected in April 1999, all samples except one contained a total gypsum content of 90.2 percent or higher, with an average gypsum content of 95.1 percent (figure 6).

Future Plans

With the data collected in the mapping, surface sampling, and drilling program, DEMR personnel will assist the tribe in: (1) producing a geologic model of the Sweetwater basin gypsum deposit, complete with map and cross sections through the south-central butte; (2) performing a preliminary resource calculation, (3) designing a preliminary mine plan for a hypothetical mine, and (4) assisting the tribes in marketing the gypsum.



Figure 5. Variations in gypsum purity from surface samples from the Sweetwater basin, Wind River Indian Reservation, Wyoming.



Figure 6. Variations in gypsum purity from drill core samples from the Sweetwater basin, Wind River Indian Reservation, Wyoming.

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CHANGES IN WYOMING'S INDUSTRIAL MINERALS INDUSTRY 1996-1999

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ABSTRACT

New developments have occurred in Wyoming's industrial minerals industry since the 32nd Forum on the Geology of Industrial Minerals in Laramie, Wyoming in 1996. The soda ash trona and bentonite industries have experienced overall growth. Gypsum and limestone production have remained constant, but have the potential for dramatic growth. The mining of zeolite ceased in 1997. The struggling dimension stone industry has increased production, but development has lagged behind the schedule predicted in 1996. The construction of a container glass plant and associated production of glass raw materials, as predicted in 1996 and imminent in 1998, is now on hold due to unforeseen market factors. Increases in railroad and highway construction have, and will, greatly increase the production of construction aggregate for local uses. An iron carbide industry, not foreseen in 1996, is in the planning stages.

INTRODUCTION

The 32nd Annual Forum on the Geology of Industrial Minerals was held in Laramie, Wyoming in 1996. This forum highlighted the development, current production, and future of the industrial minerals industry of Wyoming (Jones and Harris, 1997). This report updates developments in that industry and features the changes in production from 1996 to 1999, as well as new developments for the future.

Industrial minerals development in Wyoming exemplifies that which occurs in remote, lightly populated areas. Although production of industrial minerals for Wyoming's local economy is less than that of all but four other states, some industrial minerals produced in Wyoming are shipped to global and national markets. Wyoming leads the nation in the production of soda ash and other sodium commodities from mined trona, and in the production of bentonite. These commodities are uncommon and have global markets. Wyoming also produces significant quantities of gypsum, limestone for cement, decorative aggregate, and railroad ballast for national and regional markets. Although important to local economies, Wyoming produces relatively small amounts of construction aggregate. Commodities being developed include clay quarried for a brick plant in Salt Lake City, dimension stone (granite, marble, and limestone) for global and national markets, zeolite for national markets, and limestone for sugar beet refining and power plant emissions control in the state and region. Figure 1 shows the location of these industrial mineral sites.

TRONA

In 1996, the trona mining industry was increasing production; production was expected to increase steadily due to increasing export markets. However, after record production in 1997, production fell 4 percent in 1998. This decline was due to a drop in orders for sodium products as a result of the softening of the Asian economy. Statewide production is expected to rebound slightly in 1999, and increase slightly in the next five years. Interruptions in the growth of this industry have occurred historically, and can be expected to continue. Nevertheless, Wyoming's trona industry should grow during the next five years since it comprises the world's largest resource of minable trona, and soda ash can be produced at a lower cost from Wyoming trona than it can be manufactured synthetically.

FMC completed the acquisition of the Tg Soda Ash plant during the summer of 1999. There are presently five trona mines and sodium-product refining plants in Wyoming that are operated by four companies, FMC, General Chemical Soda Ash Partners, OCi, and Solvay Minerals (figure 1). The change in ownership of the former Tg operation is not expected to have any impact on the mining of trona or the production of soda ash.

Trona production increased steadily in the mid-1990s, peaking in 1997 at a little over 19 million short tons (st) (17 million metric tons [mt]) of trona. Due to decreases in exports to Pacific Rim countries, precipitated for the most part by the Asian money crisis, production decreased about 4 percent in 1998. Production in 1999 is expected to exceed 1998, but may not achieve 1997's record amount.

BENTONITE

Wyoming nearly achieved record production of bentonite in 1997. Production peaked in 1980 at 4.8 million st (4.4 million mt) tons when the primary use for bentonite was in oil well drilling fluid. Other uses for bentonite, particularly taconite pelletizing, environmental cleanup and protection applications, and especially kitty litter, have been increasing. These other uses fueled the growth in bentonite production from 1996 to 1997, when production reached 4.6 million st (4.2 million mt). Mine production decreased 3 percent in 1998, although output from the 10 existing bentonite mills (figure 1) increased about 1 percent that year. As of mid-1999, production was slightly ahead of 1998. This growth should continue for the next few years. Bentonite producers have expanded production, and additional capac-



Figure 1. Index map of Wyoming showing industrial mineral sites referred to in text.

ity in existing mills is available. One inactive bentonite plant in Hot Springs County (figure 1) could be reactivated if demand increases. Bentonite is mined from numerous small pits (figure 2) and blended and refined into the various products at the mills.

GYPSUM

Gypsum is quarried in Wyoming at two locations in the Bighorn Basin for the manufacture of wallboard at local plants, and small amounts of gypsum are quarried near Laramie for use as a cement additive (figure 1). In 1996, Wyoming's gypsum production was at plant capacity (about 500,000 st [450,000 mt] per year), and since there has been no additional plant construction, gypsum production has remained constant.

The demand for gypsum products, particularly wallboard, is increasing in the western United States. In mid1999, Colorado and Wyoming builders announced six- to eight-week delays in deliveries of wallboard to residential customers. It appears that there is a market for increased gypsum production from Wyoming, especially from the Bighorn Basin and southeastern Wyoming. Adding capacity at existing plants, or constructing new plants could result in increased production from Wyoming.

CHEMICAL-GRADE LIMESTONE

Chemical-grade limestone is mined for cement and for emissions control material. In 1998, Missouri Basin Electric changed the source of emissions control limestone from a quarry 40 miles (64 km) from its plant to a quarry half that distance from the plant (figure 3). The production of chemical-grade limestone in Wyoming remained constant from 1996 to 1999 at 770,000 st (700,000 mt) per year.



Figure 2. Bentonite pit in the Colony mining district, Crook County, northeastern Wyoming.



Figure 3. Hartville limestone quarry, Platte County, source of limestone for Missouri Basin Electric's Laramie River power plant.

CONSTRUCTION AGGREGATE

The production of construction aggregate in Wyoming is dependent on the amount of highway construction, railroad reconstruction, or other construction projects like the construction of a natural gas refinery. In recent years, aggregate production declined somewhat as highway construction funds declined. However, Wyoming produced 10.4 million st (9.4 million mt) of aggregate in 1997, and 11.2 million st (10.2 million mt) in 1998. Additional federal funds are available in 1999 for construction and reconstruction of highways, and with new projects underway it is estimated that the 1999 production of construction aggregate will be around 15 million st (13.6 mt).

ZEOLITE

Wyoming's only zeolite mine, located in the Washakie Basin near Bitter Creek (figure 1), was purchased by Addwest Minerals, of Denver, Colorado, in 1998. There has been no mining at this site since 1997. Stockpiled ore mined in 1997 has been shipped to a processing and packaging plant in Salt Lake City, Utah, for sale and market testing.

NEW DEVELOPMENTS

Railroad Construction Materials

To provide for increased coal transportation out of the Powder River Basin in northeastern Wyoming, the Burlington Northern Santa Fe Railroad (BNSF) is upgrading some of its routes (figure 4). This includes the construction of a double-tracked line where single tracks were formerly located, widening cuts, daylighting and widening tunnels, and upgrading portions of existing lines (figure 5). The Dakota, Minnesota and Eastern Railroad (DME) is proposing to construct a new rail line from eastern South Dakota into the Powder River Basin to transport coal to markets in the upper Midwest.

All of this railroad construction requires specialized aggregate for the construction of the railroad grades, base, and ballast. Over the past year, aggregate production from Meridian Aggregate's quarry west of

Cheyenne, and Guernsey Stone's dolomitic marble quarry near Guernsey has increased (figure 6). Several companies have been conducting exploration programs and acquiring property for future ballast quarries. One site in the Haystack Hills northeast of Guernsey has been surveyed for potential production (figure 1). The production of construction aggregates in Wyoming should increase in the next few years as railroad construction continues.

Update on Wyoming Container Glass Plant Plans

In 1998, I reported at the 34th Forum on the Geology of Industrial Minerals (Harris, 1999) that the construction of a container glass manufacturing plant for the production of beer bottles for a Budweiser Brewery near Fort Collins, Colorado (just south of the Wyoming border) was imminent. Since that time the potential market for glass beer bottles has decreased significantly.

Budweiser announced in late spring 1998, that it was accepting bids for the supply of bottles for its Fort Collins plant; however, in the fall of 1998, just before the award of the contract for bottles was to be announced, Miller Brewing Company test marketed plastic beer bottles in selected areas of the country. Budweiser immediately announced that it was delaying the award of a contract for glass beer bottles until the results of this market test were evaluated. Although the acceptance of Miller's plastic bottles is reportedly not as successful as hoped, Budweiser itself began to test market beer in plastic bottles in early 1999. As of mid-1999, Budweiser continues to evaluate the future of glass beer bottles, and plans for increased bottle supplies for the Fort Collins plant are still on hold.

As a result, plans for construction of a beer bottle glass plant in Wyoming are also on hold, as are plans for opening up raw material sources (silica sand, limestone, and feldspar) for glass manufacture, as well as plans for sale of soda ash from Wyoming to this plant.

Iron Carbide

In 1997, a group of investors from Denver, Colorado, and Vancouver, British Columbia, announced plans for the construction of an iron carbide plant in Platte County, just east of the Chicago iron mine (figure 1). Iron carbide would be produced by heating iron ore from the Chicago mine with methane piped to the site (figure 7). Iron carbide is used as



Figure 4. Construction of new bridge east of Guernsey, Platte County, for the Burlington Northern Santa Fe Railroad.



Figure 5. Burlington Northern Santa Fe Railroad double-tracked cut that replaced single-track tunnel, east of Guernsey in Platte County.



Figure 6. Guernsey Stone dolomitic aggregate quarry, Platte County, Wyoming.



Figure 7. Iron ore exposed at the Chicago open-pit iron mine, Hartville area, Platte County, Wyoming.

an additive in steel making. Water is a by-product, which could be used locally in agriculture.

The Chicago mine produced iron as recently as 1982 for steel manufacturing by Colorado Fuel and Iron Company (CF&I) at its steel plant in Pueblo, Colorado. Colorado Fuel and Iron Company abandoned the Chicago property in 1993. The iron carbide project is currently in the acquisition and permitting stage. The size of the future operation is under study.

Dimension Stone

Plans continue for the expansion of the dimension stone

industry in Wyoming. Raven Quarries, LLC, is producing pink and black granite blocks in Albany County (figures 1 and 8) which are trucked to Tijuana, Mexico, for processing into finished tile and slab. Raven Quarries closed its small Wyoming processing plant in 1999, but is proceeding with plans to construct a new processing plant in Wheatland, Wyoming. The finished slab and tile products are sold primarily to southern California builders. Raven Quarries increased production to more than 166,000 st (151,000 mt) of product in 1998.

Other companies have acquired and permitted limestone and other stone quarry sites in Wyoming (figure 9). One company with Italian expertise is negotiating the purchase of property in Laramie, where it plans to construct a plant to process limestone, marble, and travertine. In mid-1999, five companies were conducting exploration for dimension stone in Wyoming.

Wyoming has no regulations for permitting dimension stone quarries. Currently, dimension stone falls under the category "all other minerals." The requirements for obtaining mining permits for dimension stone need to be established that are suitable to the size and method of extraction of blocks. The Wyoming Legislature is planning to address this problem.

INDUSTRIAL MINERAL PRODUCTION IN WYOMING 2000-2005

The production of trona and bentonite in Wyoming should continue to increase over the next five years, as long as there is no significant change in the international economic picture. These products are sold internationally and represent significant economic benefits to Wyoming's overall economy.

Increased production of gypsum in Wyoming is a potential bright spot in the economic future of Wyoming. However, increasing production to meet the rapidly expanding domestic consumption of gypsum for wallboard will require new plant construction or the expansion of the state's two existing wallboard plants. Wyoming has adequate gypsum resources for this expansion.

Wyoming has vast resources of chemical-grade limestone. It is expected, however, that production will continue at 1996–1999 levels for the next five years unless a new mine is opened for the production of lime or limestone for use in the refining of sugar beets. No chemical-grade limestone is presently quarried in Wyoming for these uses.



Figure 8. Quarrying granite, Raven Quarries granite quarry, Albany County, Wyoming.



Figure 9. Plumbago Creek limestone quarry site, Albany County, Wyoming.



Figure 10. Outcrop of granite, Granite Mountains, central Wyoming.

The production of construction aggregate should increase 50 percent over 1998 production in the next two to three years as railroad and highway construction projects consume large amounts of aggregate. Production may decline after these projects are completed, but production should still be greater than 1996–1998 levels.

Zeolite production from Wyoming could begin again if Addwest Minerals' test marketing project is successful. The identified zeolite resources in Wyoming's Washakie Basin are adequate for increased production, and increased exploration could identify additional reserves.

The production of glass raw materials in Wyoming will depend on a chain of events. First, the test marketing of plastic beer bottles by Miller and Budweiser brewing companies must be unsuccessful. Second, Budweiser must contract for enough additional glass bottles so that the construction of a new bottling plant near the Budweiser brewery is economically advantageous. Third, the new plant must contract with Wyoming producers for raw materials. If the bottling plant is constructed, Wyoming will probably supply the necessary soda ash, limestone, and feldspar. Additional testing of Wyoming's undeveloped silica sand resources must occur before the deposits are ready for development. Otherwise, silica sand for the process will be supplied from outof-state producers.

The production of small amounts of iron carbide in Wyoming may be a possibility in the next five years. Production will depend on continued economic favorability of this product and the cost of site acquisition and permitting.

The dimension and decorative stone industry of Wyoming has great potential for growth. Wyoming has a variety of abundant stone resources (figure 10). Companies must be able to finance the construction of processing facilities in the state. Wyoming must also develop appropriate mine permitting requirements for the state's dimension stone operators.

Another industrial mineral with a potential for development is industrialgrade diamond. The company producing diamonds adjacent to the Wyoming border in Colorado is attempting to permit part of its mining operation in Wyoming and to expand production across the state line.

ACKNOWLEDGMENTS

The author acknowledges the assistance and review of this article by Richard W. Jones and W. Dan Hausel of the Wyoming State Geological Survey. Janet VanNuys of the Wyoming State Geological Survey provided editorial and layout assistance. The assistance of Phyllis Ranz of the Wyoming State Geological Survey with preparation of figure 1 is also appreciated.

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ENVIRONMENTAL IMPACTS OF MINING NATURAL AGGREGATE

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ABSTRACT

Nearly every community in the United States is dependent on aggregate (sand, gravel, and crushed stone) resources to build and maintain its infrastructure. Unfortunately, developing aggregate resources to meet societal needs causes environmental impacts.

Most environmental impacts associated with aggregate mining are benign. Extracting aggregate seldom produces acid mine drainage or other toxic effects commonly associated with mining of metallic or energy resources.

The most obvious environmental impact of aggregate mining is the conversion of land use, most likely from undeveloped or agricultural land use, to a hole in the ground. This major impact is accompanied by loss of habitat, noise, dust, blasting effects, erosion, sedimentation, and changes to the visual scene. Some of the impacts are short-lived, and most are easy to predict and easy to observe. Most impacts can be controlled, mitigated, or kept at tolerable levels and can be restricted to the immediate vicinity of the aggregate operation by employing responsible operating practices and available technology.

The intensity of environmental impacts generated as a result of mining are determined in large part by the geologic characteristics of aggregate deposits (geomorphology, geometry, and physical and chemical properties). Mining deposits that are too thin, or contain too much unsuitable material, results in the generation of excessively large mined areas and large amounts of waste material.

Mining aggregate can lead to serious environmental impacts in some situations. Some geologic environments such as active stream channels, slide-prone areas, and karst terrain are dynamic and respond rapidly to outside stimuli including aggregate mining. Some geomorphic areas and (or) ecosystems underlain with aggregate serve as habitat for rare or endangered species. Similarly, some geomorphic features are themselves rare examples of geologic phenomena or processes. Mining aggregate might be acceptable in some of these areas, but should be conducted only after careful consideration, and then only with extreme prudence. Failure to do so can lead to serious, long-lasting, and irreversible environmental consequences, either in the vicinity of the site or at locations distant from the site. Environmental impacts caused by irresponsible aggregate mining can compromise mining in an entire region.

INTRODUCTION

During the 7th Industrial Minerals International Congress at Monaco, Bob Bates (1986) stated: "It is said that mankind faces two certainties - death and taxes. Producers of industrial minerals face a third - environmental problems."

Bob Bates was right. Unfortunately, when some people think of environmental problems related to mining (which to them includes aggregate mining) they imagine huge despoiled landscapes with noxious chemicals oozing out of the rock onto the surface of scum-covered lakes filled with dead, bloated, two-headed fish. At one time those images were associated with mining of metallic or energy resources. Those images are not, and never have been, associated with aggregate resources.

It is extremely important to understand that most aggregate is used in its natural state, except for crushing, screening, and washing. Unlike most metallic resources, aggregate is not concentrated from an ore.

Many metallic ores are concentrated by nature through hydrothermal processes. Hydrothermally altered rocks commonly contain high concentrations of metal, sulfides and sulfates. It is the mining and processing of these hydrothermally altered rocks to extract the metals, and the tailings from those operations, that produce acidic mine drainage, or other toxic effects commonly associated with the metallic resources.

Sources of quality aggregate, by their very nature, do not contain the minerals that create acid mine drainage. Metallic minerals, sulfides, and sulfates all create undesirable consequences when contained in aggregate used for cement concrete. Aggregate operators specifically avoid these minerals. By avoiding metallics, sulfides, and sulfates, there is little chance for the creation of acid mine drainage at aggregate operations.

Aggregate is a low-unit-value, bulk commodity. Consequently, excavation of aggregate near the point of use, which is commonly at population centers, is most economical. In areas of high population density, resource availability, combined with conflicting land use, severely limits areas where aggregate can be developed. Large numbers of aggregate operations may be concentrated into relatively small areas, thus compounding impacts and transforming what might be an innocuous nuisance under other circumstances into an area with significant impacts.

When options for extracting aggregate are limited, identification of areas for extraction that are free from potentially serious environmental problems may not be possible. We may be forced to develop aggregate resources in areas that we otherwise might choose to avoid. Understanding what potential environmental impacts exist, and knowing how to mitigate or avoid those impacts is of utmost importance.

This report is intended to be a general discussion of the

wide variety of environmental impacts that can result from aggregate mining. The scientific and engineering research that support the discussions are cited as references. Upon reading this report, one may erroneously conclude that mining aggregate will create widespread, serious environmental damage under any conditions. To the contrary, most environmental impacts associated with aggregate mining are benign. Most impacts that occur can be controlled, mitigated, or kept at tolerable levels and can be restricted to the immediate vicinity of the aggregate operation by employing responsible operating practices. But there are significant environmental impacts that can occur if mining is carried out in certain geologic environments. Geologists have an important role in identifying those environmental impacts, and in designing plans to avoid them.

CATEGORIZING ENVIRONMENTAL IMPACTS FROM AGGREGATE MINING

Background

The following definition is modified from Kelk (1992), who defined environmental degradation or pollution as follows:

> " the alteration of the environment by man through the introduction of materials [or activities] which represent potential or real hazards to human health, disruption to living resources and ecological systems, [or] impairment to structures or amenity * * * ."

The scientific literature is replete with discussions about environmental impacts from metallic mining and coal mining. There are far fewer reports that describe details of environmental impacts from aggregate mining. One of the first comprehensive evaluations is Surface Mining of Non-Coal Minerals, (National Academy of Sciences, 1980). Two reference documents dedicated to the aggregate industry that address environmental impacts from aggregate mining are The Aggregate Handbook (Barksdale, 1991), and Aggregates (Smith and Collis, 1993). Four comprehensive collections of individual papers that describe many issues related to aggregate development are: Aggregate Resources - A Global Perspective (Bobrowski, 1998), Aggregates - Raw Materials' Giant (Lüttig, 1994), the Proceedings from the International Symposium on Aggregates (International Association of Engineering Geology, 1984), and Natural Resources in the Geological Environment (Kelk, 1992). A study of reports in these volumes will not only provide an understanding of the many different environmental impacts related to aggregate mining, but because the reports span a nearly 15-year period of time they will also give an historical perspective of the issues.

Nature of Environmental Impacts

Developing aggregate resources will create environmental impacts. The objective is to select an appropriately located resource and develop it while minimizing the impacts. One way to assess the environmental impacts is to characterize their nature. The nature of an impact can be referred to by using a number of terms that include range, timing, duration, ability to predict, and ability to control the impact.

Range of Impact

The range of the impact refers to how large an area is affected by the aggregate operation. Impacts, such as conversion of land use, are commonly (although not always) restricted to the site. Impacts, such as noise and dust, are commonly limited to the near-site area. Other impacts, such as changes to the visual scene, may be widespread.

Timing of Impact

The timing of the impact refers to how rapidly the impact develops. Impacts, such as conversion of land use, take place immediately. Other impacts may not begin to be noticed until many years after aggregate extraction begins.

Duration of Impact

The duration of the impact refers to how long the impact lasts. The impacts associated with noise commonly last only as long as the equipment generating the noise is being operated. The impacts associated with conversion of land use commonly last until the operation is reclaimed, at which time yet another conversion of land use will occur. Other impacts may last for an extended period of time.

Ability to Predict Impact

The ability to predict the impact refers to how easily one can anticipate that the impact will occur, and how easily one can predict the range, timing, and duration of the impact. Predicting the range, timing, and duration that results from conversion of land use is relatively easy; predicting those factors for some other types of impacts is more difficult.

Ability to Control Impact

The ability to control the impact refers to how easily one can avoid, minimize, or mitigate an impact. Impacts, such as dust, commonly can be avoided or minimized by using modern careful production techniques and modern technology. Other impacts may be difficult to control.

Evaluation of Impact

This report can help guide compromises between the economics of extracting aggregate and the environmental impacts of extraction. For example, one can assume that an impact that is limited to the site, has a short duration, is easy to predict and is easy to control is preferable to an impact that is far reaching, long lasting, difficult to predict, and difficult to control. Impacts that affect health and safety would be unlikely candidates for compromise.

MINING PHASES

Aggregate mining can be divided into three distinct phases - site preparation, aggregate excavation, and aggregate processing. The environmental impacts of aggregate mining are closely related to the phase of mining, and to the methods of resource extraction. Each phase of mining is typified by specific activities, with each activity having the potential to create specific types of environmental impacts.

Site Preparation

Site preparation commonly starts with removing the overburden to access the resource. The method used depends on the type and thickness of overburden to be removed. Soil and partially weathered rock can be pushed aside with a bulldozer and removed with conventional loaders and haul trucks. Harder, more-consolidated material may require drilling and blasting. Organic soil commonly is stripped separately from the rest of the overburden and stockpiled for reclamation activities. Overburden may be used to construct berms, stockpiled, or sold. When overburden removal is complete, berms, haul roads, settlement ponds, processing and maintenance facilities, and other plant infrastructure are constructed using standard building techniques.

Environmental impacts from site preparation include conversion of land use, changes to the visual scene, loss of habitat, erosion, sedimentation, noise, and dust. Historically these impacts have received the greatest public attention, and consequently are the impacts most commonly addressed in the literature (see for examples Barksdale, 1991; Smith and Collis, 1993; and International Association of Engineering Geology, 1984.)

The engineering-related environmental impacts from site preparation commonly have engineering-related solutions. The environmental impacts commonly are restricted to the site, or occur very near the site. The impacts start at the onset of mining or other construction activities, and continue only as long as the mining or construction activity is taking place. The impacts commonly are easy to predict and are easy to control using currently available technology.

Aggregate Extraction

Sand and gravel are commonly mined from pits or dredged from under water deposits. Crushed stone most often is mined from quarries and commonly requires drilling and blasting prior to excavation. Crushed stone may also be obtained from underground mines. This paper does not specifically address underground aggregate mining. The methods to excavate aggregate depend, in large part, on the geologic environment.

Sand and Gravel Pit

In upland areas, such as high stream terraces, marine terraces, and some glaciofluvial deposits, sand and gravel may occur as unsaturated deposits. If sand and gravel mining does not penetrate the water table, then the aggregate is dry and can be extracted using conventional earth-moving equipon the lay of the land and on operator preference. In some areas, such as low terraces, and some glaciofluvial deposits, if sand and gravel mining extends to a depth that penetrates the water table, then it may be mined wet or dry. In some geologic settings, wet pits can be made dry by collecting the groundwater in drains in the floor of the pit and pumping the water out of the pit. Construction of slurry walls or other barriers to ground-water flow around the pit may be required. After ground water drains or is diverted from the deposit, sand and gravel can be extracted using the dry mining techniques described above.

In some situations where the sand and gravel pits penetrate the water table, such as on flood plains or low terraces, the pit may not be able to be drained and the operator may prefer to extract the material using wet mining techniques. Wet material may be excavated using draglines, clamshells, bucket and ladder, or hydraulic dredges.

In some areas sand and gravel can be excavated directly from stream channels or from embayments in the shoreline dredged off of stream channels. Material is extracted using draglines, clamshells, bucket and ladder, or hydraulic dredges. During non-flooding times, aggregate can be skimmed from bars in channels or active flood plains using the dry mining techniques described above.

Crushed Stone Quarry

Rock quarries are commonly dry where they do not penetrate the water table, or where discharge from the water table naturally drains from the quarry, is offset by evaporation, or is otherwise insignificant. To produce aggregate, the rock is first drilled and blasted. The types of drills or explosives used vary because of the diversity of rock types used as aggregate. Blasting commonly breaks the rock into pieces suitable for crushing. If the rubble is too large, then secondary breaking may be required and usually is accomplished with hammers, drop balls, or other mechanical devices. The blasted material is dry and can be extracted using conventional earth-moving equipment, such as bulldozers, front end loaders, track hoes, and scraper graders. The equipment chosen commonly depends on the lay of the land and operator preference.

Where rock quarries penetrate the water table, the quarries commonly are dewatered by collection and pumping of the ground water. The rock is then mined by the procedures used in a dry quarry. In some geologic terrain, such as some limestone in areas of shallow groundwater, the flow of ground water into the quarry exceeds the rate at which it can be drained from the quarry. In those areas where quarries are allowed to fill with water, the rock is drilled and blasted, and the rubble is extracted using draglines, clamshells, or other equipment. The aggregate may be processed wet, or may be placed in windrows and allowed to dry before processing.

Aggregate Processing

Aggregate processing commonly consists of loading rock or sand and gravel, transporting the material to the plant, crushing, screening, washing, stockpiling, and loadout.
Material usually is transported from the mining face to the processing plant either by truck or conveyor. Material consisting of boulders or blasted rock rubble commonly goes through a primary crusher. A conveyor then moves the crushed material to a surge pile. A gate at the bottom of the surge pile releases the sand, gravel, or rock rubble at a constant feed rate to a secondary crusher and screening system where it is sorted by size. Particles that are too large go back through the crushing and screening process. Depending on the type of material being processed, and on the final product, the material may be washed. After screening, sorting, and washing, if necessary, conveyors move the material to stockpiles. Upon sale, the final product is loaded on trucks, railcars, or barges for transport to the final destination.

ENVIRONMENTAL IMPACTS OF MINING

Aggregate resources cannot be obtained without causing some environmental impacts. Most of the environmental impacts generated during site preparation and processing activities are engineering-related, and are typical of nearly any construction project. Many engineering-related impacts are restricted to the site, start when construction starts and occur only as long as construction activities take place, are easy to predict, and are easy to control using standard engineering techniques.

Many environmental impacts generated as a result of mining are dependent on the geology of the mine site. Some deposits are relatively stable, are well understood, and are easy to characterize. These deposits include older glaciofluvial deposits and higher fluvial terraces as well as many clastic sedimentary rocks. Geologic-related environmental impacts in those geologic systems commonly are easy to identify and predict. Aggregate extraction can take place in many of these areas with minimal impacts on the environment. However, in some settings aggregate mining alters the geologic conditions which, in turn, alters the dynamic equilibrium of the area.

Geologic environments that are dynamic and difficult to characterize include active stream channels, slide-prone areas, and karst terrain. Predicting whether or not geologicrelated environmental impacts will occur in these geologic systems is difficult, as is predicting their potential extent and severity. When impacts do occur they may be fairly innocuous and restricted to the site, or they may be severe and impact areas well beyond the limits of the aggregate operation. The impacts may manifest themselves some time after mining activities have begun, and continue on well after mining has ceased. Widespread impacts commonly are difficult to control. The order that impacts are listed in this report is not intended to reflect their relative importance.

Conversion of Land Use

It should be remembered that the land use immediately preceding mining might not be the original land use. Civilizations in many parts of the world have created enormous impacts on the landscape, and what we are view today is only the most current landscape. The land use at any particular site may have changed many times. Any change in land use creates an environmental impact. Building a house or a highway causes environmental impacts. In comparison, the land disturbed to build a house or a highway is about 100 times greater than the land disturbed to provide the aggregate for those purposes. So, the conversion of land use to aggregate operations is a fairly efficient use of the land. If one considers that the aggregate operation is a temporary land use, and that the land will ultimately be converted into yet another land use, the total environmental impact is diminished even more.

The most obvious environmental impact of site preparation is the conversion of land use, most likely from undeveloped or agricultural lands, to an aggregate operation. The impact to the site commonly is quite dramatic because openpit mining, which is the common method of winning aggregate resources, substantially alters the landscape. The impact is predictable and controllable because the mine is a designed facility.

Conversion of land use may impact an area or item of special scientific interest or significance. In some instances, the geologic deposit may be a rare feature itself. For example, Gonggrijp (1994) described how the only esker system in the Netherlands has been extensively mined for aggregate. Conducting a pre-mining inventory of the site for historical or archeological sites, significant paleontological sites, or unusual mineral assemblages can minimize this impact.

Ironically, the casual identification of an area or item of special scientific interest may only occur because aggregate extraction uncovers a relatively large area at a rather slow pace. Unfortunately, some people perceive that if something of scientific importance is found on their property they are in for a bureaucratic nightmare. Many scientific organizations are able to respond quickly to such serendipitous discoveries. For example, the Utah Geological Survey maintains a Rapid Recovery Service that recovers paleontological resources without cost to the landowner and with little or no disruption to the operation. Learning about the procedures to follow before items of scientific interest are found could reduce impacts to the mining operations in the event discoveries are made.

Another means of minimizing environmental impacts caused by conversion of land use is through the development of super quarries. A single huge operation at an environmentally acceptable site may be preferable to many smaller quarries at scattered locations. However, to be a viable concept, the super quarry depends on cheap, high-volume transport (Kelk, 1992) and support from the local populace and government.

With most aggregate operations, conversion of land use to mining is temporary. After mining has been completed, the land can be reclaimed and converted to yet another land use (Arbogast and others, 1998). In many instances, the second use is equal to or more acceptable than the original use.

Change to Visual Scene

Accompanying conversion of land use is a change to the visual scene, either from the site or from locations remote from the site. The change, which can be either temporary or permanent, is a very subjective topic; what is acceptable to some people is objectionable to others. The nature of this impact depends on the topographic setting, natural ground

cover and type of operations. The change to the visual scene for quarries (as opposed to most pits) commonly is an issue because most quarries have a very long duration, which may result in unpleasant visual impacts and semipermanent nuisances to the local environment.

The change to the visual scene can be predicted by using standard off-the-shelf geographic information systems with line-of-site calculation capabilities. Impacts can be mitigated through mine design, limiting active extraction areas, staining fresh rock to make it look weathered, sequential reclamation, buffering, and screening (including berms, tree plantings, fencing, or other landscaping techniques). Overburden and soil can be stockpiled in out-of-the-way places. Impacts can be mitigated by good housekeeping practices, such as maintaining equipment and locating equipment below the line of site or in enclosed structures.

Loss of Habitat

Site preparation results in loss of habitat in the actual mined area, but unless relocated, vegetation and wildlife that is not mobile is destroyed. Mobile wildlife may leave the site for other areas. Some areas of aggregate serve as habitat for rare or endangered species. Mining in some geologic environments can create a ripple effect that can create secondary impacts on habitat (see below). Mining aggregate might be acceptable in some of these areas, but should be conducted only with extreme prudence.

Habitat destruction cannot be eliminated, but can be controlled by regulations. Pre-mining site inventories can identify rare or endangered species. Buffers can be set aside as wildlife habitat. Selected animals or plants can be relocated. Sequential reclamation can increase habitat. In some cases, the site can be reclaimed to the original habitat. Creation or improvement of habitat off site can offset the loss of habitat on site.

Erosion and Sedimentation

Site preparation and aggregate extraction result in the removal of vegetation, soil cover, and changing the natural land surface slopes. These activities can promote erosion, which may increase sediment load and sedimentation in nearby stream valleys.

Erosion and sedimentation commonly can be controlled using standard engineering practices. The amount of ground disturbance for facilities can be limited by making roads, drainage ditches, and work areas fit the site conditions. Disturbed areas can be covered with vegetation, mulch, or other protective cover, and can be protected from storm water runoff by the use of dikes, diversions, and drainage ways. The amount of disturbance during excavation of material can be minimized through mine planning and sequential reclamation activities. Sediment can be retained on site by using retention ponds and sediment traps. Regular inspections and maintenance can help ensure effective erosion control.

Noise

Aggregate producers are responsible for assuring that the noise emitted from the pit or quarry does not exceed levels set by regulations. The impacts of noise are highly dependent on the sound source, the topography, land use, ground cover of the surrounding site, and climatic conditions. The beat, rhythm, and pitch of noise affect the impact of the noise on the receiver. Topographic barriers or vegetated areas can shield or absorb noise. Sound travels farther in cold, dense air than in warm air, and travels farther when there are atmospheric inversions than without inversions.

An important factor in determining a person's tolerance to a new noise is the ambient (background) noise to which one has adjusted. In general, the more a new noise exceeds the existing background noise level, the less acceptable the new noise will be. In an urban or industrial environment, background noise may mask noise from an aggregate operation, whereas the same level of noise from an operation in a rural area or a quiet, residential neighborhood may be more noticeable to people who are accustomed to quiet settings. Furthermore, ambient noise generally is an accumulation of noises and does not have a single, identifiable source. If the mining noise is identifiable, the perception of noise probably will be great. For example, the noise from a single backup alarm can often be picked out from an equally loud engine noise.

The primary source of noise during site preparation and aggregate extraction is from earth-moving equipment and from blasting (see below). The impacts of noise can be mitigated by constructing berms early in the site preparation process, proper maintenance of equipment, and by limiting the hours of operation.

Noise generated during processing is from crushing equipment, screening equipment, and trucks. The impacts of processing noise can be mitigated through various engineering techniques. Landscaping, berms, and stockpiles can be constructed to form sound barriers. Noisy equipment (such as crushers) can be located away from populated areas, and can be enclosed in sound-deadening structures. Conveyors can be used instead of trucks for in-pit movement of materials. Noisy operations can be scheduled or limited to certain times of the day.

The truck traffic that often accompanies aggregate mining can be a significant noise source. The proper location of access roads, the use of acceleration and deceleration lanes, and careful routing of trucks can help reduce this noise. Workers are protected from noise through the use of enclosed, air-conditioned cabs on equipment and, where necessary, the use of hearing protectors.

Regular inspections and equipment maintenance can help ensure effective noise control measures.

Dust

Federal, state, and local regulations put strict limits on the amount of airborne material that may be emitted during site preparation and operation. Site conditions can affect the impact of dust generated during aggregate mining operations. Those conditions include proximity to population centers, ambient air quality, air currents and prevailing winds, the size of the operation, and other nearby sources of dust.

Dust may occur as fugitive dust from excavation, from haul roads, and from drilling and blasting, or can be from plant-generated sources, such as crushing, and screening. A carefully prepared and implemented dust control plan can Controlling fugitive emissions commonly depends on good housekeeping practices rather than control systems. Dust control techniques include the use of water trucks, sweepers, and chemical applications on haul roads, control of vehicle speed, construction of windbreaks and plantings, and the use of truck and tire washing equipment.

The impacts from processing-generated dust commonly can be mitigated by use of dry or wet control systems. Dry techniques include covers on conveyors, vacuum systems, and bag houses, which remove dust before the air stream is released to the atmosphere. Wet suppression systems consist of pressurized water (or surfactant treated water) sprays located at dust generating sites throughout the plant. Workers are protected from dust through the use of enclosed, airconditioned cabs on equipment and, where necessary, the use of respirators and regular health screening. Regular inspections and maintenance of plant and equipment can help ensure effective dust control measures.

Blasting

Blasting usually is restricted to quarry operations. Blasting may occur daily or as infrequently as once or twice a year. Some potential impacts from blasting are ground vibrations, noise, dust, and flyrock. Geology, topography, and weather affect the impacts of blasting. The technology of rock blasting is highly developed, and when blasting is properly conducted, the environmental impacts should be negligible. By following widely recognized and well-documented limits on ground motion and air concussion, direct impacts from ground shaking and air concussion can be effectively mitigated. Those limits, and methods to measure them, are discussed in Moore and Richards (1999), Bell (1992), Berger and others (1991), and National Academy of Sciences (1980).

When an explosive is detonated enormous amounts of energy are released. Most of the energy of a properly designed blast works to displace rock from the quarry face. The remaining energy is released as vibrations through and along the surface of the earth and through the air.

Most of the energy that goes through the earth comes to the surface within a few meters of the detonation and travels along the surface in the form of waves, which may cause ground shaking. Ground shaking can be monitored with seismic equipment and can be limited by reducing the size of the blast or by employing time-delay blasting techniques. A small amount of the energy is transmitted through the rocks as shear waves, which commonly are insignificant.

There are concerns that blasting can cause slope stability problems. Khawlie (1998) reported that landslides and other earth movement occurred in Lebanon due to improper use of explosives.

When a blast occurs, some energy will escape into the atmosphere causing a disturbance of the air. Part of this disturbance is subaudible (air concussion), and part can be heard (noise). Air concussion is most noticeable within a structure, particularly when windows and doors are closed. The air concussion creates a pressure differential outside and inside the structure, causing it to vibrate.

The most frequent public complaint made about quarrying near population centers is about noise. Blasting noise generally increases with the amount of explosive, with specific atmospheric conditions, and with proximity to a blast. The area in front of a blast commonly receives more noise than an area behind a blast. People differ greatly in their response to blasting (National Academy of Sciences, 1980).

Poorly designed or poorly controlled blasts may cause large rocks and dust to be projected long distances from the blast site (flyrock and fugitive dust), which are serious hazards. Flyrock and fugitive dust deserve careful attention, and can be controlled with carefully designed and executed blasting plans.

Chemical Spills

Maintenance of equipment may result in the accidental spill of chemicals such as solvents, lubricants, or fuels, which can contaminate surface or ground water. Leaking underground storage tanks can pollute ground water. Limiting the amount or type of chemicals on hand, storing all chemicals and petroleum products in impervious material containment areas, and careful operating, safety, and training procedures can control accidental spillage.

Ground Water Disturbance

The ability to predict the environmental impacts to the ground water system is highly dependent on the local geologic conditions. In some situations, such as with homogeneous unconsolidated deposits, simple layered unconsolidated deposits or consolidated rocks, or other deposits or rocks with well-defined hydrologic properties and boundaries, predicting and controlling the range, timing, and duration of impacts is relatively easy. In other situations, particularly deposits with highly variable hydrologic properties, bedrock with fracture flow, and karst areas, predicting impacts to the hydrologic system can be extremely difficult. In many situations, hydrologists can recognize the complexities of the systems and therefore can assign a confidence level to their predictions.

Depending on the geologic and climatic conditions, pits and quarries can act as recharge areas or as discharge areas. In semiarid or arid climates where excavations penetrate the water table, evaporation from water in pits or quarries can lower the water table. Under some geologic and climatic conditions, removing vegetation from the land surface can reduce evapotranspiration and ultimately increase ground water. In humid areas, precipitation can flow into aggregate mines and recharge ground water where pits do not penetrate the water table, or pits penetrate the water table and are mined wet.

If the excavation penetrates the water table and the pit is mined dry, water will be pumped or otherwise removed from the pit or quarry. The pit or quarry will become a discharge point, and this ground water discharge may lower the water table near the operation and, in turn, impact nearby wells. In highly permeable deposits, slurry walls might be necessary to isolate the pit from the water table. Water removed through dewatering can be returned to nearby streams, which may serve to recharge the aquifer downstream from the pit. The impacts to the water table from dewatering can be monitored by use of observation wells. Jordan and others (1995) describe modeling techniques to establish sand and gravel mining standards for ground water protection. The technique utilizes a USGS program called MODFLOW, which determines values for various parameters that should be maintained to minimize impacts on the ground water. Parameters include pit area, spacing between pits, setback from the high water mark, and extraction depth. Miller (1988) describes modeling techniques to analyze quarry dewatering.

Lingley (1994) concluded that ground-water quality problems related to aggregate mining, in or above, large alluvial aquifers such as those in the Pacific Northwest seldom significantly impact the community or environment. However, he also noted two occasions where gravel mining accidentally breached the lateral or seat-seals of perched aquifers, causing loss of water and other damage.

Mas-Pla and others (1999) concluded that gravel mining in a tidal river in the Baix Fluvià area in northeast Spain caused a decline of the water table head on the unconfined aquifer, and dredging in the lower reaches reduced the head of the water table to zero. This process allowed ground water mixing with seawater, and thus salty-water intrusion from the river to the aquifer.

In some areas of sand and gravel mining, changes in ground-water quality have been attributed to the removal of soil that had been acting as a protective layer, filtering, or otherwise reducing contaminants to the ground water (Hatva, 1994). Many heavy metals, easily degraded organic substances, and bacteria and viruses are retained relatively well in the natural soil layer. Under an exposed gravel layer the retention is much weaker. The level of impact depends on a number of factors, which include the thickness of material removed, the surface area involved, the total volume of the aquifer, and recharge to the aquifer. Impacts can be mitigated by controlling recharge in aggregate operations or by locating resource extraction pits outside of recharge areas.

Moore and Hughes (1979) investigated the effects of quarry blasting on ground water turbidity in Calhoun County, Alabama. The study area is underlain with carbonate rocks. Ground water is stored in the residual material overlying bedrock, and in openings along faults, joints, fractures, and bedding planes in the bedrock. Wells produce water from the residuum and from fractures and cavities in the bedrock. The investigators determined that there was no correlation between blasting and water turbidity.

The ability to predict impacts of mining in karst terrain is more problematic. Hobbs and Gunn (1998) concluded that quarrying in the unsaturated zone in karst terrain is likely to result in relatively local impacts such as increased runoff, reduced water quality, re-routing of water through the aquifer, and local reduction of ground-water storage.

Mining below the water table in karst areas may create more serious problems. Karst areas are dynamic and environmentally sensitive. Poorly designed or poorly controlled blasting can fracture the surrounding rock, resulting in the disruption of ground-water flow paths. Old choked passages can be flushed and become operational again, and operational conduits can become abandoned (Hobbs and Gunn, 1998). On rare occasions drilling can intercept localized fracture zones (Jansen and others, 1999). Any changes in the patterns of ground water movement can result in changes in the quantity of water flowing through the system. The yields of down-gradient wells or springs may be significantly altered (Jansen and others, 1999; Ekmekci, 1993) and may cause lowering of the water table and sinkhole collapse. A similar impact may occur if mining requires large-scale dewatering (Hobbs and Gunn, 1998).

Aggregate mining in karst terrain may also impact water quality. In some karst areas, the target limestone acts as a protective cover for the underlying aquifer. If the protective cover is removed, the hole created by the mining may act as a sinkhole and convey surface water to the ground water system. If the surface water is contaminated, the ground water can become polluted. This condition can also occur where a thick, well-developed unsaturated zone is removed by mining (Hobbs and Gunn, 1998).

Hobbs and Gunn (1998) outline a method to characterize the nature of a karst aquifer, and to assess risk from aggregate mining. Carbonate aquifers are classified into one of four groups based on storage, type of flow, and type of recharge. Storage ranges from high to low; flow ranges from conduit to diffuse, and recharge ranges from concentrated to dispersed. Their four karst aquifer groups are:

Group 1 aquifers which have high storage capacity, conduit flow, and variable recharge. The ability to predict the impact of quarry dewatering is very difficult, and is dependent on the likelihood of the workings intersecting an active conduit;

Group 2 aquifers which have low storage capacity, conduit flow, and variable recharge. The ability to predict the impact of quarry dewatering is very difficult, but with low storage, the number of water supplies and size of springs supported by the aquifer is likely to be small;

Group 3 aquifers which have low storage capacity, diffuse flow, and dispersed recharge. These are thin limestones with seasonal springs, and typically are minor or nonaquifers. They present no problem from a geohydrologic point of view, and the potential impact can easily be predicted by treating them as homogenous aquifers; and

Group 4 aquifers which have high storage capacity, diffuse flow, and variable recharge. These aquifers provide a useful resource and may support moderately large springs which may in turn provide stream base flow. The potential impact can easily be predicted by treating them as homogenous aquifers.

Surface Water Disturbance

Land-based aggregate mining may remove vegetation that normally retards runoff, create an impervious surface layer that prevents infiltration, or otherwise change runoff patterns. Some aggregate operations can alter the configuration of streams. These factors may lead to faster, higher peak runoff and in higher peak stream flow. Constructing infiltration basins can retain runoff and mitigate the impact of mining disturbances.

Dewatering pits or quarries commonly lowers the water table in the vicinity of the pit or quarry, and may decrease the flow of nearby streams and lower the levels of nearby lakes. The impact of pit dewatering on nearby streams and lakes depends on a number of factors. These include the type of deposit (floodplain, stream terrace, alluvial fan, marine terrace, glaciofluvial, and others), the hydrologic properties of the deposit, the thickness of water table penetrated, where the drained water is discharged, and how the water in the pit or quarry is managed. Pit dewatering impacts can be limited by the use of slurry walls or by returning water drained from the pit to streams or lakes.

Wash-water discharge and storm runoff over active or abandoned mining sites can increase the turbidity of streams. Turbidity is generally greatest at mining and wash-water discharge points and decreases with distance downstream. Turbidity can be controlled by containing runoff and by filtering or containing wash water.

Little is known about how aggregate mining affects surface water chemistry. Changes are primarily local in nature and subtle (Nelson, 1993). Forshage and Carter (1973) investigated a dredge site and an upstream reference area on the Brazos River in Texas and found no significant differences between the sites in dissolved oxygen, pH, specific conductance, chlorides, or hardness. Martin and Hess (1986) found that dissolved oxygen, temperature, pH, and total hardness were similar in dredged and reference areas in the Chattahoochee River, Georgia, but reported decreases in dissolved oxygen downstream from dredged areas. Webb and Casey (1961) reported increases in temperatures downstream from dredging activity.

Aggregate mining on flood plains may impact streamchannel geometry. During floods streams may flow through sand and gravel pits located on active flood plains, resulting in changes in channel position. This can substantially alter the spatial distribution of the energy and force of the stream or river (Graf, 1979). When steams flow through pits, bedload may be captured in the pit. The ability to predict flooding and capture of the pit largely depends on how well the hydrology and history of the adjacent stream are known.

Levees or dikes may protect floodplain pits from flooding, and can keep bedload in the channel. Dikes prepared with engineered armored spillways at a low point allow controlled flooding and can help prevent pit capture (Norman and others, 1998).

Mining sand and gravel from stream channels may be accomplished with little impact to the environment, but has the potential to create very serious environmental impacts. The nature and severity of the impacts are highly dependent on the geologic setting and characteristics of the stream. Impacts may be particularly serious if the stream being mined is an eroding stream. The dramatic changes to such river systems where in-stream mining is being improperly managed have been described by Mossa and Autin (1998), Kondolf (1997), Florsheim and others (1998), to name but a few.

Removal of gravel from some streams, particularly aggrading streams, may be accomplished without causing adverse environmental impacts if the amount of material being removed does not exceed the natural replenishment rate. Even some eroding streams, in particular those underlain by large gravel layers deposited under different conditions than exist at present, may support gravel extraction with no serious environmental impacts. Jiongxin (1996) described such a situation on the Hanjiang River in China where downcutting stopped when coarse bed material was reached. Similar situations exist where coarse gravels of glacial origin underlie modern stream deposits.

The principal cause of in-stream mining impacts is the removal of more material than the system can replenish. Impacts can result from extracting too much material at one site, or the combined result of many small but intensive operations (Rowan and Kitetu, 1998). The removal of gravel from a stream changes its cross section and commonly increases its gradient. Increasing the gradient of the stream can cause upstream incision. Removing sand and gravel from streams, particularly eroding streams, commonly causes a decrease in bedload. A decrease in bedload can cause downstream incision. The stream may change its course, thus causing bank erosion and the undercutting of structures. In-stream mining can also result in channel bed armoring, increases in suspended sediment load, lowering of alluvial water tables, and stagnant low flows. All these impacts can result in major changes to aquatic and riparian habitat (see below).

The best method of mitigation of the impacts of instream mining is prevention. Kondolf (1998) suggested a number of strategies to limit the environmental impacts of instream aggregate mining. One method is to define a minimum elevation for the thalweg (the deepest part of the channel) along the river and to restrict mining to the area above this line. Another method is to estimate the annual bedload and to restrict extraction to that amount or less. Difficulties exist, however, in realistically determining the annual bedload.

Restoring streams or mitigating the impacts of in-stream mining requires reduction or cessation of the removal of sand and gravel. The Giffre River in the northern part of the French Alps rehabilitated itself following extensive extraction of gravel from the river channel (Piégay and Peiry, 1997). River restoration was largely due to the fact that after the amount of material extracted from the channel was reduced, the bedload supply greatly exceeded extraction.

Stream recovery from impacts caused by sand and gravel mining is highly dependent on the local geologic conditions. Recovery in some streams can be quite fast. Using streambed elevation data, Jacobson (1995) reported that the Meramec River, Missouri recovered within two years after channel dredging stopped. The relatively quick recovery of streambed elevation in the river was indicative of a river with an abundant bedload. Conversely, the Big Rib River, Wisconsin, only reached the early stages of recovery 20 years after the stream had been mined (Kanehl and Lyons, 1992).

Landslides

Aggregate operations should avoid areas of known landslides and areas with slope, aspect, and geologic conditions that are favorable for mass movement. Aggregate operations on an existing landslide, or near the toe or head of a landslide deposit can remobilize the slide. Even in areas where natural factors are not conducive to slope failure, aggregate mining can cause landslides. Goswami (1984) investigated landslides in Gauhati, northeastern India, and attributed the failure to numerous, closely spaced aggregate mines that had disrupted the natural equilibrium of the hill slopes and their natural drainage conditions.

If landsliding does take place, it is likely to occur near, but not necessarily at the mining site. Landsliding is likely to occur after mining starts, but will probably be triggered as a result of weather conditions. Slides could be a single event, or could continue over an extended period of time. Modern geologic engineering techniques can fairly accurately identify existing landslides and landslide prone areas, but generally are ineffective at predicting precisely where or when landsliding will occur.

Secondary Impacts on Habitat

Mining in some geologic environments can create a ripple effect that can impact habitat. Mine-related erosion can cause bank failure, which can cause loss of riparian habitat, and can cause loss of shade along stream banks. Channel shortening can increase flow rates, which can reduce the occurrence of coarse woody debris in the channel. In-stream mining can also result in channel bed armoring, increases in suspended sediment load, lowering of alluvial water tables, and stagnant low flows. All these impacts can result in major changes to aquatic and riparian habitat. Meador and Layher (1998) have summarized the impacts of aggregate mining on aquatic habitat.

Effects of mining on fish communities vary within and among streams. No major differences in fish species composition, diversity, relative abundance, or biomass were reported in a comparison of dredged and non-dredged control areas in the Tennessee and Cumberland Rivers in Tennessee (Nelson, 1993). Gravel-dredging operations in the Brazos River were associated with a decrease in sport fishes and benthic macroinvertebrates (Forshage and Carter, 1973). Gravel mining on flood plains in Alaska produced severe channel alterations, which were thought to have resulted in elimination or reduction in fish populations (Woodward-Clyde Consultants, 1980).

Rivers may possibly be restored through gravel replenishment. In some areas, the construction of dams has created environmental impacts that are similar to, but more severe than, those from in-stream mining. Adding gravel to the stream to replace the sediment lost to dams has restored salmon habitat in streams below dams. Gravel replenishment has been done on streams in California and on the Rhine River on the border between France and Germany (Kondolf, 1997).

Norman (1998) described how ponds resulting from aggregate mining along the Wyonoochee River in Washington have been reclaimed for off-channel salmon habitat. Requirements for successful reclamation are that the ponds have good access for fish to enter and leave the main river channels; low risk of avulsion, flooding or drought; and adequate food supply, cover, and water quality.

Many aggregate mining operations result in the preservation of existing habitat through the creation of buffer areas. The buffer areas around many aggregate operations retain all the characteristics of the original habitat, and may even be planted to increase vegetative cover. In some populated areas, mine buffers are a significant part of the total available open space.

Wildlife from the surrounding area may seek the protection afforded by the buffers. Such is the case at an active gravel pit located near the South Platte River, just downstream from Denver, Colorado. A Bald Eagle roosting tree occurs on the property, and thirty-seven acres of prime aggregate property were set aside as special habitat for the eagles. There commonly are six or more eagles on the property from mid-November through mid-April.

Some active aggregate operations serve as habitat for rare or endangered species. The Lakeside Daisy is one of the most spectacular wildflowers in the United States. It is also one of the most rare, and is listed as a Federal threatened species and Ohio endangered species. The Lakeside Daisies are drought resistant, calcium-loving plants that grow in full sun in areas of horizontal limestone or dolomite bedrock maintained in an open state by drought. Most of the population of the Lakeside Daisy occurs in an active quarry on the Marblehead Peninsula in Ohio. The only other sites where they grow naturally are the Bruce Peninsula, and Manitoulin Island in Ontario, Canada. The Daisy once occurred in Illinois, but is now extinct there except for plants that have been transplanted into scientific study plots such as the abandoned gravel pit known as the Morton Arboretum Dolomitic Prairie Restoration.

Mined-out aggregate operations can also be reclaimed as natural habitat. Quarry Cove, on the Oregon coast, is a quarry that has been converted into a man-made tidal zone, fed and nourished by wave action (Thompson, 1996). Quarry Cove, which was developed by the U.S. Bureau of Land Management, provides a variety of wildlife habitats and is expected to have a species diversity comparable to a natural tidal pool. Visitors (the site is wheel-chair accessible) can view nature taking its course as marine life invades the area. The cove is an exciting example of an exhausted site becoming a "natural" biological laboratory with community outreach.

POST-MINING ENVIRONMENTAL IMPACTS

The after-mining use of the land is an important aspect of reducing environmental impacts of aggregate extraction (Arbogast and others, 1998). Once an aggregate operation has ceased, the site may be reclaimed or abandoned. However, in most countries abandonment is seldom an acceptable alternative. Abandoned mines frequently become sites for unplanned and unregulated uses such as waste disposal and spontaneous recreation. If an operation penetrated the water table and is left dormant, the pit or quarry probably will fill with water and become an unattractive nuisance. Stagnation, eutrophication, and illegal dumping can degrade water quality.

Most aggregate permits issued today require a formal reclamation plan. Natural factors that impact how an aggregate operation can be reclaimed include the configuration of the mine, whether or not the mine penetrated the water table, the local geology, and the local climate. Forward-looking mining operators who employ modern technology and work within the natural restrictions can create a second use of mined-out aggregate operations that often equals or exceeds the pre-mined land use.

Wisely restoring a pit or quarry's environment requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception. Operating mines and reclaimed mine sites can no longer be considered isolated from their surroundings. Analysis of mine workings needs to go beyond site-specific information and relate to the regional context of the environment. Understanding mine and reclamation design can turn features perceived by the public as being undesirable (mines and pits) into something desirable (Arbogast and others, 1998).

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WESTERN PHOSPHATE FIELD GEOLOGY, PRODUCTION, AND CURRENT RESEARCH

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ABSTRACT

Voluminous deposits of commercial-grade phosphate occur in sedimentary strata in a 350,000 km² (135,000 mi²) area of the middle Rocky Mountains of North America known as the Western Phosphate Field. The Permian marine strata that host the phosphate were deposited on the western margin of the North American craton and subsequently deformed, first by folding and thrust faulting of the Laramide orogeny, and then by Cenozoic Basin and Range block faulting. Carbonate fluorapatite is the primary phosphorus-bearing mineral. Organic matter is abundant in some strata, and both biogenic and non-biogenic pyrite are also present. Certain strata are enriched in several trace elements, especially in arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), molybdenum (Mo), selenium (Se), vanadium (V), uranium (U), and zinc (Zn). Phosphate has been mined from the Western Phosphate Field for nearly 100 years. Phosphate mining and processing constitutes the largest mineral industry of Idaho, producing more than \$600 million in processed mineral value in 1997. Resource management agencies, phosphate producers, and others are concerned about the release of Se from phosphate mine wastes, especially at Maybe Canyon, and the potential effects that Se and other trace elements may have on the environment and on human health.

U.S. Geological Survey (USGS) Mineral Resources Team scientists initiated a multidisciplinary study of the Permian Phosphoria Formation and related rocks in the southeastern Idaho sector of the Western Phosphate Field in response to a request by the U.S. Bureau of Land Management (BLM). Studies to date reveal that Se is present in several phases, including native Se, and in an as yet unidentified form, possibly an organo-Se compound. Selenium is also present in pyrite and sphalerite. Selenium concentrations range from 1.2 to greater than 1,000 parts per million (ppm) in samples collected from exposures of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation (Meade Peake) at Enoch Valley. The results suggest that Se concentrations vary spatially across strata and with depth, perhaps comparable to spatial variations of phosphate and organic carbon concentrations throughout the Western Phosphate Field demonstrated in previous studies.

Some Se-enriched strata may be of adequate dimension to allow selective extraction during mining. Such units could be handled separately from the main ore process or waste streams and isolated in order to reduce the potential for release of Se to the environment.

INTRODUCTION

Location and Purpose

The middle Rocky Mountains of North America host voluminous deposits of phosphate rock. Known as the "Western Phosphate Field" (figure 1), this area covers approximately 350,000 km² (135,000 mile²), including portions of eastern Idaho, western Montana, western Wyoming, northern Utah, northwest Colorado, and northeastern Nevada. The deposits, which have been mined for nearly 100 years, currently constitute the sole source for commercial-grade phosphate in the western United States.

Current studies of the Western Phosphate Field by the USGS began in late 1997 in response to a request by the BLM for continuation of a series of 7.5-minute (1:24,000) phosphate resource investigations in southeastern Idaho, begun in the 1980s (for example, Derkey and others, 1983). The scope of the effort was subsequently broadened to include major geoenvironmental research components in response to industry and resource management agency concerns about adverse impacts to livestock grazing in areas associated with the release of Se from a waste impoundment at the inactive Maybe Canyon mine. The study integrates collaborative efforts by USGS Geologic, Water Resources, and Biological Resources Divisions; University of Idaho; BLM, U.S. Forest Service (FS) and its Rocky Mountain Research Station; and regional phosphate producers. Project goals include: (1) characterization of the main ore bodies and waste zones of the Meade Peak; (2) geoenvironmental investigations focused on trace element residence, mobility, and pathways; and (3) revised estimates of grade and tonnage of existing phosphate resources on public lands.

In 1998 and 1999, the first two years of a planned fiveyear project, eight stratigraphic sections across the Meade Peak, two each at Enoch Valley, Dry Valley, Rasmussen Ridge, and Smoky Canyon, were measured and sampled for analyses of geochemical, mineralogical, petrochemical, and physical properties, and for water leaching studies. Geophysical surveys were also conducted across selected sections. Studies in 1999 also included a multidisciplinary watershed investigation to assess (1) toxicology and deter-

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Figure 1. Western phosphate field showing Permian rocks, and phosphate mines, prospects, and processing plants.

mine reaction pathways of Se and other trace elements in selected mine dumps and in surrounding waterways and pastures, (2) analyses of archived samples from previous USGS studies, and (3) development of a digital database of historic and active mines.

Previous Studies

Scientists of the USGS and other agencies, academia, and industry have studied the Phosphoria Formation and related rock units in the Western Phosphate Field throughout much of the twentieth century. The hundreds of papers that have been published on this subject are too numerous to cite here, however, mention of selected references is essential. For over 50 years, pioneering workers such as Mansfield (1918, 1920, 1927, 1933), McKelvey and others (1953a, 1953b, 1959, 1967), Sheldon (1963, 1989), Service and Popoff (1964), Service (1966, 1967), and Gulbrandsen and Krier (1980), to name a few, focused predominantly on delineation and evaluation of phosphate resources and on the origin of the deposits. Work accomplished in the 1940s and 1950s, exemplified by Sheldon (1959) and others, concentrated on uranium exploration, and later Maughan (1975, 1976, 1979a,b, 1984) and others studied petroleum sourcerock potential. Research in recent decades by Gulbrandsen (1966), Piper (1974), Desborough (1977), Altschuler (1980), and others produced a significant body of literature on the unusual chemistry of the Meade Peak. The depositional and tectonic history of the Idaho-Wyoming section of the Western Phosphate Field is provided by Armstrong and Oriel (1965, 1986). Medrano and Piper (1992, 1995) and Piper and Medrano (1994) also reported on mineralogical, traceelement, and major-element composition as an indicator of environment of deposition. Phosphate deposit origin, demand, and commodity data are reported in Herring (1995), Herring and Fantel (1993), and Herring and Stowasser (1991), and the geochemistry of Se is described in Herring (1990).

Geologic Setting and Phosphate Minerology

The Permian Phosphoria Formation comprises a sequence of marine strata, primarily carbonaceous and phosphatic mudstone, siltstone, phosphorite, dark calcium and magnesium carbonates, black shales, and chert deposited about 250 million years ago.

The Phosphoria Formation is about 60 m (200 feet) thick and is divided into three members at its type locality of Phosphoria Gulch in southeastern Idaho. From oldest to youngest, these are the Meade Peak Member, the Rex Chert Member, and an informally named cherty shale member (Sheldon, 1989). Elsewhere, the upper cherty shale grades into the phosphate-rich Retort Phosphatic Shale Member (Retort). The Phosphoria Formation also intertongues to the northeast and south of the southeast Idaho phosphate district with the Shedhorn Sandstone and Park City Formations (Sheldon, 1989). In the core of the southeast Idaho phosphate district, the Meade Peak unconformably overlies the Grandeur Tongue of the Park City Formation and the Pennsylvanian-Permian Wells Formation. Figure 1 shows the Western Phosphate Field defined by exposures of Permian rock units, primarily the Phosphoria Formation, and the distribution of phosphate mines and prospects.

Deposition of these sediments in an upwelling, nutrientrich environment (Mosier, 1986) occurred over a period of about 10 million years along the western margin of the North American craton. As a result of variations in the original depositional environment, such as water depth during deposition, distance from the ancient shoreline, and subsequent deformation, the strata are generally thickest in southeastern Idaho and generally thin or pinch out to the north, east, and southeast but with considerable local variation. This relationship is best illustrated in a restored section (figure 2) across southeastern Idaho and western Wyoming. Intense Mid-Cretaceous to early Eocene (Armstrong and Oriel, 1986) compression during the Laramide orogeny deformed the Phanerozoic strata into folds and thrust faults, and subsequent Cenozoic Basin and Range block faulting severely complicate this stratigraphic sequence (Sheldon, 1989).

The primary phosphorus-bearing mineral is carbonate fluorapatite ($Ca_5[PO_4, CO_3]_3[F, OH]$). The principal minerals found in unweathered rocks include quartz, buddingtonite (NH₃-feldspar), albite, illite, calcite, and dolomite (Gulbrandsen, 1974; Desborough, 1977). Organic matter is abundant (greater than 20 percent) in some strata, and both biogenic and non-biogenic pyrite are present in low but variable concentrations. The Meade Peak is especially enriched in several trace elements compared to average phosphorite,



Figure 2. Restored section from eastern Idaho through western Wyoming showing stratigraphic relations of the Permian Phosphoria Formation and equivalents (modified from McKelvey and others, 1967).

with significant concentrations of As, Cd, Cr, Cu, Mo, Se, U, V, and Zn (Altschuler, 1980). Rare earth elements are enriched in the Phosphoria Formation and occur principally in the carbonate fluorapatite.

PHOSPHATE - THE COMMODITY

Discovery, Mining, and Production History

Phosphate has been mined and processed in the Western Phosphate Field for nearly 100 years. A brief description of the relevant mining history is provided by Cathcart (1991). Phosphate was discovered in Cache County, Utah in 1889, however, exploration and development of phosphate did not commence until 1904. Production was first reported in 1906 from a mine near Montpelier, Idaho; however, marketable phosphate production was not recorded until Van Horn (1911) noted that 0.5 percent of total U.S. phosphate production was from western deposits. Phosphate production rose slowly in the first half of the twentieth century. Cathcart (1991) reported that about 14,500 metric tons (mt) (16,000 short tons [st]) were shipped in 1914 and 58,900 mt (64,900 st) were shipped in 1925. Mining was predominantly by underground methods until the 1940s, when the transition to open-pit mining methods significantly increased production rates, as shown in figures 3a and 3b, and reduced unit cost. During this period, western phosphate production increased from about 716,000 mt (789,000 st), or 7.5 percent of U.S. production, in 1948, to a high of about 7 million mt (8 million st), or 17.2 percent of U.S. production, in 1994. In general over the last 10 years, western phosphate production ranged from five million to seven million mt (6 to 8 million st), and the proportion of total U.S. production ranged from 12 to 14 percent.

Cumulative annual production of the five open-pit mines (table 1) currently operating in the Western Phosphate Field ranges from five to six million mt (6 to 7 million st) of phosphate rock, about 12 to 14 percent of total U.S. production. Four of the five mines develop thick, high-grade units in the Meade Peak Member of the Phosphoria Formation in the southeastern Idaho phosphate district (figure 4); the remaining mine, Little Brush Creek (a.k.a. Vernal mine), is in northeastern Utah. Table 1 also shows the method and distance of transport from the mines to the processing plants as well as the plant type.

Ore and Waste Zones and Resources

Phosphate is mined from two zones in the Meade Peak that range from 5 to 18 m (16 to 59 feet) in thickness and typically contain from 20 to 35 percent P_2O_5 . These ore zones enclose a middle waste zone that is about 25 to 30 m (80 to 100 feet) thick and is comprised of low-grade phosphatic shale that typically averages less that 16 percent P_2O_5 . Material from the middle waste zone is extracted but impounded in dumps or back-filled into the surface mine pits behind active mining. Generally, mineable phosphate beds in this area are 1.5 m (4.9 feet) thick or greater. Thin, low-grade beds in the upper and lower phosphate-rich units must be blended with extracted ore, whereas thin high-grade beds in the middle waste zone are not recovered.



Figure 3a. U.S. and western phosphate production, 1948 through 1997.



Figure 3b. Western elemental phosphorus percentage of total U.S. production, 1948 through 1997.

Summaries of resources and reserves for the Western Phosphate Field, as well as mine parameters and ore characteristics, are presented by Sheldon (1989) and Cathcart (1991) (tables 2 and 3). Based on selected criteria, Sheldon (1989) estimated that, at an average grade of 24 percent P_2O_5 , the field contains a reserve base (including inferred reserves) of 1.6 billion mt (1.8 billion st) and a subeconomic resource of 6.0 billion mt (7 billion st). Estimated subeconomic resources by underground mining at a grade of 28 percent include 4.0 billion mt (4.4 billion st) above entry level and an additional 13 billion mt (14 billion st) below entry level to a depth of 305 m (1,000 feet). Cathcart (1991) reported resources of the same magnitude using similar stipulated conditions (table 3) on composition (for example, Fe₂O₃, Al₂O₃, MgO, and CaO). The dip of steeply-dipping beds in southeastern Idaho typically limits the depth of open pit mining operations to 90 to 120 m (300 to 400 feet).

Utilization and Processing of Phosphate

Phosphorus, the sought-after component of phosphate (P_2O_5) rock, is an essential element for plant and animal nutrition and also has numerous industrial applications. The principal use for phosphorus is as a fertilizer; other chemical applications include use in water softeners, detergents, and food additives. Phosphate rock may be processed by one of two different methods (table 1) to yield either fertilizer or elemental phosphorus products.

MINE	COMPANY	MINE LOCATION	PLANT LOCATION	PLANT TYPE	MINE TO PLANT	DISTANCE
Dry Valley	Astaris LLC	Dry Valley, Idaho	Pocatello, Idaho	elemental phoshorus/ electric furnace	rail	164 km
Enoch Valley	Monsanto	Enoch Valley, Idaho	Soda Springs, Idaho	elemental phosphorus/ electric furnace	truck	32 km
Rasmussen Ridge	Agrium U.S. Inc.	Rasmussen Ridge, Idaho	Conda, Idaho	fertilizer/ wet process phosphoric acid/ acidulation	rail	45 km
Smokey Canyon	J.R. Simplot Company	Smoky Canyon, Idaho	Pocatello, Idaho	fertilizer/ wet process phosphoric acid/ acidulation	slurry pipeline	138 km
Little Brush Creek	Simplot-Farmland Ltd.	Vernal, Utah	Rock Springs, Wyoming	fertilizer/ wet process phosphoric acid/ acidulation	slurry pipeline	155 km

 Table 1.

 Phosphate mines, plants, and mode of ore transport in the western phosphate field.

Resources of t	Table 2. rces of the western phosphate field.		
CLASSIFICATION	RESOURCE	P ₂ O ₅ GRADE	
Open-Pit Mining			
Reserve base	1.6 billion mt (1.8 billion st)	24 % avg.	
Subeconomic resource	6.0 billion mt (6.6 billion st)	24 % avg.	
Underground Mining			
Subeconomic resources above entry	4.0 billion mt (4.4 billion st)	28 %	
Subeconomic resources below entry	13 billion mt (14 billion st)	28 %	

Fertilizers

Approximately 90 percent of phosphate rock mined and beneficiated in the U.S. is treated with H_2SO_4 , a wet-process method referred to as acidulation that produces phosphoric acid and phosphogypsum waste; the waste is placed in surface impoundments. Typically, the phosphoric acid is reacted with NH₃ to produce N- and P-containing fertilizer, most commonly diammonium phosphate (DAP) or monammonium phosphate (MAP). Fertilizer plants are operated by J.R. Simplot Company in Pocatello, Idaho, and by Agrium U.S., Inc. in Conda, Idaho.

Table 3. Phosphate open-pit mine parameters an phosphate fie	nd ore quality i ld.	n the western
PARAMETER	QUALITY	ζ
P ₂ O ₅ content	minimum	18%
P_2O_5 content	average	24%
Fe_2O_3 - Al_2O_3 content	maximum	3%
MgO content	maximum	1.5%
CaO: P ₂ O ₅ ratio	maximum	1.55
Overburden: ore ratio	maximum	3.5:1
Backslope angle	maximum	40°
Mining width of bed	minimum	1.5 m
Down-dip mine (floor) width	maximum	76 m

Elemental Phosphorus (P4)

Elemental phosphorus is produced by smelting a mixture of agglomerated phosphate rock, lump coke, and silica in an electric furnace. The resulting phosphorus vapor is condensed and stored under water. Numerous secondary products can then be created. Elemental phosphorus plants are operated by FMC Corporation in Pocatello, Idaho and by Monsanto in Soda Springs, Idaho; these plants have been the sole producers of elemental phosphorus in the U.S. for the past six years (see figure 3b). In 1997, the combined processed mineral value of the four operating phosphate



Figure 4. Annotated Landsat Thematic Mapper (TM) image (June 1997) showing selected phosphate mines, processing plants, and related features in southeast Idaho (utilizing lab-stretched 7-3-1 bands). Note that the Dry Valley mine is now operated by Astaris, LLC (formerly FMC Corporation), and the Enoch Valley mine is now operated by Monsanto (formerly Solutia, Inc.).

mines and processing plants were the largest component of Idaho's mining industry, totaling more that \$600 million (S. Jasinski, oral communication, 1999).

A byproduct of phosphate processing in southeast Idaho is vanadium pentoxide. Until the late 1990s, approximately 2,000 mt (2,200 st) of vanadium pentoxide were produced annually (Hilliard, 1996) by the Kerr-McGee Chemical Corporation plant (figure 4) in Soda Springs from waste created in Monsanto's elemental phosphorus process.

GEOENVIRONMENTAL ISSUES AND STUDIES

Selenium and Other Trace Elements

Anomalous concentrations of several trace elements – especially arsenic, cadmium, chromium, copper, molybdenum, selenium, uranium, vanadium, and zinc – are present in the phosphatic ore and waste (Desborough, 1977; Desborough and Poole, 1983). These elements pose geoenvironmental challenges to mining, processing, disposal of the

waste rock, and possibly product applications. Maughan (1984) demonstrated that several constituents of the Meade Peak, particularly phosphate (figure 5), organic carbon, and silver, are selectively concentrated in certain areas of the Western Phosphate Field. This may be a result of variations in the environments of deposition or subsequent migration associated with hydrothermal or other processes. The distribution of the trace elements of concern may also exhibit significant spatial variance.

As a consequence of one documented case of Se release that resulted in toxicosis in pastured horses in 1996, Se is of greatest environmental interest, especially where it is found in mine waste materials, soils, and plants. Subsequent studies confirm additional Se releases associated with phosphate mining and mine waste disposal. Specifically, the practice of disposing of waste rock in cross-valley-filled dumps with French drains, a standard phosphate industry practice since the 1970s, has led to at least one incident of Se release, and concentration in grazing land (Möller, 1998).

In early 1997, phosphate companies and resource management agencies in southeastern Idaho, including the BLM and FS, formed an Industry/Interagency Selenium Working Group (SeWG) in order to respond cohesively and decisively to the environmental challenge. Participants of the SeWG negotiated strategies and support to determine the nature and extent of the release and impacts of Se associated with mining and waste disposal. The SeWG also attempted to develop mining and waste management practices designed to reduce or prevent adverse impacts in the future.

Selenium – Essential and Hazardous to Life

Selenium is a naturally occurring solid mineral. An essential nutrient for mammals, it can be metabolized in both inorganic and organic form. In the body, Se functions, among other things, as an antioxidant, as does vitamin E. Selenium also occurs in many other forms and is involved in several metabolic pathways, such as those involving selenoamino acids. However, Se can also be harmful to humans and animals when consistently consumed in amounts that are not much higher than concentrations recommended for good nutrition.

Soils in some parts of the United States, especially the western states, contain high levels of bioavailable Se. Selenate compounds can readily migrate from water into plants that can alter them into organic Se compounds such as selenomethionine [Agency for Toxic Substances and Disease Registry (ATSDR), 1996]. In addition, some forage plants accumulate Se to concentrations that are harmful to grazing livestock. Humans can also be exposed to excessive Se if they eat grains and vegetables produced in soils with high Se concentrations. In fresh water containing high concentrations of Se, such as agricultural water drainage basins in the San Joaquin Valley in California, fish may contain Se concentrations of more than 5 ppm. For instance, Se concentrations in fish in the Kesterson Reservoir in the San Joaquin Valley have been measured (dry weight) as high as 170 ppm (ATSDR, 1996).

110

112



146

In its "Toxicological Profile for Selenium," the Agency for Toxic Substances and Disease Registry (1996) describes a wide range of symptoms experienced by mammals exposed to Se. Symptoms of brittle hair and deformed nails result from chronic exposure to concentrations only slightly higher than nutritionally recommended amounts. In extreme cases of exposure, acute symptoms may include pulmonary edema, severe gastrointestinal effects, tachycardia, loss of feeling or control in the extremities, convulsions, or death. H_2Se is extremely toxic; however, the only Se compound demonstrated to be carcinogenic in animals is Se sulfide. Exposure to high concentrations of inorganic Se compounds has been shown to cause birth defects in birds, but this has not been demonstrated in humans or other mammals (ATSDR, 1996).

U.S. Geological Survey Research Activities

In response to a BLM request for assistance, and in order to understand the abundance, mineral residence, and availability of the environmentally sensitive elements, especially Se, the USGS initiated a series of integrated, multidisciplinary studies directed toward:

- resource and reserve estimations of phosphate in eight 7.5-minute quadrangles;
- determination of elemental and mineralogical residence, and petrochemical characteristics, of phosphate ore and waste rock;
- establishing mobilization and reaction pathways, transport mechanisms, and disposition of Se and other geoenvironmentally-sensitive elements associated with the occurrence, development, and societal use of phosphate;
- geoenvironmental assessment of Se in soil, water, plants, and indicator organisms in affected and background areas;
- identification of geophysical signatures associated with phosphate and black shales including spectral radiometric, electromagnetic, resistivity, and magnetic surveys across sections; and
- improving understanding of the depositional origin of phosphates in the Western phosphate field to advance the existing descriptive and tonnage and grade models, leading to development of a geoenvironmental model.

To begin characterization of element distribution and mineral residence, two sections of the Meade Peak exposed at the Enoch Valley mine (figures 4 and 6) in southeast Idaho were measured and sampled in June 1998 (Tysdal and others, 1999). In order to ascertain the effect of weathering with depth, one section (A, also referred to as "weathered") was collected from a bench near the pre-mining land surface and the other section (B, also referred to as "less weathered") was collected about 30 m (100 feet) below that level. The sections were composite-channel sampled across the entire Meade Peak – the lower phosphate, the middle waste, and the upper phosphate zones, as well as upper and lower bounding waste units. Sampled intervals are units of consistent lithology or are distinct mine units identified by company personnel. This sampling approach allows for analytical characterization of the whole member as a sequence of channel samples over its entire thickness. All of the samples were submitted for detailed chemical analysis. Selected samples were also collected for thin section, microprobe, and scanning electron microscope analysis. In similar fashion, two strati-



Figure 6. Northerly view of Enoch Valley mine, Caribou County, Idaho, showing locations of stratigraphic sections A and B.

graphic sections each were subsequently measured and sampled in 1998-1999 at the Dry Valley, Rasmussen Ridge, and Smoky Canyon mines in southeast Idaho. The analytical results of the latter samples were not available for this report. Detailed thin- and polished-section, scanning electron microscope, microprobe, and ion probe analyses of samples were also planned.

Studies in 1999 also included: (1) a multidisciplinary watershed investigation to characterize soil, water, plant, and faunal levels of Se, and to determine reaction pathways of Se in mine dumps and in surrounding waterways and pastures; (2) analyses of archived samples from earlier studies; (3) geologic mapping in support of resource estimates; and (4) development of a digital database of historic and active mines.

The recent USGS phosphate studies have produced four reports (Desborough and others, 1999; Herring and others, 1999a; Piper, 1999; and Tysdal and others, 1999). These and subsequent reports are released as open-file reports in order for the raw data to be immediately accessible to others studying the geoenvironmental issues associated with phosphate mining.

PRELIMINARY CONCLUSIONS

Selenium Residence

The form or mineral residence of Se in the Meade Peak is an important factor in its release into the environment. Grauch and others (1999) report that Se is present in at least three phases (or minerals) in samples from the Dry Valley and Enoch Valley mines: as native Se, in pyrite, and in sphalerite. There are multiple generations of both pyrite and sphalerite; at least one generation of each phase is seleniferous. The two sulfide phases may represent the early diagenetic Se residence. Selenium may also occur as an organo-Se compound. Native Se is the most common phase, and it may account for most of the Se in rocks with high Se content and in some low-Se rocks. It occurs as small crystals (generally less than 1 micrometer in diameter) in veins and in open spaces (presumably secondary porosity resulting from alteration and pre-modern weathering). The age of native Se, relative to deposition, is unknown, but most of it crystallized after lithification of the Meade Peak rocks and probably before present day weathering. Despite the relatively low solubility of native Se, rinds with low Se content on samples with otherwise high Se content indicate that native Se is mobilized during weathering. Desborough and others (1999) report that Se content of one sample of pyrite from Dry Valley mine ranged from less than 100 ppm to about 2,000 ppm.

Stratigraphic Sections and Chemical Analyses

Chemical analyses for the samples from sections A and B at Enoch Valley are presented by Herring and others (1999a, b), and table 4 lists weighted average concentrations for Se, As, Cd, Cr, Cu, Ni, V, and Zn. Phosphate and Se concentrations of samples collected from the weathered (A) and less-weathered (B) sections are plotted in figures 7, 8, 9, and 10, respectively. Overall, Se concentrations across the sections are high (figures 8 and 10), especially relative to the average abundance of Se in shales, about 0.6 ppm (Carmichael, 1989). Se concentrations are higher in the deeper, less-weathered section (B) at this site, ranging from 3.4 to 1,040 ppm in contrast to the weathered section (A) that ranges from 1.2 to 216 ppm.

Compositional variability between the sections is pronounced. The distribution of Se is not correlated between the weathered (A) and less-weathered (B) sections (figures 7-10; table 4). Selenium concentrations clearly increase with depth but not proportionally among the zones. Selenium concentrations in the middle waste zone of the weathered section are more than twice that in the phosphatic zones; whereas, the upper phosphatic zone of the less-weathered section has twice the concentration of Se of that in the middle waste zone.

The results suggest that selected strata with high Se concentrations may be of adequate dimension to allow selective extraction during the mining process. Such units could be handled separately from the main process or waste streams, or isolated, by encapsulation for example, so as to reduce release of Se to the environment.

ACKNOWLEDGMENTS

Numerous individuals have contributed to the current studies by the USGS in the Western Phosphate Field. The authors would like to thank William Lee and Peter Oberlindacher of the Idaho State Office, BLM, for their foresight and perseverance in proposing the studies and providing support. Jeff Cundick, BLM in Pocatello, and Jeff Jones and Tony Varilone, FS, in Soda Springs, have provided logistical support and guidance over the duration of the study. In addition, collaborative research associated with the Western U.S. Phosphate project includes contributions by the following: Michael Amacher and Ray Brown with the FS Rocky Mountain Research Center in Logan, Utah; Mickey Gunter, mineralogist, and Andrew Knudsen, graduate student, at the



Figure 7. Phosphate (%) in stratigraphic section A.



Figure 8. Selenium (ppm) in stratigraphic section A.



Figure 9. Phosphate (%) in stratigraphic section B.





Weighted average concentration, ppm, of selected trace elements, and percent in parenthesis, of element in each of the three section intervals. Percentages may not equal 100 due to rounding of numbers.								
	Se	As	Cd	Cr	Cu	Ni	V	Zn
Average Abundance in Shale ¹	0.6	6.6	0.3	100	57	95	130	80
Weathered Section (A)								
Upper Phosphate	12	19	108	1407	99	140	652	897
	(1%)	(3%)	(13%)	(5%)	(5%)	(4%)	(8%)	(6%)
Middle Waste	70	35	28	2393	139	175	287	724
	(80%)	(73%)	(25%)	(78%)	(68%)	(65%)	(30%)	(50%)
Lower Phosphate	34	24	147	1064	116	178	1239	1300
	(19%)	(24%)	(63%)	(17%)	(27%)	(32%)	(62%)	(44%)
Less-Weathered Section (B)								
Upper Phosphate	317	13	68	887	58	98	317	793
	(20%)	(4%)	(6%)	(5%)	(5%)	(4%)	(7%)	(4%)
Middle Waste	147	31	41	1556	95	238	401	1130
	(65%)	(59%)	(26%)	(68%)	(55%)	(61%)	(23%)	(37%)
Lower Phosphate	48	27	147	817	96	190	1676	2416
	(15%)	(38%)	(68%)	(26%)	(41%)	(36%)	(70%)	(59%)

Table 4.

University of Idaho; Janie Castle, aquatic biologist, at Colorado State University; Mark Hardy, hydrologist, with the USGS Water Resources Division in Boise, Idaho, and Lee Ischinger, USGS Biological Resources Division, Ft. Collins, Colorado. We appreciate the efforts of Judy Weathers, USGS Mineral Resources Team, Menlo Park, California, who prepared many of the illustrations in this paper.

Operations staffs for several phosphate mining and pro-

cessing companies provided important data, access, logistical support, and technical guidance. These staff include, but are not limited to: Alan Haslam, Rob Squires, and Dan Kline with Agrium U.S., Inc.; Rick Bullis, Scott Lusty, and Kelly Ransom with Astaris, LLC (formerly FMC Corporation); Larry Raymond and Pat Avery with J.R. Simplot Company; Tom Boden with Rhodia Inc.; and Mike Vice, Ray Petrun, and David Farnsworth with Monsanto (formerly Solutia, Inc.).

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RECYCLED AGGREGATE – FLOW ANALYSIS AND ECONOMICS

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ABSTRACT

Recycled materials are increasingly being used in road construction to supplement natural aggregate derived from crushed stone, sand, and gravel. An understanding of the amount of substitution that is taking place, its economics, and factors affecting the level of substitution is useful in estimating the potential for recycling and in assessing the total supply of aggregate.

While U.S. consumption of recycled aggregates from crushed concrete is estimated to have increased 160 percent between 1994 and 1996; it comprised less than 5 percent of total aggregates consumed in 1995. Construction waste supply is regional, and is determined by infrastructure decay and replacement rates. Aggregate recycling rates are greater in urban areas where infrastructure is being replaced, natural aggregate resources are limited, disposal costs are high, or strict environmental regulations prevent disposal. Recycling is expected to increase as construction contractors attempt to save on transportation, disposal, and new material costs. Aggregate producers include recycled material as an option to consumers in order to prolong the life of their reserves and improve their range of products. Recycled aggregates can be a supplement for natural aggregates in selected applications, but their use should be evaluated locally based upon relative cost, quality, and market factors.

Because aggregate recycling is often affected by local and regional transportation systems, disposal and tipping fees, resource supply, the market for specific products, and municipal support, costs for three representative fixed site operations of different sizes were modeled. Under study conditions, all were found to be profitable, but highly

dependent upon local tipping fees and market prices, which can differ significantly by location. Smaller operations were found to have different operational dynamics, often requiring creative marketing or incentives to maintain profitability.

INTRODUCTION

The U.S. Geological Survey (USGS) is researching the use of recycled aggregate in construction applications. Urban growth requires new infrastructure, and construction aggregates are important components of this infrastructure; however, natural aggregate resources are often constrained by urbanization, zoning regulations, increased costs, and environmental concerns. U.S. Geological Survey studies trace the flow of construction aggregates, analyze the factors influencing aggregate recycling, and assess the effects of recycling on the natural aggregates industry. The studies should assist informed decision making by operators, suppliers, consumers, and regulators. The two studies discussed here are part of the USGS materials flow program.

The USGS conducted studies to evaluate whether recycled aggregate should be included in the total supply picture of aggregate; recycled products are now being included in USGS mineral yearbook chapters for sand and gravel and crushed stone. A graphic representation of aggregate use in construction applications was developed using materials flow methodologies (Kelly, 1998). Materials flow is a systems approach that can show the quantitative comparison between the consumption of natural aggregate (sand and gravel, and crushed stone) and recycled aggregate (crushed concrete, and asphalt pavement).

The economics of recycling aggregate was also evaluated (Wilburn and Goonan, 1998). Aggregate recycling economics was found to be favorable under the specified conditions, which included location, aggregate quality, availability, and transportation factors.

AGGREGATE FLOW AND SUBSTITUTION

Aggregates account for more than two-thirds of U.S. non-fuel minerals production. Figure 1 shows natural aggregate consumption in the United States from 1900 to 1996, with projections to 2020. Note that consumption data for crushed stone and sand and gravel are cumulative. A steep



Figure 1. Cumulative natural aggregate consumption in the United States (historical and projected). Source: U.S. Bureau of Mines/U.S. Geological Survey Minerals Yearbook, various years.

rise in consumption occurred during the period 1945 to 1965, corresponding to the post-World War II construction boom and the construction of the Interstate Highway System. Dips occurred in the recession years of 1975, 1982, and 1991, all related to economic conditions during those years. In general, the use of crushed stone increased at a faster rate than that of sand and gravel. Total natural aggregate consumption exceeded 2.2 billion metric tons (mt) (2.4 billion short tons [st]) in 1996.

Recycled aggregate consumption accounted for less than 5 percent of total consumption in 1996. Even so, the consumption of recycled aggregate increased by 160 percent during the period 1994 to 1996.

As illustrated in figure 2, materials flow analysis uses a systems approach to track the flow of materials through an economy; from the time it is first extracted from the ground, through production and manufacturing, through consumption in various end uses, and through the recycling or land filling of this material. Two points should be emphasized: first, the entire movement of materials from process to process is part of a single industrial cycle; second, materials can either be recycled or returned to the Earth (by means of dissipative emissions or land filling) at any point in this cycle.

The USGS has been working to quantify the flow stream for many commodities. It has conducted materials flow analyses of more than 12 mineral commodities. As shown in figure 3, materials flow provides a method for analyzing complex relationships. This diagram presents much information, but a very important relationship is the amount of substitution that is occurring between natural aggregates (sand and gravel, and crushed stone) and recycled aggregate (scrap concrete and scrap asphalt pavement).

Figure 3 reflects construction use

only. Approximately 83 percent of crushed stone, and 94 percent of sand and gravel produced annually are used in construction. Sections of the diagram can be examined separately showing flow splits to various end uses. The figure represents a static view of a very dynamic process. Assessing flow changes from year to year allows for a more complete understanding of this industry.

Figure 4 illustrates the substitution that is taking place in road and building construction. End uses for crushed cement concrete are compared to the corresponding end uses for natural construction aggregates. Substitution favors road construction use because (1) concrete from pavement is highly

quantities of material in million metric tons).

accessible and (2) crushing operations are highly portable. The greatest amount of substitution occurs as road base. Substitution is likely to occur in road base use because crushed concrete has surface properties limiting its use in top pavement layers.

Crushed concrete has a surface with more irregularities than natural aggregate, when used for making cement concrete, so more cement is required to fill the nooks and crannies. This reduces its economic competitiveness, because cement is the most expensive component of cement concrete. The economic competitiveness of crushed concrete is similarly reduced when used for making bituminous concrete









Figure 4. Relative flows of natural and recycled aggregate for construction uses, 1996 (numbers adjacent to flow arrows are quantities of material in million metric tons).

because crushed concrete is more absorptive than natural aggregate in this application and more liquid asphalt binder is required.

AGGREGATE RECYCLING ECONOMICS

To study the costs of recycling aggregate, the USGS developed several cost models of different sized recycling operations (Wilburn and Goonan, 1998). Transportation costs were excluded from these models, since they are typically incurred by the construction contractor, rather than the recycler. The capital costs reported in figure 5 reflect costs for new equipment in the Denver, Colorado area.

Although initial capital costs for recycling operations are significant, unit capital costs are expected to decrease over time as equipment is depreciated. The figure shows that the smaller scale operation is the most capital intensive, averaging about \$8/mt (\$7/st); estimated unit capital costs for larger operations range from \$4/mt to \$5/mt (\$3.60/st to \$4.50/st).



Figure 5. Estimated 1996 capital costs per unit of production (y-axis) for two different size operations (x-axis).

Figure 6 shows the breakdown of the principal operating cost and revenue components for recycling operations. Overhead was found to be the largest component of operating cost, averaging about 30 percent of the total unit operating cost. Labor costs accounted for a further 20 to 23 percent of the total unit operating cost. It is interesting to note that larger operations, rated at a capacity of two to three times the modeled smaller operation, only require one or two more equipment operators to handle the increased capacity. Consequently, productivity for a small operation (22,000 mt/person) (24,000 st/person) is much lower than for a large operation (52,000 mt/person) (58,000 st/person). Costs related to equipment (maintenance and recovery of capital) are also significant to a recycling operation.



Figure 6. Estimated 1996 operating costs for two different size operations and unit revenues for all recycling operations.

The principal sources of revenue for an aggregate recycler are product prices and tipping fees. A tipping fee is charged by the recycler to process material from a contractor. Since alternative landfill prices in the Denver area are low, product prices for recycled material in the Denver area are correspondingly low. The average market price for recycled road base in Denver was assumed to be \$5.23/mt (\$4.74/st) in 1996. The larger the operation, the greater the impact of revenues on operation economics. Because unit operating costs for a large plant are lower, the same unit revenues can generate a larger profit. Higher unit production costs for a small plant may be offset, however, by the mobility of such plants. Larger operations need to be able to acquire a sustained, quality feed volume to meet their higher production level.

Figure 7 shows how the Denver area estimates compare to reported national ranges for product price, operating cost,



Figure 7. Estimated range of operating costs and revenues, Denver and the United States (Denver data from Hawkins, 1996, and United States data from Deal, 1997).

and tipping fee. Reported U.S. product prices for recycled aggregate materials range from about \$0.50/mt to \$17/mt (\$0.45/st to \$15.42/st), depending upon product type and location. Tipping fees also vary regionally. The average Denver area tipping fee of \$1.10/mt (\$1.00/st) falls at the low end of the U.S. range shown in figure 7. Available data indicates that costs have not changed significantly since 1996.

Quantity and price of locally available natural aggregate often can set the price for recycled aggregate. Local tipping fees are set based on the volume of construction waste locally processed, availability of disposal sites, aggregate demand, transportation factors, and legislation. Operating costs are influenced by technical parameters such as production rate, which affect equipment and labor requirements, but are not greatly influenced by regional supply or demand variations.

Transportation distances and costs affect operational dynamics since the amount available for recycling is in part based on the relative costs to the construction contractor of delivering and paying a tipping fee to the recycler, the costs of transporting construction debris to competitors, or disposing of this material in a landfill. Each kilometer (0.6 mile) that a metric ton (1.1 st) of aggregate is hauled can add \$0.13 (\$0.19 for each st per mile) to its unit production cost. So, for lower valued products such as road base, distance is critical. Feed availability and consistency are also important. Product pricing is often outside the control of the recycler, and often is determined by the availability of natural aggregate. Quality and uniformity can pose a risk to the recycler. It may be difficult to maintain predictable sources of supply and revenue due to fluctuations in available material. Small-

er operations often require creative marketing to maintain their profit level. Plant location and efficiency influence profitability.

CONCLUSIONS

Aggregate recycling is becoming an increasing component of aggregate supply. It can supplement natural aggregate in some applications. The aggregate recycling industry is locally influenced by the availability of natural aggregate. Materials flow analysis is useful to track materials substitution, and can provide an indication of the potential for future recycling efforts. The economics of recycling aggregate were found to be favorable, given specified conditions. The national picture may vary, however, from the Denver area model reported here. Quality of available aggregate, costs, and transportation factors must be considered.

CONTACTS

Material for this paper was extracted from two USGS circulars available on the Internet at http://minerals.er.usgs. gov/minerals/pubs/. Additional information on the economics of aggregate recycling may be obtained from David Wilburn (303-236-8747, extension 337; wilburn@usgs.gov) or Thomas Goonan (303-236-8747, extension 228; goonan @usgs.gov); Information on aggregate substitution and materials flow may be obtained from Thomas Kelly (303-236-8747, extension 269; kellyt@usgs.gov), and general information on the USGS materials flow activity may be obtained from Eric Rodenburg (703-648-4911; erodenbu@usgs.gov).

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SEPARATION RAPIDS RARE METALS PROJECT, KENORA, ONTARIO, CANADA

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ABSTRACT

The Separation Rapids property, located approximately 60 km (37 miles) north of Kenora, Ontario, Canada, is host to one of the largest rare metal pegmatite deposits in the world. This pegmatite was named the Big Whopper by its discoverer, Dr. Fred Breaks of the Ontario Geological Survey, because of the exceptional length and width of the surface exposure. The property is readily accessible from a main, all-weather road via a network of secondary logging roads. The main line of the Canadian National Railway passes through the village of Redditt, just 40 km (24 miles) south of the property.

The Big Whopper is one of the complex-type (petalite sub-type) class of rare metal pegmatites that are geochemically the most highly evolved in the spectrum of granitic pegmatites. Such deposits are economically important as resources for the rare metals lithium, tantalum, cesium, and rubidium. While complex-type pegmatites are found in many areas of the world, most are too small to be profitably mined, however, with an inferred resource in excess of 15 million metric tons (mt) (17 million short tons [st]), the Big Whopper is only the fourth deposit of its type in the world with the size required to be of major economic importance. The other three deposits, which are currently in production, are the Tanco mine in Manitoba, the Bikita mine in Zimbabwe, and the Greenbushes mine in Western Australia.

The Big Whopper is situated in the eastern continuation of the Archean Bird River greenstone belt which also hosts the Tanco pegmatite, approximately 60 km (37 miles) to the west. The principal commodities identified in the portions of the Big Whopper pegmatite explored to date are petalite (LiAlSi₄O₁₀) and rubidium-rich K-feldspar. These are industrial minerals with important applications in the glass and ceramics industries. The Big Whopper also contains substantial quantities of lepidolite, a lithium, rubidium-mica which is the principal ore mineral for rubidium metal. Tantalum and cesium occur in anomalous levels with the petalite mineralization, and the possibility of finding zones of high enrichment in these valuable high-tech metals elsewhere in the deposit is excellent. Such enriched zones are typical of pegmatites as highly evolved as the Big Whopper.

To date, the geological mapping and diamond drilling work completed by Avalon have delineated the Big Whopper pegmatite system over a strike length exceeding 1.5 km (0.9 miles), over widths ranging from 10 m to 80 m (30 feet to 260 feet) in thickness, and to a vertical depth of close to 300 m (1,000 feet), where it remains open. The pegmatite system consists of a vertically oriented massive petalite pegmatite dyke striking 280 degrees that is flanked by amphibolites containing a swarm of narrower albite and petalite dykes which have all undergone intense deformation in a high strain zone resulting in folding and intense shearing. The Big Whopper exhibits a mineralogical zonation pattern which is complicated by the superimposed deformation that has both folded and stretched the deposit.

Drilling has defined a dilute geological resource totaling 7.1 million mt (7.8 million st) grading 1.283 percent Li₂O, 0.346 percent Rb₂O, and .007 percent Ta₂O₅ over a strike length of 600 m (2,000 feet), and to a vertical depth of 250 m (820 feet), where it remains open. The petalite and rubidium-rich-K-feldspars contained in the Big Whopper all appear to be of superior quality. The grades are consistent with a petalite content averaging 25-30 percent and a rubidium-rich-K feldspar content averaging 15-20 percent. The remainder of the rock consists mainly of albite, several types of mica, and quartz. Accessory minerals include columbite-tantalite, cassiterite, apatite, garnet, and gahnite.

Market studies show that the deposit is located close enough to existing transportation infrastructure to access rapidly growing, major markets in the glass and ceramics industries, both in the northeastern U.S. and Europe. There are only three competing lithium minerals producers in the world with the Bikita mine in Zimbabwe being the only major producer of petalite. The other lithium deposits produce spodumene, a less desirable lithium mineral.

Lakefield Research Limited has successfully designed a process to produce an ultra-pure petalite concentrate containing up to 4.65 percent lithium oxide, and as little as 0.014 percent iron oxide, low levels of soda and potash, and negligible amounts of other trace elements. With these specifications, Avalon will have an excellent quality product for glassceramics applications such as Corningware®, CERAN® stove tops, and other thermal shock-resistant products. Lakefield is presently designing the balance of the flowsheet to produce separate concentrates of rubidium-rich K-feldspar, albite, mica, tantalum, tin, and high-purity quartz. Initial test work indicates that the feldspar products will be of exceptional quality. The K-feldspar concentrates contain 11-12 percent K₂O and 1 percent Rb₂O, while the sodaspar contains over 10 percent Na₂O, and both have very low iron $(0.01 \text{ percent Fe}_2O_3).$

A preliminary economic model shows that with an initial production rate of 90,000 mt (100,000 st) per year, expanding to 170,000 mt (190,000 st) per year over 5 years, the project is capable of generating over CDN \$10 million per year in pre-tax cash flow by year 5 on a capital cost of approximately CDN \$30 million.

PROJECT BACKGROUND

The Separation Rapids property, located approximately 60 km (37 miles) north of Kenora, Ontario, Canada (figure 1) is host to one of the largest rare metal pegmatite deposits in the world. This pegmatite was named the Big Whopper by its discoverer, Dr. Fred Breaks of the Ontario Geological Survey, because of the deposit's exceptional length and width of exposed surface. Following public disclosure of the discovery in July 1996, the property was staked by Kenora prospectors Robert Fairservice and James Willis. Avalon Ventures Limited optioned the property from the two prospectors in October 1996, and carried out a Canadian (CDN) \$1.5 million exploration program from May 1997 to August 1998, consisting of grid construction; ground magnetometer surveys; overburden stripping; detailed geological mapping; trenching; mineralogical studies; and two phases of diamond drilling totaling 8,751 m (28,712 feet) in 57 holes. This program was accompanied by scoping-level metallurgical and market studies to develop a flowsheet for processing the ore and to identify the size and value of the markets for the principal mineral commodities present in the deposit. This work led to the initiation of a prefeasibility study which was completed in June 1999, and subsequently updated in October 1999. Project expenditures to October 1999 total approximately CDN \$2.6 million.



Figure 1. Location map of Separation Rapids project, Ontario, Canada.

The Big Whopper is one of the complex-type (petalite sub-type) classes of rare metal pegmatites that are geochemically the most highly evolved in the spectrum of granitic pegmatites. Such deposits are economically important resources for the rare metals lithium, tantalum, cesium, and rubidium. While complex-type pegmatites are found in many areas of the world, most are too small to be profitably mined. With a resource of 13.8 million mt (15.2 million st), and open at depth, the Big Whopper is the fourth-largest deposit of its type, and only the second deposit to be enriched in the rare and valuable lithium mineral petalite. The other three lithium deposits currently in production are the Tanco mine in Manitoba, the Bikita mine in Zimbabwe, and the Greenbushes mine in Western Australia.

OWNERSHIP AND ACCESS

The Separation Rapids property consists of seven mineral claims, totaling 842 ha (2,080 acres), and is 100 percent owned by Avalon, subject to a 2 percent Net Smelter Royalty interest retained by the vendors, of which 1.0 percent can be re-purchased at any time for CDN \$1.0 million cash. To acquire its 100 percent interest, Avalon paid the vendors CDN \$100,000 in cash and 200,000 treasury shares over a four year period, while incurring exploration expenditures in excess of CDN \$600,000.

The property is readily accessible from a main, allweather road via a network of secondary logging roads. The main line of the Canadian National Railway passes through the village of Redditt, 25 miles (40 km) south of the property (figure 2).

INDUSTRIAL APPLICA-TIONS AND MARKETS

The rare metals which make up this deposit are regarded as "metals of the future" because of their numerous high-technology applications in the aerospace, electronic, computer, chemical, and ceramics industries. Demand for these metals continues to grow as new applications are developed. For example, tantalum is used to produce the small-size electronic capacitors required for laptop computers, cell-phones, and a host of other electronic products, and no other metal can match its performance in this application. Cesium has an important new application in the form of cesium formate, a specialty drilling fluid developed by U.S.-based multinational company, Cabot Corporation, (owner of the Tanco mine) for use in deep, high-pressure, hightemperature oil wells.



Figure 2. Regional geology and location map of Separation Rapids project in relation to the Canadian National Railroad (C.N.R), Canadian Pacific Railroad (C.P.R.), and nearby population centers.

The principal commodities identified by exploration to date in the Big Whopper pegmatite are petalite (LiAlSi_4O_{10}) and rubidium-rich K-feldspar. These are industrial minerals with important applications in the glass and ceramics industries. Petalite is a very rare lithium mineral, mainly used to make thermal shock-resistant glass-ceramic products, such as Corning's famous Corningware® cookware. Demand for lithium minerals in glass applications is increasing because of its recent introduction into the manufacture of container glass and fibreglass, where it provides significant technical and economic benefits. Petalite is also used in certain ceramics applications, such as glazes and clay bodies. In Asia, it is commonly used to produce thermal shock-resistant earthenware pottery and dinnerware.

The current world market for lithium minerals used in glass and ceramic manufacturing is approximately 150,000 mt (165,000 st), of which 30,000 to 35,000 mt (33,000 to 39,000 st) is petalite produced by Bikita Minerals in Zimbabwe. The balance, 115,000 to 120,000 mt (127,000 to 132,000 st), is mainly low-iron spodumene produced in Australia and Manitoba. Some glass and ceramics manufacturers also use a chemical form of lithium (lithium carbonate), but lithium minerals are generally preferred in this market due to the additional alumina and silica credits contained in the mineral product, all in a pre-mixed, iron-free form. Petalite is particularly desirable because of its very low iron con-

tent (a colorant in glass applications) compared to spodumene. Petalite also has a technical advantage in ceramics applications over spodumene, which has the undesirable property of expanding 30 percent in volume upon firing. The use of lithium in glass and ceramics applications continues to expand throughout the world because of the increased durability it imparts to the glass or ceramic product (particularly thermal-shock resistance).

The availability of a large, new, low-cost source of petalite in North America is expected to result in market growth for this mineral as North American manufacturers are introduced to this valuable, but little-known, mineral previously only commercially available from central Africa. Market studies show that the Big Whopper deposit is well situated in respect to transportation infrastructure to access major markets in the glass and ceramics industries, both in the northeastern United States and Europe. Furthermore, the deposit has the advantage of being located in a politically and economically stable jurisdiction that provides greater security of long-term supply than central Africa.

Rubidium-rich K-feldspar (potash feldspar) is also a premiere quality product for many ceramics and glass applications, including electrical porcelain for large electrical insulators, where rubidium greatly increases the insulating capacity. U.S. demand for potash feldspar in 1997 totaled approximately 58,000 mt (64,000 st), for use as a flux in ceramics manufacture, and also in certain specialty glasses where it inhibits warping of the product. Like petalite, rubidium-rich-K feldspar is not currently available in North America, so its potential market size is unknown. However, indications from earlier market research show that the contained rubidium will augment the effectiveness of the K-feldspar in all of its current ceramic and glass applications.

The Big Whopper also contains substantial quantities of lepidolite, a lithium-rubidium-mica, which is the principal mineral for rubidium metal. Tantalum and cesium occur in anomalous levels with the petalite mineralization, and the possibility of finding zones of high enrichment in these valuable high-technology metals elsewhere in the deposit is excellent. Such enriched zones are typical of pegmatites as highly evolved as the Big Whopper. Other potential mineral by-products include mica, sodium feldspar, garnet, tin, and quartz. Furthermore, the virtual absence of fracturing indicates that some parts of the deposit may also have potential as a source of decorative or ornamental stone if areas of attractive coloration can be identified.

GEOLOGY AND RESOURCES

As a result of geologic mapping and diamond drilling, the Big Whopper pegmatite system has been delineated over a strike length of more than 1.5 km (0.9 miles), over widths ranging from 10 to 80 m (30 to 260 feet) in thickness (figure 3), and to vertical depths of nearly 300 m (1,000 feet), where the resource remains open (figure 4). The pegmatite system consists of a vertically oriented, massive petalite pegmatite dyke striking 280 degrees, hosted by metamorphosed mafic volcanic rocks (amphibolite), and flanked by a swarm of narrower albite and petalite dykes (figure 4). The system has undergone intense deformation in a high strain zone, resulting in folding, shearing, and creation of boudinage structures (figure 5).

The drilling program defined a total petalite resource of 11.6 million mt (12.8 million st), grading 1.34 percent Li₂O and 0.30 percent Rb₂O over a strike length of 600 m (2,000 feet) and a vertical depth of 250 m (820 feet), where it remains open. These mineral grades are consistent with a petalite content averaging 25 ± 5 percent, and a rubidium-rich-K-feldspar (microcline) content averaging 10-15 percent. The remainder of the rock consists mainly of albite, lithium, muscovite, lepidolite, and quartz (table 1). Important accessory minerals include spodumene, spessartine, cassiterite, and columbite-tantalite (table 2).

The mineralized zone is well-exposed at the surface, in a low, dome-shaped hill, where it averages 55 m (180 feet) in width over a strike length of 300 m (1,000 foot), and is readily amenable to mining by low-cost, open-pit methods. A conceptual open-pit mine designed for the pre-feasibility study contains a probable reserve of 5.6 million mt (6.2 million st) grading 1.41 percent Li₂0, at a cut-off of 1.0 percent for an estimated petalite content of 1.2 million mt (1.3 million st).

METALLURGICAL AND ENVIRONMENTAL STUDIES

Lakefield Research Limited designed a new selective flotation process to produce an ultra-pure petalite concentrate grading 4.75 to 4.85 percent lithium oxide, with as little as 0.014 percent iron oxide, low levels of soda and potash, and negligible amounts of other trace elements. With these specifications, Avalon will have an excellent quality product for glass-ceramics applications such as Corningware®, CERAN®



Figure 3. Geology and rare metal mineral occurrences of the Separation Rapids property, Ontario, Canada.



Figure 4. Cross section 4+60W of Big Whopper pegmatite showing lithium and rubidium grades over measured intervals. Location of section line is shown in figure 5.



Figure 5. Geology of Big Whopper pegmatite and baseline grid showing location of section line 4+60W in figure 4.

Table 1. Big Whopper pegmatite essential minerals.				
Name	Formula	Relative Abundance		
Petalite	LiAlSi ₄ O ₁₀	20-35 %		
Microcline	(K,Rb)AlSi ₃ O ₈	10-15 %		
Albite	NaAlSi ₃ O ₈	25-30 %		
Quartz	SiO ₂	15-25 %		
Lepidolite	$(K,Rb)(Li,Al)_2(Al,Si)_4O_{10}(OH,F)_2$	0-15 %		
Lithium Muscovite	$K(Al,Li)_2(Al,Si)_4O_{10}(OH,F)_2$	5-10 %		

Table 2. Big Whopper pegmatite accessory minerals.			
Name	Formula	Relative Abundance	
Spodumene	LiAlSi ₂ O ₆	Very Common	
Spessartine	$(Mn,Fe)_3Al_2Si_3O_{12}$	Very Common	
Cassiterite	SnO2	Common	
Columbite-tantalite	(Mn,Fe)(Nb,Ta)2O6	Common	
Apatite	(Ca,Mn) ₅ (PO ₄) ₃ F	Rare	
Zircon	(Zr,Hf)SiO ₄	Rare	

stove tops, and other thermal shock-resistant ceramic products. The process flowsheet designed by Lakefield also provides for the recovery of separate concentrates of rubidiumrich K-feldspar, albite, spodumene, mica, tantalum, and tin. The rubidium-rich K feldspar concentrate is an excellent product, containing approximately 11.7 percent potash, 1.1 percent Rb₂O, and less than 0.03 percent Fe₂O₃.

Another important, positive attribute of the project is that the ore is environmentally benign, containing no toxic, radioactive, or acid-generating minerals. In fact, there will be relatively little waste material to dispose of, since most of the mineral constituents of the ore are marketable commodities. Avalon Ventures Limited has already completed an environmental baseline study in the project area, ensuring that local environmental sensitivities were identified at an early stage. The lack of hazardous materials in the deposit will help avoid delays in obtaining operating permits, as well as reducing the cost of tailings monitoring and disposal.

The company has also been proactive in establishing a dialogue with the First Nations of the area, and has recently signed a Memorandum of Understanding with the Wabaseemoong Independent Nations of Whitedog, Ontario to address their concerns regarding resource development in their traditional land use area and access to employment opportunities. Whitedog is located 35 km (22 miles) southwest of the project area and is the closest community.

ECONOMIC MODEL AND FUTURE PLANS

The pre-feasibility study, completed by independent engineering consultant Micon International Limited, in June 1999, and subsequently updated in October 1999, concluded that the project is economically viable and should proceed to a full feasibility study. In fact, the economic analysis prepared for the updated study showed the project to be highly profitable. Based on a production rate starting at 90,000 mt (100,000 st) per year, increasing to 170,000 mt (190,000 st) per year by year five, and remaining constant thereafter over a projected 20-year mine life; the project shows a Discounted Cash Flow Rate of Return of 39.5 percent, and a Net Present Value of CDN \$53.5 million (pre-tax) at an eight percent discount rate. This scenario assumes financing of capital costs, estimated at CDN \$29.8 million, on a 75/25 debt/equity ratio, and results in a payback period of just 3.2 years. Operating costs, including milling, administration, and mining of ore and waste average CDN \$51.63 per mt (\$46.85 per st), compared to an in-situ ore value of CDN \$150 per mt (\$165 per st). In this model, the mine would have an annual production of 17,000 to 32,000 mt (19,000 to 35,000 st) of high-quality petalite concentrates averaging 4.41 percent Li₂O, 6,000 to 12,000 mt (7,000 to 13,000 st) of rubidiumrich K-feldspar, 25,000 to 50,000 mt (28,000 to 55,000 st) of sodaspar at 10.1 percent soda, 3,000 to 5,000 mt (3,300 to 5,500 st) of spodumene at 5.0 percent Li₂O, at least 25,000 mt (28,000 st) of mica, and 10 mt (11 st) of tantalum concentrates.

Avalon Ventures Limited is planning to proceed with a full feasibility study in the year 2000 at an estimated cost of CDN \$5.0 million. This study will include a bulk-sampling program of 5,000 mt (6,000 st) of ore for processing in a pilot plant, and the subsequent production of bulk samples of concentrate for evaluation by potential end-users. A positive feasibility study could lead to plant construction and mine development in 2001, with initial production targeted for 2002. Avalon's long-term objective is to build on the success of the Big Whopper discovery by identifying and developing new rare-metal deposits and becoming a major supplier of strategic raw materials for the high-tech industries in the new millennium.

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JADE AND RHODONITE DEPOSITS, BRITISH COLUMBIA, CANADA

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ABSTRACT

Jade is a commercial term encompassing green, white, black or yellow-brown jadeitite and nephrite. Jadeitite consists of Na-rich pyroxene, whereas nephrite consists of prismatic to acicular amphiboles of the tremolite-actinolite series forming bundles that are randomly oriented and interlocked. Nephrite is tougher (harder to break) than jadeitite. Its fracture strength is about 200 MN/m² whereas that of jadeitite is about 100 MN/m2. On the other hand, jadeitite has a higher hardness (7 compared to 6.5 on the Mohs scale). There are over fifty known nephrite occurrences in British Columbia (B.C.). These occurrences consist of individual blocks, boulder fields, talus blocks and in situ occurrences. Most of the in situ occurrences are lens or cigar shaped. They occur at, or near the contact of ultramafic/mafic rocks (mainly serpentinites) with cherts, and other metasedimentary or igneous felsic rocks of Mississippian to Jurassic oceanic terranes such as Cache Creek and Slide Mountain. These contacts are commonly interpreted as shear/fault related. In general, it is believed that the B.C. nephrite formed by metasomatic exchange between ultramafic and silica-bearing rocks. Impurities in B.C. nephrite are spinel group minerals (chromite, magnetite, picolite), diopside, uvarovite, titanite, chlorite, and talc.

Jadeitite is slightly denser than nephrite and good quality material sinks in methyl iodine. There are no known jadeitite occurrences of economic interest in B.C., but there are at least four geographic areas where favorable lithologies, and metamorphic conditions (P/T) required for the formation of jadeitite coincide. These are Bridge River, Pinchi Lake, Dease Lake, and Jennings River. These areas are known to contain small concentrations of jadeite, or are characterized by blueschist or eclogite-grade metamorphic conditions.

Rhodonite and pyroxmangite are MnSiO₃ polymorphs. These minerals are pyroxenoids and are macroscopically and microscopically very similar. For brevity, both are grouped together under the term "rhodonite". Most of the B.C. occurrences are hosted by late Paleozoic chert sequences and are lens shaped and concordant. The common association of rhodonite with iron formations, jasperoids, and/or volcanogenic sulphide deposits in southwestern B.C. permits the delineation of favorable horizons using magnetic or electromagnetic geophysical methods. Geographic associations between manganese showings and sulphide deposits, and the hydrothermal chemical signature of the rhodonite occurrences from this area, suggest a genetic link between rhodonite and volcanogenic sulphide deposits.

The typical rhodonite rocks consist of rhodonite, pyroxmangite, neotocite, black amorphous Mn-oxides, Mn-bearing garnet, \pm epidote, \pm chlorite, \pm rhodochrosite, \pm parakutnah-orite, \pm Mn-bearing calcite, \pm iron oxides and hydroxides. Garnet \pm epidote forms yellow patches and layers within the rhodonite. Within some of the rhodonite occurrences, the garnet is altered to chlorite. Rhodonite-bearing rock is commonly cross cut by secondary manganese oxide veins, creating a characteristic web-like texture. In several localities, the contorted bedding planes are readily recognized. Mn-calcite and quartz also crosscut rhodonite. Rhodonite deposits hosted by high grade metamorphic rocks may contain pyroxmangite. Rhodonite is an important gemstone and ornamental stone in B.C., second only to nephrite in dollar value. B.C. nephrite and rhodonite have been used for the past 100 years in local jewelry and ornamental applications. More recently they have been used in table tops, and they have potential as upscale materials in tile-making. There may be a market for tiles made from lower grade materials that were previously extracted and stockpiled. The prices of nephrite, jadeitite, and rhodonite vary widely with quality, but gem and ornamental grade stones are relatively highly priced materials and they trade world-wide.

INTRODUCTION

Jade is a commercial term encompassing green, white, black or yellow-brown jadeite and nephrite materials of gem or ornamental quality. Jadeitite is a rock that consists essentially of jadeite, a sodium-rich pyroxene, however, this term does not imply gem or ornamental quality (Bates and Jackson, 1987). Nephrite consists of prismatic to acicular amphiboles of the tremolite-actinolite series forming bundles that are randomly oriented and interlocked. The density of British Columbia (B.C.) nephrite varies from 2.95 to 3.01 g/cm³ (Leaming, 1978a). Jadeite is slightly denser than nephrite and good quality jadeitite sinks in methyl iodine.

Nephrite is tougher (harder to break) than jadeite. Its fracture strength is about 200 MN/m^2 (29,000 lb/in²) whereas that of jadeite is about 100 MN/m^2 (14,500 lb/in²). On the other hand, jadeite has a higher hardness (7 compared to 6.5 for nephrite on the Mohs scale).

Nephrite and jadeite are used in jewellery as gemstones, and as carving and ornamental stones. The world market for jade, both nephrite and jadeitite, is estimated at 300 metric tons (mt) (330 short tons [st]) per year, and three quarters of this originate in B.C. (Scott, 1996). Nephrite accounts for all of the current B.C. production. The price of raw jade varies from less than \$CDN 10.00 to \$100.00 per kg (\$CDN 4.50 to \$45.00 per lb.) on retail scale, depending on the quality and size of the transaction. In general, jadeite commands a higher price than nephrite.

Rhodonite and pyroxmangite are MnSiO₃ polymorphs valued for their distinct pink color and hardness of 5.5 to 6.5. These minerals are pyroxenoids and are macroscopically and microscopically very similar. The density of rhodonite varies from 3.57 to 3.76 g/cm³ and that of pyroxmangite varies from 3.61 to 3.91 g/cm³. While rhodonite has been known in B.C. for at least a century, pyroxmangite was reported for the first time in 1995 (Simandl and Church, 1996). It is possible that several occurrences previously described as rhodonite also contain pyroxmangite. For brevity, both are grouped together under the term "rhodonite". Rhodonite was an important gemstone and ornamental stone in B.C., second only to nephrite until 1997, when its commercial production ceased.

NEPHRITE

Geologic Setting

In western North America, a broken belt of rocks favorable for jade exploration extends southward from Alaska through B.C. and California to Mexico (Leaming, 1995). In B.C., the nephrite occurs as individual blocks, boulder fields, talus blocks, and in situ occurrences. There are over 50 known nephrite deposits and occurrences in B.C. (figure 1). The in situ deposits occur at, or near, the contact of ultramafic/mafic rocks (mainly serpentinites) with cherts and other metasedimentary rocks, or rarely with igneous felsic rocks of Mississippian to Jurassic oceanic terranes, such as Cache Creek and Slide Mountain. There are at least 17 occurrences located in southern B.C. along the Coquihalla River, Fraser River, Hozameen and Bridge River areas, in Shulaps, and the Cadwallader Range.

Important commercial activity took place in central B.C. in the Mount Ogden area, where at least nine occurrences are located, and to a lesser extent, in the Mount Sidney Williams area. Cry Lake and Dease Lake areas, where 22 nephrite occurrences are reported, and the Cassiar mine are the most productive camps of northern B.C. Most of the nephrite occurrences are described by Learning (1978a). All of these, and some recently discovered occurrences are contained in "Minfile," a computerized database established and maintained by the British Columbia Geological Survey. This database is posted on the Internet and is available to the public at the following web address: http://www.em.gov.bc.ca/mining/geolsurv/minfile.



Figure 1. Location of the key nephrite camps in southern British Columbia (also referred to as "Lillooet area"), central British Columbia (also called "Omineca Segment" or Mount Ogden area, and northern British Columbia (Cassiar mine and Cry/Dease Lake area), Canada.

Figure 2 shows Dease Lake nephrite camp and illustrates the regional geological setting of B.C. nephrite occurrences. Near the Dease Lake camp, ancestral North America is geologically separated from the accreted terranes by the Kutcho fault. These terranes were brought to their present position by the subduction of an oceanic plate under the North American continent and subsequent margin-parallel movement. The nephrite occurrences are located mainly within the rocks of Cache Creek terrane, although at least one occurrence is located within the King Salmon allochthon. The Cache Creek terrane is a melange of Mississippian to Jurassic, oceanic, mafic to ultramafic, volcanic and intrusive rocks, shallow-water carbonates, cherts, and argillaceous sediments (Monger and others, 1991). The Thibert fault separates the Cache Creek terrane from the Quesnellia terrane. The Quesnellia terrane consists mainly of Paleozoic and Mesozoic, mafic to felsic, volcanic arc-related, plutonic and sedimentary rocks. Cache Creek terrane is also separated from the King Salmon allochthon by the Nahlin fault. The King Salmon allochthon consists of the Kutcho volcanic assemblage of limestones, marbles, siltstone, and argillaceous sediments (Monger and others, 1991). Most of the known, in situ occurrences are lens- and cigar-shaped or tabular.

The B.C. deposits occur mainly along the contacts of tectonic inclusions of country rocks, dikes, and mafic rock layers within serpentinites, or at the contact of serpentinite with the country rock, as described in other parts of the world by Coleman (1967). Tectonic contacts seem to predominate. Where nephrite is found in situ, it may be separated from the country rocks by a "white rock" or it may contain irregular zones of such rock.

Nephrite is a nearly monomineralic rock consisting of very fine and interlocked bundles of acicular tremolite crys-

tals, however, it commonly contains small concentrations of spinel group minerals (chromite, magnetite, picotite), diopside, chrome diopside, uvarovite, titanite, chlorite, and talc.

The term "white rock" has been used in different ways. In the literature, it is described as rodingite or calc-silicate rock containing hydrogarnet, diopside, wollastonite, and tremolite (Coleman, 1967 and Leaming, 1978a). In the field, B.C. prospectors also use this term to describe white-colored, post-nephrite selvages and alteration zones which are fabriccontrolled. Preliminary examination of the "white rock" samples adjacent to the Polar Jade deposit at Serpentine Lake, and the Mount Ogden deposits indicate that they consist mainly of quartz and euhedral crystals of epidote-group minerals. Such a rock may be referred to as epidosite. In at least one locality at Mount Ogden, "white rock" consists of up to 90 percent white hydro-garnet (it can be referred to as garnetite). It is possible that many of the previously described white zones are not typical rodingites.

The famous "N" zone located in the Kutcho area is shown on figure 3. This deposit was exploited systematically over a number of years by the Jade West Group of Companies. The excavation extends for 50 metres (160 feet) along the strike of the deposit. In 1997, the maximum thickness of the nephrite exposed was approximately 3 metres (10 feet). According to Tony Ritter of the Jade West Group of Companies, the nephrite zone followed the slope of the mountain (dipslope) and was mined to a depth of approximately 15 metres (50 feet) in the downdip direction. The company is currently evaluating a number of other nephrite occurrences that have the same geological setting and are located in close proximity to this deposit.

An unnamed deposit, shown in figure 4, is a typical example of a small, in situ occurrence. Other good examples illustrating the nephrite-country rock relationship, in typical



Figure 2. Typical regional geological setting of nephrite Kutcho deposits, Cry/Dease lake area, northern British Columbia (modified from Leaming, 1978b, and Thorstad and Gabrielse, 1986).


Figure 3. Renowned "N" zone of the Kutcho area, northern British Columbia, was one of the largest high-quality deposits in B.C. The deposit was exploited by Jade West Group of Companies.



Figure 4. New unnamed nephrite occurrence, Kutcho Creek area, showing a typical positive relief.

form and size of the deposits, are the Hell Creek and Jim Creek nephrite occurrences. These occurrences, associated with the Shulaps ultramafic body in the Bridge River area in southern B.C. are shown on figures 5 and 6 respectively. In many cases, the contacts between the nephrite and country rocks are shear/fault related, as illustrated by the cross section of the Hell Creek deposit (figure 5), where the nephrite-bearing zone was traced along intermittent outcrops for at least 900 metres (3,000 feet). However, most of the production came from a small area less than 15 metres (50 feet) in length, less than 3 metres (10 feet) wide, and less than 6 metres (20 feet) deep (Leaming, 1978a). A major nephrite body was mined within the chrysotile open pit of Cassiar Mining, Inc. This deposit is no longer accessible, however, some nephrite is still recovered from mine dumps.

Origin of Deposits

Learning (1978a) proposes several origins for nephrite deposits. Most of the B.C. nephrite occurrences formed by contact metasomatic exchange between serpentinized ultramafics and country rocks (commonly metasediments). There is a wealth of published data on the stability field of tremo-



Figure 5. Hell Creek nephrite deposit associated with the Shulaps ultramafic body, Bridge River area, southern British Columbia; vertical cross section from Learning (1978a).



Figure 6. Jim Creek nephrite deposit associated with the Shulaps ultramafic body, Bridge River area; plan view from Learning (1978a).

lite in marbles, and to lesser extent, in ultramafic rocks. Curves A and B on the generalized Pressure/Temperature (P/T) diagram (figure 7) delimit the common range of conditions where tremolite is reported. This range extends from low pressure, contact-metamorphic environments to the regional metamorphic trends commonly referred to as Barrovian and Buchan. The tremolite field is certainly reasonable for the geological situations where: (1) the fluids were internally buffered during metamorphism, (2) thermodynamic equilibrium was attained, and (3) common chemical compositions of the protolith exist. There are, however, some important differences between these conditions and those corresponding to the formation of B.C. nephrite.

The systems responsible for the formation of B.C. nephrite were probably externally buffered, because of the association between nephrite and faults. Relative spatial distribution of the serpentinite, rodingite, nephrite, and metasediments is typical of metasomatic reaction zones



Figure 7. Diagram showing the common pressure-temperature conditions needed for tremolite stability constrained by curves B and C, jadeite stability field (A), and three schematic metamorphic paths numbered 1, 2, and 3.

where thermodynamic equilibrium, at the scale of the deposit, was probably not attained in most cases. Furthermore, since good quality nephrite deposits are nearly monomineralic rock, tremolite should have remained stable at higher temperatures than shown.

Nephrite Prospecting

Nephrite and jade occur as alluvial, colluvial, and in situ deposits. Boulders found in active alluvial environments may have a smooth polished surface, but most are found along glaciofluvial terraces and eskers, or as semi-angular blocks in talus. Such blocks are characterized by a rough weathering skin that may be chamois, brown, gray, or white. This skin may be from few to tens of centimetres in thickness (figure 8), rendering the blocks difficult to identify by an untrained prospector. If a massive nephrite block is struck with a hammer, the blow leaves little or no mark and the hammer springs back with unexpected intensity.



Figure 8. White and colored skin well exposed on a freshly cut nephrite block; Jade West stockpile, Kutcho Lake area. Hammer handle is 60 centimeters (24 in.) in length.

Large nephrite blocks are commonly test drilled or sawed using circular saws. The saws range from small portable units to some that approach 2 metres (7 feet) in diameter and are moved with heavy machinery (figure 9). The prospector assesses the color, impurities, fracture density, and fabric (grain) of the nephrite. Learning (1978a) discusses nephrite grading in detail. Grading charts for lapidary purposes were produced by a number of organizations, including Jade N Gem Corporation (California). Because most of the easily accessible blocks located near existing roads have already been recovered, most current exploration takes place in isolated areas. Only promising blocks are recovered and moved to civilization. Specialized, all-terrain, heavy equipment or helicopters may be required for transportation (figure 10).

Most prospectors explore for in situ deposits. Such deposits are commonly located at or near serpentinitemetasediment contacts and are marked by the downslope accumulation of nephrite talus blocks. Individual talus blocks may weight more than 20 mt (22 st) or more. Nephrite blocks may also form fans along the direction of the glacial movement and alluvial blocks may be found downstream from the in situ deposits. Following nephrite block trains and fans up-slope is a valuable prospecting method. The most favourable geological settings for nephrite deposits are at, or near, the contacts between ultramafic rocks and metasediments. The presence of "white rock" (rodingite) is considered a favorable indicator in nephrite exploration.



Figure 9. Larger diameter diamond saw on the move, Kutcho Lake area.



Figure 10. Off-road heavy machinery commonly used to move large blocks.

Epidote or vesuvianite-bearing siliceous rocks are also known to occur adjacent to nephrite mineralization. Furthermore, nephrite is also known to occur in the same geological setting as talc and chrysotile deposits, as illustrated by Phillips and Hess (1936) for a number of foreign examples, and by the nephrite occurrences within the Cassiar chrysotile open pit.

Past Use And Potential For Future Development

Nephrite table tops from B.C. appear in many North American homes and offices. Most of the carving-grade nephrite is exported overseas for semi-mechanized carving, and a portion of it finds its way back to B.C. in the form of finished products. However, the highest quality nephrite is bought by local artists and transformed into pieces of art. The best known and largest sculpture made of B.C. nephrite is probably the Buddha which was commissioned for the Wat Dhammongkol Monastery in Bangkok, Thailand. The Buddha was carved from a 32 mt (35 st) nephrite boulder. This single transaction was worth about \$CDN 350,000 to the Jade West Group of Companies (Scott, 1996). A good discussion on jade work for the hobbyist is provided by Leedham (1999). Future prospecting and development of nephrite occurrences for lapidary purposes and carving will continue at the current or at an accelerated pace.

Long-running companies in the nephrite business, such as Jade West Group of Companies, have accumulated extensive stockpiles of lower grade material, that are not suitable for lapidary or ornamental purposes as by-products of their traditional high-quality nephrite mining. These stockpiles have potential as raw material for natural stone tile making. Although nephrite tiles are not likely to replace the main stream materials, such as granite and marble, they may represent an exotic upscale niche market.

JADEITE

Origin of Deposits

Like nephrite, jadeite deposits are expected to occur in close relationship with ultramafic rocks. However, they also occur in rocks subjected to ultra-high pressure and low temperature metamorphic conditions. Such rocks are called eclogites. In many parts of the world, eclogites are commonly associated with blueschist-grade rocks. The jadeite stability field is shown in figure 7, above curve A. There are three hypothetical metamorphic paths identified as 1, 2, and 3. Most rocks follow the common metamorphic path 1, and never reach the jadeite stability field. In other cases, where jadeite-bearing rocks are formed, they are subsequently destroyed during uplift by re-equilibrating at higher metamorphic temperatures and lower pressures (path 2). Only the rocks that follow path 3 reach the jadeite stability field, and do not pass through the high-temperature metamorphic environment during uplift, are likely to contain jadeite when they reach the surface again. A rapid uplift is therefore required for preservation and transportation of eclogite rocks into near surface-environments. Jadeite occurrences are therefore expected to be much less common than nephrite.

Potential Deposits

There are currently no known commercial occurrences of jadeite in B.C. In fact, there are less than 10 known areas in B.C. where blueschist-conditions were reached or exceeded. Four areas, where favorable P/T conditions for the formation of jadeite were reached and at least partially preserved during the exhumation process are: (1) Bridge River, (2) French Range, (3) Pinchi Lake, and (4) Jennings River (figure 1).

Paterson (1973) described the geology of the Pinchi Lake area and recognized rocks metamorphosed to blueschist facies. He also located a number of eclogite-grade boulders. The source of eclogite boulders remains enigmatic. Jadeitebearing outcrops and boulders in this area contain jadeite as a minor constituent and there are no known occurrences of gem or ornamental grade jadeite. A reconnaissance in this area demonstrated that both blueschist and eclogite lithologies might be effectively detected using heavy mineral exploration methodology described by Simandl and others (1998).

Blueschist-facies rocks were also described in the Bridge River area by Schiarizza and others (1997), and according to Neil B. Church, British Columbia Geological Survey, (verbal communication, 1999) there are additional blueschist occurrences. No eclogite-facies rocks were reported here. A number of nephrite occurrences were reported in the same general area, and it may be worthwhile to make sure that some of the nephrite boulders reported from this locality are not, in fact, jadeite. Sodium pyroxene-bearing, garnet-amphibolite outcrops were reported in the Jennings River area (Nelson, 1999). Geologic mapping of this area is in progress, but detailed metamorphic conditions have not yet been established. No composition data for the sodium pyroxenes and garnet were available at the time of this writing (late 1999). Petrographic examination indicates that both pyroxenes and garnets are strongly retrograded. In fact, pyroxene in most samples was transformed entirely into amphiboles. Blueschist facies rocks were also reported in the French Range area by Monger (1969) and by Mihalynuk and others (1999).

All the areas listed above would be worth exploring if sodium-bearing pyroxenes and other indicator minerals are encountered in outcrops, boulders, or in heavy mineral concentrates. Heavy mineral sampling is the most effective reconnaissance method to determine if an area contains lithologies and mineral assemblages within the jadeite stability field. The most favorable settings for jadeite in these areas are along contacts of ultramafic lithologies with country rock, or along tectonic blocks within ultramafic rocks. Where the area was not covered, at least, by regional mapping, a heavy minerals survey is the reconnaissance method of choice. Uvarovite and chromite indicate ultramafic lithologies. Blue, sodium-rich amphiboles such as glaucopyhane/ crossite, and sodium-rich pyroxenes such as jadeite/omphasite are considered heavy mineral indicators of favorable (blueschist/eclogite facies) metamorphic conditions. Heavy mineral prospecting methods in combination with boulder tracing and traditional prospecting methods, are recommended for jadeite deposits.

RHODONITE

Geologic Setting

The most recent overview on rhodonite occurrences in B.C. is given by Simandl and others (1998). Manganesebearing rocks occur in a wide variety of geological environments including skarns, veins, shale-hosted manganese horizons, and cherts associated with massive sulfides (Laznicka, 1985,1992). In some of the skarns and veins, rhodonite may be a primary mineral, in others it may be a product of contact or regional metamorphism of the manganese-bearing protolith. There are over 40 known rhodonite occurrences in British Columbia (figure 11). Most of these occurrences are concentrated in the Cowichan Lake area of southern Vancouver Island (Massey, 1995a, b, c), and in a well constrained area south of Penticton, in south-central British Columbia, near the United States border. Some of the key occurrences located outside of these two areas are Rose (Hancock, 1992), Hollings (located on Saltspring Island) (Cowley, 1979), Snowy Creek (Nelson and others, 1990), and Clearcut (Simandl and Church, 1996). Most of these occurrences are hosted by late Paleozoic chert sequences and are lens-shaped and concordant. Geologic data is available via the Internet at http://www.em.gov.bc.ca/mining/geolsurv/minfile.

Mineralogy of Rhodonite Deposits

Typical rhodonite rocks consist of rhodonite, neotocite, black amorphous manganese oxides, manganese-bearing garnet, ±epidote, ±chlorite, ±rhodochrosite, ±parakutnahorite, ±manganese-bearing calcite, ±iron oxides, and hydroxides (Danner, 1976, and Simandl and others, 1998). Garnet ±epidote forms yellow patches and layers within the rhodonite. Within some rhodonite occurrences, the garnet is altered to chlorite. Rhodonite-bearing rock is commonly cross cut by secondary manganese oxide veins, creating a characteristic web-like texture. In several localities, the contorted bedding planes are readily recognized. Manganese calcite and quartz also crosscut rhodonite. Rhodonite deposits may also contain pyroxmangite (Simandl and Church, 1996). A cross section of the Clearcut rhodonite prospect is shown in figure 12. It is a typical occurrence, although it is located in higher-grade metamorphic rocks than other B.C. rhodonite deposits. The Clearcut prospect is known to contain both pyroxmangite and rhodonite.

Rhodonite Exploration Methods

The common association of rhodonite with iron formations, jasperoids, and/or volcanogenic sulfide deposits in



Figure 11. Geographic distribution of rhodonite occurrences in British Columbia, Canada.



Figure 12. Schematic cross section of the Clearcut rhodonite deposit (from Simandl and Church, 1996). For location see figure 11.

southwestern B.C. permits the delineation of favorable horizons using magnetic or electromagnetic geophysical methods. Geographic associations between manganese showings and sulfide deposits, and the hydrothermal chemical signature of the rhodonite occurrences from southwestern B.C., suggest a genetic link between rhodonite and volcanogenic sulphide deposits (Simandl and others, 1998). Rhodonite deposits occur mostly in clusters. Fresh, high-grade rhodonite rocks are extremely tough, although rhodonite weathers to form soft, pitch black manganese oxides. Several of the occurrences in the Cowichan Lake area, where weathering was deep, were considered a potential source of manganese ore (Sargent, 1956). On Vancouver Island, the country rocks have high magnetic susceptibility and can be located using geophysical methods. Rhodonite boulders that commonly occur downslope, downstream, or down ice from the rhodonite occurrences are characterized by black, manganese oxide staining, the same as rhodonite-bearing outcrops. It is possible that some rhodonite occurrences may represent the distal equivalent of volcanogenic massive sulphide deposits. Rhodonite and pyroxmangite and manganese-rich garnet are also heavy minerals, and stream sediment sampling as described above may be an effective exploration tool.

SUMMARY

British Columbia is renowned for its nephrite production, and value-added processing is becoming well established. Value-added work involves mainly carving and jewelry, but in the future may extend into tile making. There are currently no known occurrences of jadeite-bearing rocks of economic interest. However, as regional mapping of the province continues, more areas affected by high-pressure metamorphism that are favorable for jadeite exploration will be identified. The rhodonite deposits of B.C. are well known and value-adding parallels that described for nephrite, however, the market is more competitive, and there has been no commercial production of rhodonite since 1997.

ACKNOWLEDGMENTS

The authors thank Jade West Group of Companies for providing access to their properties and other logistical support. We would also like to thank Kirk Makepeace, president of the company, and Tony Ritter, who managed the exploration campaign for Jade West in 1997, for sharing their experience and hands-on approach. Thanks also to Barney Kovacs from Cassiar Mining, Inc. for the permission to visit the Cassiar Chrysotile operation in northern B.C., and prospectors such as Dave Jaworsky and Ron Walton who kept us abreast of new rhodonite discoveries. Richard Franklin from Pacific Geoscience Center drafted most of the figures. This paper was reviewed and improved by comments from D.V. Lefebure of the British Columbia Geological Survey and Kirk Makepeace from Jade West Group of Companies.

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THE MINING OF INDUSTRIAL MINERALS IN CHILE -AN OVERVIEW

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ABSTRACT

A brief overview of industrial mineral exploration and exploitation in Chile is given. World class deposits of salt, lithium, nitrate, and iodine are present in northern Chile. The potential for further exploration and exploitation of these deposits, as well as the substantial reserves of other mineral commodities such as gypsum, anhydrite, volcanic rocks, and borates are discussed. In conclusion, industrial minerals mining in Chile has considerable potential, particularly as joint ventures between foreign and domestic companies. This has been demonstrated in the extraction of nitrates, lithium, iodine, and diatomites. However, as outlined in this paper, a number of factors need to be overcome before the true potential of the Chilean industrial minerals industry can be realized.

INTRODUCTION AND BRIEF HISTORICAL REVIEW

The history and economic development of Chile has been strongly influenced by mining. From the beginning of its modern history, the economy of Chile has been based on its mineral resources, particularly the world-class reserves of copper, molybdenum, lithium, and iodine.

It is not widely appreciated that the Chilean mining industry initially developed as a result of the extraction of "non metallic" or industrial minerals. Chilean mining history started with the exploitation and export of natural nitrates and their associated commercial product "salitre" (saltpeter). Until 1914, Chile was the world's largest producer of this product, used for fertilizer and gun powder, when "synthetic nitrate" was developed in Germany. Chile was also the second-largest producer of boron for a short time at the beginning of the 20th century, through the exploitation of ulexite from the salt flats in the high Andes. Boron production largely ceased, however, when exploitation of boron deposits in the USA, Turkey, and Argentina commenced. These borate deposits had big advantages in terms of grade, reserve size, and more efficient extraction methods. In turn, the nitrate industry, which thrived during a continental war, decreased in importance and almost disappeared in 1930, with the onset of world economic depression.

Since the 1930s, the importance of industrial minerals in Chile has steadily declined, with only minor increases associated with exploration for barite and volcanic sulphur in the 1980s. In contrast, the importance of metals has increased during the last 70 years, with the exploitation of widely distributed, low-grade, porphyry copper deposits, and more recently with important discoveries of precious- and basemetal deposits.

CURRENT INDUSTRIAL MINERAL ACTIVITY

The mining of industrial minerals is concentrated in northern Chile. The main products include brines and evaporites; Chile is the world's leading producer of lithium, iodine, and natural nitrates, and has substantial reserves of salt, gypsum, and anhydrite. The domestic demand for calcium carbonate is being met through current operations, and some products, such as borates and boric acid, may be marketed internationally. Starting in August 1999, boric acid will be produced as a by-product of lithium brine extraction from the Salar de Atacama plant located in the central part of the Salar, approximately 180 km (112 mi) east of Antofagasta. It is not known what impact this will have on Chilean industrial mineral exports.

Current investment in Chilean industrial minerals is roughly 8 to 10 percent of that in the metallic sector. Industrial mineral exports are about US \$400 million, with imports of about US \$200 million. The value of exports has grown significantly in the last ten years, but this does not necessarily indicate expansion of the industrial minerals sector, rather that the demand and market price for some specific products (iodine and lithium) has increased.

The Corporación Chilena del Cobre (COCHILCO, 1997, 1999) is the institution responsible for the collection of statistics on Chilean industrial minerals production. Industrial mineral products are divided into four groups based on their market significance.

Group 1 Mineral Commodities

Group One includes mineral commodities whose reserve size and geological characteristics give them a competitive advantage in world markets. These commodities (and their manufactured products) are derived almost exclusively from brines, evaporites, and other saline deposits and include: borates (ulexite; the principal Chilean boron-bearing mineral, boric acid, and refined borax); iodine (iodine, iodates, and iodides); lithium carbonate; potassium; "salitre" (potassium nitrate, sodium nitrate, and potassium salitre); and sodium chloride.

The exploitation of "salitre" and iodine from nitrate deposits is dominated by four companies: (1) Sociedad Química y Minera de Chile (SOQUIMICH), (2) DSM Minera S.A., (3) Compañia de Salitres y Yodo de Chile (COSAY-ACH), and (4) Potash Corporation of Saskatchewan Yumbes (a Canadian company that bought the Yolanda company from KAP Resources, another Canadian company). In 1998, nitrate production reached 661,000 metric tons (mt) (728,000 short tons [st]), with 90,000 mt (99,000 st) of sodium sulphate, as a by-product of nitrate extraction, together with approximately 10,000 mt (11,000 st) of iodine.

Lithium and potassium are produced by Sociedad Chilena del Litio, owned by German investors (Metal Gesellschaft) and SOQUIMICH. Borates are produced by SOQUIMICH and several other small companies. Potassium chloride production in 1998 was approximately 500,000 mt (550,000 st), ulexite - 280,000 mt (300,000 st); potassium sulphate - 89,000 mt (98,000 st); lithium carbonate -28,000 mt (31,000 st); and lithium chloride - 4,000 mt (4,400 st). Figure 1 shows a typical ulexite mine in the Ascotan salt flat in northern Chile.

Salt is produced by Salinas de Punta de Lobos (figure 2) who own what is possibly the largest and highest quality salt deposit in the world; a salt flat and underlying basin 40 km (25 mi) long, with an average width of 4 km (2.5 mi), and an average depth of 100 m (300 ft). The basin is filled with pure halite (over 99 percent NaCl). Mining operations are located 22 km (14 mi) from the coast, and the company operates its own harbor and ships for transportation. Between 1994 and 1998, Salinas de Punta de Lobos produced about 4.4 million mt (4.8 million st) of salt annually for export primarily to the USA, Canada, and Brazil.

Group Two Mineral Commodities

Group Two includes mineral commodities that are relatively abundant in Chile and have "favorable" geological characteristics. These commodities and their manufactured products have a low unit price, high production volumes, and are mainly used in the construction and ceramics industry. These include: calcium carbonate (limestone used for the production of cement and lime), cement, clays, gypsum (for use in the cement industry), iron oxides, lime, and pyrophyllite. The average annual production of minerals and related products for this group from 1994 through 1998 is as follows:

calcium carbonate - 6.0 million mt (6.6 million st) (maximum production of 6.3 million mt [6.9 million st] in 1994),
cement - 3,000 mt (3,300 st),
clays - 19,200 mt (21,100 st),
gypsum - 543,000 mt (597,000 st),
iron oxides - 60,000 mt (66,000 st),
lime - (estimated) 1.2 million mt (1.3 million st), and
pyrophyllite - 2,000 mt (2,200 st).

Production on a company by company basis is not available, but in the case of calcium carbonate and gypsum, most of the production is associated with the cement manufacturers.

Group Three Mineral Commodities

Group Three includes of a number of mineral commodities and rocks that are relatively abundant throughout Chile. These minerals have "average" geological characteristics and are exploited at low levels. The demand for these products is variable within domestic markets, where they compete with imported materials. Some are of sufficient quality to be exported, but most are of very low quality, even for domestic markets. The group includes: abrasives (pumice and garnets), aluminium sulphate, barite, bentonite (Na and Ca), calcium carbonate (chalk, precipitated and granular), "cimmite", diatomite, feldspar, kaolin, perlite, phosphates (superphosphates, ammonium phosphates, phosphatic rocks, and guano), building and decorative stone (marble and granite), siliceous rocks (silica, quartz, and siliceous sands), sodium sulphate, sulphur (crude and sublimated), talc, and wollastonite. Production data is not available for this group.



Figure 1. Ulexite removal in the Ascotan salt flat in northern Chile (latitude 21°29' south, longitude 68°19' west). Salar de Ascotan is one of the larger boron deposits in Chile.



Figure 2. General view of the Loberas salt mine. This is one of several mines of Compañia Mineral Salinas de Punta de Lobos. The mine is in the Salar Grande basin in northern Chile, 80 km (50 mi) south of Iquique and 20 km (12 mi) from the coast (70° west, between 20°45' and 21°45' south). The Salar Grande basin is 40 km (25 mi) long and 4 km (2.5 mi) wide, and contains a massive body of nearly pure halite 100 m (300 ft) thick.

Group Four Mineral Commodities

Group Four consists of mineral commodities which, in general, are not present in Chile and are consequently imported. These commodities include: aluminium oxides, andalusite, asbestos, chromite, fluorite, magnesium, mica, natural graphite, and sodium carbonate.

THE FUTURE OF INDUSTRIAL MINERALS IN CHILE

Industrial mineral production for 2001, according to COCHILCO (1999), is projected to be:

13,000 mt (14,000 st)
1,570,000 mt (1,730,000 st)
260,000 mt (290,000 st)
685,000 mt (754,000 st)
34,000 mt (37,000 st)
46,000 mt (51,000 st)

The industrial minerals industry in Chile can be considered to be underdeveloped. There is considerable exploration potential for industrial minerals, not only in new areas of northern Chile, but also in and adjacent to the large deposits that are currently being exploited (such as those in the Salar de Atacama and the Salar Grande). Potential also exists in the central and southern parts of Chile.

Opportunities for investment are present for large, medium, and emerging national and international companies, either through joint ventures or by direct participation. This is illustrated by the presence of Celite (a U.S.-based company) which has operations in the northernmost part of Chile to explore and exploit diatomites. Another example is the anticipated exploitation of nitrate/iodine deposits by PCS Yumbes in the Second Region of Antofagasta in the near future.

Joint ventures could make use of the technical expertise and experience of international companies, particularly in the extraction of low-grade minerals, and/or provide access to world markets. In return, companies benefit from the quality of Chilean deposits, the excellent mining infrastructure, and very favorable legal regulations for foreign investors.

During the last 30 years, following discovery of the lithium/potassium deposits in the Salar de Atacama, the perception in Chile is that industrial minerals represent the future of mining, and that the country has some of the most important industrial mineral resources in the world. One of these perceptions is incorrect! Industrial minerals are not the future for Chile, they are the present; and Chile must ensure that it is not left behind.

In Chile, knowledge of industrial minerals has improved considerably in recent years, particularly through the efforts of the Servicio Nacional de Geología y Minería de Chile (for example Gajardo, 1998), the Corporación de Fomento de la Producción (1995), and research projects carried out at the Universidad Católica del Norte (Chong, 1994, 1996). This body of knowledge notwithstanding, there are a number of factors that must be overcome in order to achieve significant improvements in the industrial mineral sector. These factors include:

- a limited knowledge of the international marketing of products, with the exception of companies such as SOQUIMICH and Salinas de Punta de Lobos;
- (2) the low level of industrial development in Chile and its neighboring countries, and the subsequent low demand for industrial minerals;
- (3) the lack of regional integration (particularly in the Andean region) in the production of different industrial minerals, which could result in an increase in the added value of products;
- (4) the non-treatment of ores prior to export;
- (5) the absence of applied technology and scientific research that has resulted in a lack of knowledge concerning some deposits and ores. This has produced gaps between exploration, exploitation, and processing techniques, and has inhibited the generation of new products, by-products, and co-products;
- (6) the perpetuation of old information concerning deposits, such as the inclusion of some deposits as potentially attractive mining targets even when they are proven to be non-economic;
- (7) the low profile of the industrial minerals sector within specialized teaching institutions; and
- (8) the lack of a strong relationship between the producer and consumer.

Other factors that limit the development of the industrial minerals sector are the geographical position of Chile in relation to international markets and the lack of investment.

CONCLUSIONS

The potential for exploration and exploitation of industrial minerals in Chile is huge, however, a number of factors must be overcome before Chile's industrial minerals industry can realize its full potential. In the last 10 years, several Chilean and foreign companies have invested in Chile's industrial minerals sector, but the rate of development is slow considering that Chile is the world's largest supplier of iodine and lithium. The Andean Macrozone, an area that includes southern Peru, northern Chile, northwest Argentina, and southwest Brazil, is an important regional market for Chile's industrial minerals. Northern Chile also has the potential of becoming an important source of phosphates for use in the manufacture of fertilizers.

ACKNOWLEDGMENTS

This report comprises part of Research Project 1970030, supported by the Fondo Nacional de Investigación Científica y Tecnológica de Chile (FONDECYT). The report was also supported by the Comisión Nacional de Ciencia y Tecnológia de Chile (CONICYT) - British Council research link SAN/ 984/82.

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GEOLOGY AND DISTRIBUTION OF CLAY DEPOSITS FOR BUILDING BRICKS AND ROOFING TILES IN CHILE

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ABSTRACT

Clays for building bricks and roofing tiles in Chile are classified as common clays and ball clays, with deposits of sedimentary and residual origin, both Cenozoic in age.

Deposits are known from north to south, through 11 of the 13 Chilean Administrative Regions, 18° to 39° South latitude, and from west to east, through three of Chile's main geomorphic features, namely the Coastal Plains, Coastal Range, and Intermediate Depression.

Alluvial and lacustrine sedimentary common clay deposits are located in the northern and southern Intermediate Depression. The average chemical composition of clay deposits in I and II Regions, is 58 percent SiO₂, 16 percent Al₂O₃, and 4 percent Fe₂O₃ by weight; the primary minerals are sericite, quartz, feldspar, and albite. The average chemical composition of clays in Metropolitan, VI, and VIII Regions, is 52 percent SiO₂, 16 percent Al₂O₃, and 6 percent Fe₂O₃ by weight; the primary minerals are montmorillonite, quartz, and plagioclase.

Residual common clay deposits occur in the Intermediate Depression and in the Coastal Range internal basins, VII, VIII, and IX Regions, and they represent surficial alteration of pumice beds and crystalline rocks. The average chemical composition of clay deposits derived from crystalline rocks is 58 percent SiO₂, 17 percent Al₂O₃, and 9 percent Fe₂O₃ by weight; the primary minerals are sericite, quartz, and clinochlore. Clay deposits formed from pumice beds contain 47 percent SiO₂, 24 percent Al₂O₃, and 10 percent Fe₂O₃ by weight; the primary minerals are kaolinite, feldspar, and cristobalite.

Sedimentary ball clay deposits are located in the Coastal Plains and Coastal Range, VI, VII, VIII, and IX Regions, between 34° and 39° South latitude. The average chemical composition of the ball clay deposits is 51 percent SiO₂, 28 percent Al₂O₃, 5 percent Fe₂O₃ by weight; the primary minerals are kaolinite, quartz, and sericite (illite?).

These clay deposits supply the Chilean building sector with over one million metric tons (mt) (1.1 million short tons [st]) of material per year. The average growth rate of clay consumption during the period 1993 through 1997 was 10 percent annually. The clays are used by both mechanized plants and handcraft facilities.

INTRODUCTION

The production of clays for building bricks and roofing tiles in Chile has increased to more than one million mt (1.1 million st) per year (Gajardo, 1998). This is primarily due to the average growth rate of the building sector of more than 10 percent annually from 1993 to 1997. Consequently, mechanized brick plants and handcraft facilities have consumed more common clays and ball clays to meet the increased demand.

The center of brick and roofing tile production and consumption in Chile is between latitudes 33° and 42° South in the Metropolitan to X Administrative Regions (figure 1). The population within this area is approximately 11.4 million people, representing 76.8 percent of Chile's population; the density is about 172 inhabitants per square mile (66 inhabitants per km²) (INE, 1998).

Because of the large increase in the demand for domestic industrial minerals, primarily in the building sector, several different research projects have been carried out by the Chilean Geological and Mining Survey (Servicio Nacional de Geología y Minería, SERNAGEOMIN), under the author's coordination. Several unpublished reports have been written on industrial minerals located within 11 of Chile's 13 Administrative Regions. These reports contain new geological, technological, and marketing information regarding common clays and ball clays for building products.

This paper is based on the geological and marketing data obtained from these research projects, as well as previous research programs in the I, III, VI, VII, VIII, IX, and Metropolitan Regions, which were carried out from 1973 to 1998 (Hauser, 1973; Pimentel, 1973; Gajardo, 1974; Marti, 1974; Gajardo and Gutiérrez, 1992; Gajardo and Gutiérrez, 1993; Gajardo and Carrasco, 1997; Gajardo and others, 1997; and Gajardo, 1998).

GENERAL GEOLOGICAL AND GEOMORPHIC SETTING

Common clays and ball clays used in the manufacture of building brick and roofing tile in Chile are from Cenozoic deposits of sedimentary and residual origin (Gajardo, 1991; Gajardo, 1994; Gajardo and Carrasco, 1997). These deposits are located within the geomorphic areas in Chile, known from west to east as the Coastal Plains, Coastal Range, Intermediate Depression, Pre-Andean Range, and Andean Range (Fuenzalida, 1965; Börgel, 1983). The most important clay deposits are located in the Coastal Plains, Coastal Range, and Intermediate Depression areas (figure 1).

Coastal Plains Area

The Coastal Plains are small areas, not wider than 30 km (19 mi), located between the Pacific Ocean and the Coastal Range, with a maximum elevation of 240 m (790 ft) above sea level (figure 1). The plains correspond to Cenozoic forearc basins filled with sedimentary clastic, biogenic, and evaporitic sequences which lie unconformably over Paleozoic to Cenozoic, plutonic, metamorphic, and sedimentary rocks (SERNAGEOMIN, 1982).

The Coastal Plains in II to IV Regions (figure 1) are filled mainly with clastic, biogenic, and evaporitic sequences containing diatomites, phosphorites, limestones, and gypsum deposits (Salas and others, 1966; Ferraris and Di Biase, 1978; Moscoso and others, 1982; Rojo, 1985). No ball clays and few suitable common clays for red ceramics have been found in these sequences. Ball clays are absent because of a lack of surficial alteration processes over the plutonic or metamorphic parent rocks for kaolinite and illite generation. Suitable common clays are rare due to contamination by common salt, carbonate, and sulphate.

The Coastal Plains in V to IX Regions (figure 1) are filled with a Cenozoic clastic sequence, known as the Navidad Formation (Cecioni, 1978), which contains quartz sand and ball clay deposits. Ball clays originated during the Early Miocene (Gajardo, 1994) as a result of the surficial alteration of a Paleozoic igneous-metamorphic assemblage (González-Bonorino, 1970) which occurs in the Coastal Range from the V to X Regions. The ball clays were subsequently deposited in a lacustrine environment. The ball clay deposits are part of a 15- to 20-m (50 to 70 ft) thick clastic sequence which outcrops in the Coastal Plains and Coastal Range (Gajardo, 1991; Gajardo, 1994). These deposits contain the most important clays of this type in Chile. Ball clay layers are 1.5to 7-m (5 to 23 ft) thick, and are interbedded with sandstone and siltstone. The average chemical composition is 51 percent SiO₂, 28 percent Al₂O₃, and 5 percent Fe₂O₃ by weight; the primary minerals are kaolinite, quartz, and sericite (illite?) (Gajardo, 1998).

Coastal Range Area

The Coastal Range is a positive feature located in Chile's coastal area, and extends mainly from I to X Regions (figure 1). The range is 3,200 km (2,000 mi) long with a maximum elevation of approximately 2,500 m (8,200 ft) above sea level (Fuenzalida, 1965; Börgel, 1983). The Coastal Range is composed of several different type of rocks. Plutonic, volcanic, and volcano-clastic Mesozoic rocks are found in northern to south-central Chile, I to VII Regions, while igneous and metamorphic Paleozoic rocks are found in VIII through X Regions (SERNAGEOMIN, 1982).

In the VI and VII Regions, Cenozoic sedimentary

sequences hosting ball clay deposits are located only along the western slope of the range. In the VIII and IX Regions, where the Coastal Range is composed of crystalline rocks, sedimentary ball clay deposits exist on both sides of the range.

General geological characteristics, such as layer thickness, host rocks, morphology, and mineralogical and chemical composition of Coastal Range ball clay deposits are similar to the ball clay deposits in Coastal Plain area.

Intermediate Depression Area

The Intermediate Depression is a tectonic basin situated between the Coastal Range and the Andean Range, and is divided into the Northern Intermediate Depression and Southern Intermediate Depression (Fuenzalida, 1965; Börgel, 1983) (figure 1). The Northern Intermediate Depression extends from I to III Regions. This area contains the Atamaca Desert, one of the most arid areas in the world, where unique nitrate and iodine deposits occur (Ericksen, 1981; Chong, 1984). The northern depression is filled with sedimentary sequences of alluvial (clays and sandstones), biogenic (limestones and diatomites), evaporitic (common salt, sodium sulphate), and chemical (iodine and nitrates) origin, accumulated from the Late Oligocene when the basin first developed by normal faulting (Mortimer and Saric, 1975).

Alluvial sequences are the main sources of common clay deposits in I Region. The northernmost deposit in I Region is a 10- to 15-m (30 to 50 ft) thick layer of clay, interbedded with sandstone and pumice (Salas and others, 1966). The average chemical composition of this clay deposit is 52 percent SiO₂, 15 percent Al₂O₃ and 5 percent Fe₂O₃ by weight; the primary minerals are montmorillonite, quartz, and albite. The southern deposits, of alluvial origin, are represented by 0.5- to 2-m (2 to 7 ft) thick clay layers interbeded with sandstone (Pimentel, 1973). The average chemical composition of these clay deposits is 62 percent SiO₂, 16 percent Al₂O₃ and 4 percent Fe₂O₃ by weight; the primary minerals are quartz, plagioclase, and K-feldspar (Gajardo and others, 1997).

The Southern Intermediate Depression, known as Central Valley, is a tectonic basin developed through normal faulting beginning in the Early Miocene (Padilla, 1981; Godoy, 1986). The depression extends from the Metropolitan to X Regions, ending in the Ancud Gulf (figure 1). The depression is filled with alluvial and lacustrine deposits in its northern part, Metropolitan and VI Regions (Valenzuela, 1978), and mainly with volcanic, laharic, and glacial deposits in its southern part, from VII to X Regions (Marangunic and others, 1979; Varela and Moreno, 1982; Moreno and Varela, 1982).

Lacustrine sequences in the Metropolitan and VI Regions, with thicknesses up to 400 m (1,300 ft) in the Metropolitan Region (Valenzuela, 1978), are the source of common clays which occur in 1- to 2.5-m (3 to 8 ft) thick layers, covered by a 0.2- to 0.5-m (0.7 to 1.6 ft) thick topsoil. The average chemical composition of the clay deposits in the Metropolitan Region is 52 percent SiO₂, 16 percent Al₂O₃, and 7 percent Fe₂O₃ by weight; the primary minerals are montmorillonite, quartz, and plagioclase (Gajardo, 1998).

Residual common clay deposits are located in VII, VIII, and IX Regions, and are the result of surficial alteration of



Figure 1. General geological and geomorphic map of Chile.

both pumice deposits that outcrop in the Central Valley, VII and IX Regions, and Paleozoic granitic rocks located in internal basins of the Coastal Range in the VII Region (Hauser, 1973; Marti, 1974; Gajardo and Carrasco, 1997).

Residual common clays formed by the alteration of pumice layers are part of a soil profile of high fertility, approximately 2- to 5-m (7 to 16 ft) thick, locally known as "trumaos". The average chemical composition of these clay deposits is 47 percent SiO₂, 24 percent Al₂O₃, and 10 percent Fe₂O₃, by weight; the primary minerals in VII Region are clinochlore, quartz, and pyrophyllite (Gajardo and Carrasco, 1997). Residual clays formed by the surficial alteration of granitic rocks, known as "maicillo," outcrop in 1- to 2-m (3 to 7 ft) thick, irregular bodies with little or no cover. The average chemical composition of these clay deposits is 58 percent SiO₂, 17 percent Al₂O₃, and 9 percent Fe₂O₃ by weight; the primary minerals are quartz, clinochlore, and amphibole (Gajardo and Carrasco, 1997).

Pre-Andean and Andean Range Areas

No economic clay deposits, either for white or red ceramics, have been found in the Pre-Andean and Andean Range areas in Chile.

GEOLOGY AND DISTRIBUTION OF CLAY DEPOSITS

Based on the above general geological and geomorphic information, and the location of the most important markets for building materials in Chile, the most important clay deposits will be described. This description is based on an informal subdivision of the country into the Northern area, containing the I, II, and III Regions (figure 2); the Central area, containing the IV, V, Metropolitan, and VI Regions (figure 3); and the South-Central area, containing the VII, VIII, IX, and X Regions (figure 4).

Northern Area

The Northern area contains the I, II, and III Regions with an estimated population of approximately 1.1 million people, 7.4 percent of the Chilean population. The population is located mainly in four cities, Arica and Iquique in I Region, Antofagasta in II Region, and Copiapó in III Region (INE, 1998) (figure 2).

In I Region, common clays are produced from an alluvial deposit known as Casas Grandes to supply building brick manufacturers in Arica (figure 2). The Casas Grandes deposit is a 10- to 15-m (30 to 50 ft) thick layer in the Concordia Formation (Salas and others, 1966) (table 1), and is the only deposit currently exploited for use in Arica (Gajardo and others, 1997). Clay consumption is approximately 15,000 to 20,000 mt (16,000 to 22,000 st) per year, and brick production is nearly 4 million bricks per year. The deposit contains a large reserve and can easily supply current and future demand in this area.

Brick production in II Region is supplied from alluvial common clay deposits located 20 km (12 mi) from the city of

Antofagasta (figure 2). Because all of the products are handmade, no figures for clay reserves, clay consumption, or brick output are available.

Brick consumption in III Region is supplied by production from the Central-South area. The most well known deposit in III Region, Don Máximo (figure 2), is part of a Cenozoic lacustrine sequence 20- to 25-m (65 to 80 ft) thick, located west of Copiapó (table 1). This deposit is still undeveloped, although it has been studied since 1974 (Gajardo, 1974). Cement blocks, rather than clay bricks, are mainly used for construction purposes in this region.

Central Area

The Central area contains the IV, V, Metropolitan, and VI Regions with an estimated population of 8.8 million people located mainly in four cities, La Serena in IV Region, Valparaíso in V Region, Santiago in Metropolitan Region, and Rancagua in VI Region. The population of the Central area represents 59 percent of the total Chilean population (INE, 1998) (figure 3).

Clays from alluvial deposits known as Cerámicas Santiago, Cerámicas Batuco, Cerámicas Chilenas, and PRINCE-SA supply the building brick manufacturers in Santiago, the capital city and the main building products market in the country (Gajardo, 1998) (table 2). These deposits of 1- to 2.5-m (3 to 8 ft) thick clay layers are part of a lacustrine sequence, up to 400 m (1,300 ft) thick, composed of sandstone, clays, and pumice, that fill the northern part of the Intermediate Depression in the Metropolitan Region (Valenzuela, 1978). Clay consumption is approximately 0.5 million mt (0.6 million st) per year, and highly mechanized brick production from the Metropolitan Region is approximately 20 million bricks per year. Based on available geological information, these deposits can supply the current and future demand for building clay in this area.

There is no brick production in the IV, V, and VI Regions, and brick consumption in these regions is supplied by production from the Metropolitan Region, which also includes floor and roofing tiles. Approximately 10 to 15 percent of these three regions' requirements is supplied by handmade brick production, consisting of clay, sand, and straw. The San Ramón deposit of alluvial-lacustrine origin in VI Region, is still a prospect although it has been studied since 1981 (Gajardo, 1981).

South-Central Area

The South-Central area contains VII, VIII, IX, and X Regions, with an estimated population of 4.7 million people, 32 percent of the Chilean population. The population is located mainly in Talca in VII Region, Concepción in VIII Region, Temuco in IX Region, and Puerto Montt in X Region (INE, 1998) (figure 4).

Sedimentary and residual deposits supply clays for building brick manufacture in VII Region, north and southwest of Talca (Gajardo and Carrasco, 1997). Brick production is handmade and no production figures are available. The main market for VII Region brick production is Santiago in Metropolitan Region.

A 2- to 3-m (7 to 10 ft) thick, stratiform deposit north of



Figure 2. Distribution of primary common clay deposits in the Northern area.

Table 1. Geological and analytical characteristics of the Casas Grandes, Pozo Almonte, Quebrada de Pasos, and Don Máximo common clay deposits.							
Characteristics	Casas Grandes	Pozo Almonte	Quebrada de Pasos	Don Máximo			
Distance to market	10 km E of Arica	2 km E of Iquique	74 km SE of Iquique	40 km W of Copiapó			
Origin	Sedimentary, Alluvial	Sedimentary, Alluvial	Sedimentary, Alluvial	Sedimentary, Lacustrine			
Morphology	Stratiform	Stratiform	Stratiform	Stratiform			
Thickness (m)	10 - 15	1 - 2	0.5 - 1	15 - 18			
Chemical Composition (by weight)	$\begin{array}{l} 52.04\% {\rm SiO}_2 \\ 14.66\% {\rm Al}_2 {\rm O}_3 \\ 5.03\% {\rm Fe}_2 {\rm O}_3 \end{array}$	62.2% SiO ₂ 16.20% Al ₂ O ₃ 3.81% Fe ₂ O ₃	61.53% SiO ₂ 16.1% Al ₂ O ₃ 4.28% Fe ₂ O ₃	52.64% SiO ₂ 16.33% Al ₂ O ₃ 6.30% Fe ₂ O ₃			
Mineralogical Composition	Montmorillonite Quartz Calcite Albite Kaolinite	Sericite Quartz Albite Kaolinite Gypsum	Sericite Quartz K Feldspar Plagioclase Biotite	_			
Activity	Exploitation	Prospect	Prospect	Prospect			

Source: Gajardo, 1974; Gajardo and others, 1997.

Table 2. Geological and analytical characteristics of the Cerámicas Santiago, Cerámicas Batuco, Cerámicas Chilenas, and PRINCESA common clay deposits.							
Characteristics	Cerámicas Santiago	Cerámicas Batuco	Cerámicas Chilenas	PRINCESA			
Distance to market	24 km N of Santiago	23 km N of Santiago	16 km NW of Santiago	13 km N of Santiago			
Origin	Sedimentary,	Sedimentary, Lacustrine	Sedimentary, Lacustrine	Sedimentary, Lacustrine Lacustrine			
Morphology	Stratiform	Stratiform	Stratiform	Stratiform			
Thickness (m)	1 - 2	1.5 - 2.5	1 - 2	1 - 2.5			
Chemical Composition (by weight)	52.09 % SiO ₂ 16.11% Al ₂ O ₃ 7.04 % Fe ₂ O ₃	53.76 % SiO ₂ 16.17 % Al ₂ O ₃ 7.12 % Fe ₂ O ₃	49.46 % SiO ₂ 16.71 % Al ₂ O ₃ 8.20 % Fe ₂ O ₃	52.10 % SiO ₂ 16.30 % Al ₂ O ₃ 7.40 % Fe ₂ O ₃			
Mineralogical Composition	Quartz Plagioclase Gypsum Calcite	Montmorillonite Quartz Plagioclase	Montmorillonite Quartz Plagioclase Gypsum	Montmorillonite Quartz Plagioclase Clinochlore			
Activity	Exploitation	Exploitation	Exploitation	Exploitation			

Source: Gajardo (1998).



Figure 3. Distribution of primary common clay deposits in the Central area.



Figure 4. Distribution of primary common clay deposits in the South-Central area.

Characteristics	San Rafael	Cauquenes	San Miguel
Distance to market	6-10 km N of Talca	140 km SW of Talca	160 km SW of Talca
Origin	Residual	Residual	Sedimentary, Lacustrin
Morphology	Stratiform	Irregular	Stratiform
Thickness (m)	2 – 3	1 – 2	1.5 – 2
Chemical Composition (by weight)	46.78% SiO ₂ 24.92% Al ₂ O ₃ 8.37% Fe ₂ O ₃	58.28% SiO ₂ 16.53% Al ₂ O ₃ 9.22% Fe ₂ O ₃	55.11% SiO ₂ 26.45% Al ₂ O ₃ 4.82% Fe ₂ O ₃
Mineralogical Composition	Not available	Sericite Quartz Clinochlore Amphibole Hematite	Kaolinite Quartz Sericite
Activity	Exploitation	Exploitation	Exploitation

Source: Marti (1974); Gajardo and Carrasco (1997).

Table 4.

Geological and analytical characteristics of the Despensa and Tambillos ball clay deposits, and the Metrenco and Loncoche common clay deposits.

Characteristics	Despensa	Tambillos	Metrenco	Loncoche
Distance to market	105 km SE of Concepción	108 km SE of Concepción	6 km S of Temuco	90 km S of Temuco
Origin	Sedimentary, Lacustrine	Sedimentary, Lacustrine	Residual	Residual
Morphology	Stratiform	Stratiform	Stratiform	Stratiform
Thickness (m)	5 – 7	4 – 5	3.8 - 5	2.5 – 3
Chemical	50.01% SiO ₂	48.63% SiO ₂	48.46% SiO ₂	46.69% SiO ₂
Composition	32.21% Al ₂ O ₃	25.43% Al ₂ Õ ₃	25.27% Al ₂ Õ ₃	22.87% Al ₂ Õ ₃
(by weight)	2.34% Fe ₂ O ₃	9.45% Fe ₂ O ₃	11.67% Fe ₂ O ₃	10.56% Fe ₂ O ₃
Mineralogical	Kaolinite	Kaolinite	Kaolinite	Kaolinite
Composition	Quartz	Quartz	Cristobalite	Feldspar
*	Sericite	Sericite	Quartz	Quartz
Activity	Exploitation	Exploitation	Exploitation	Prospect

Source: Hauser (1973); Gajardo and Gutierrez (1993); Gajardo (1998).

Talca, known as San Rafael (table 3), was formed by the surficial alteration of pumice beds during the Cenozoic (Marti, 1974). The Cauquenes deposit southwest of Talca was formed by residual processes on granites and metamorphic rocks of Paleozoic age during the Cenozoic (table 3). San Miguel is a sedimentary ball clay deposit of lacustrine origin, 1.5- to 2-m (5 to 7 ft) thick, with a clastic overburden 5 to 6 m (16 to 20 ft) thick (Gajardo and Carrasco, 1997). Sedimentary ball clay deposits supply building brick manufacturers in the VIII Region and the northern part of IX Region (figure 4). The brick industry in this area requires approximately 0.2 million mt (0.22 million st) per year of ball clays for bricks and floor and roofing tiles to supply Santiago, Concepción, and other regional cities. The Despensa and Tambillos ball clay deposits (table 4) of lacustrine origin are the most important in VIII Region (Gajardo and Gutierrez, 1993), and the Gerardo Naour is the most important deposit in IX Region. Established reserves from these deposits and from surrounding areas can easily supply a growing local market.

Clays from the residual deposits in the southern part of IX Region, such as Metrenco and Loncoche (table 4), were formed by the surficial alteration of pumice beds during Cenozoic times (Hauser, 1973). These clay deposits supply the building brick requirements of the Temuco area, whose consumption is approximately 0.15 mt (0.2 million st) per year. These deposits are well known and exploited for both mechanized and handcraft operations in this area (Gajardo, 1998); reserves are adequate for any foreseeable increase in the demand.

CONCLUSIONS

Common clays and ball clays used for building bricks and roofing tiles, with deposits of sedimentary and residual origin, both Cenozoic in age, are widely distributed in three of the four main geomorphic areas of Chile; Coastal Plains, Coastal Range, and Intermediate Depression. From I Region in the north to IX Region in the south, the most important clay sources are in the southern Coastal Plains, the southern Coastal Range, and the southern Intermediate Depression.

The southern Coastal Plains and the southern Coastal Range, from VI Region to the south, contain the most important sedimentary ball clay deposits in Chile. These deposits originated through the surficial alteration of Paleozoic igneous and metamorphic rocks during Early Miocene, and in the subsequent sedimentation of the residual clays in a lacustrine environment. Ball clay layers are 1.5- to 7-m (5 to 23 ft) thick, interbedded in sandstone and siltstone, with an average composition of 51 percent SiO₂, 28 percent Al₂O₃, and 5 percent Fe₂O₃ by weight; the primary minerals are kaolinite, quartz, and sericite.

The southern Intermediate Depression, also known as Central Valley, contains lacustrine common clay deposits in its northern part, Metropolitan to VI Region, and residual common clay deposits in its southern part, VII to IX Regions. Lacustrine deposits in VII Region are 1- to 2.5- m (3 to 8 ft) thick, with an average composition of 52 percent SiO₂, 16 percent Al₂O₃, and 7 percent Fe₂O₃ by weight; consisting of montmorillonite, quartz, and plagioclase. Residual common clays formed by the alteration of pumice deposits are 2 to 5 m (7 to 16 ft) thick with an average composition of 47 percent SiO₂, 24 percent Al₂O₃, and 10 percent Fe₂O₃ by weight; the primary minerals are clinochlore, quartz, and pyrophyllite.

An informal subdivision of the country according to geological, geomorphic, and market information into a Northern, Central, and South-Central area, shows that the most populous area is the Central area, comprising IV to VI Regions, with 8.8 million people, or 59 percent of Chilean population. The largest brick manufacturers in this area supply the requirements of Santiago, the capital city, in Metropolitan Region, and principal cities in IV, V, and VI Regions with a total of approximately 20 million bricks per year from lacustrine common clay deposits.

The second-most important area is the South-Central, with an estimated population of 4.7 million people, 32 percent of the Chilean population. The main source of clay for brick production comes from residual common clay deposits, in VII and IX Regions, and from sedimentary ball clay deposits in VIII Region, which mainly supply the Central and South-Central area's requirements. Mechanized brick production from deposits in IX Region requires approximately 0.15 million mt (0.16 million st) per year of residual clays, to supply Temuco and southern South-Central area requirements. Mechanized brick production in VIII Region requires approximately 0.2 million mt (0.22 million st) per year of ball clays to supply Concepcion and other cities of the South-Central area and the Metropolitan Region.

Based on the quality and quantity of reserves, and the distribution of deposits, the future demand for both common clays and ball clays can easily be supplied by known deposits. This is especially valid in the Central and South-Central areas where significant growth of the building industry is anticipated.

ACKNOWLEDGMENTS

The author highly appreciates the manuscript revision by Dr. Waldo Vivallo and Dr. Arturo Hauser, of the Chilean Geological and Mining Survey.

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THE COEXISTENCE OF NAHCOLITE-TRONA IN CENTRAL ANATOLIA-TURKEY

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ABSTRACT

Two rare evaporite minerals, nahcolite (NaHCO₃) and trona (Na₂CO₃•NaHCO₃•2H₂O), are both widely used in the production of sodium carbonate (Na₂CO₃). The largest natural carbonate deposits (trona) are in Wyoming, USA, the second largest deposits are in Turkey, in a lacustrine basin (Beypazari) where nahcolite and trona are located within the Miocene Hirka Formation. The Hirka Formation is mainly composed of bituminous shale, claystone, marlstone, tuff/tuffite, and dolomitic limestones. Although numerous trona beds are interbedded within the above mentioned sedimentary units, there are only two beds of trona that are of economic interest. The lower part of the lower trona bed is rich in double carbonates such as pirrsonite (NA2CO3• CaCO₃•2H₂O) and gaylussite (Na₂CO₃•CaCO₃•5H₂O), indicating a change in Ca/Na ratio in the solutions which are responsible for the formation of soda occurrences. In contrast, the upper part of the upper trona bed is rich in nahcolite. This minerological pattern has been found in every drillhole in the basin.

While both trona beds average up to 10 m (33 ft) thick, the average thickness of nahcolite is approximately 0.5 m (1.6 ft). Also, thin section studies show that many fibrous and lath-like trona crystals contain small radial nahcolite crystals; all of them are euhedral and equi-dimensional. Geochemical studies of major, minor, and trace element contents also support this coexistence. Macroscopic and microscopic observations reveal that the nahcolites principally were formed as a result of an incongruent dissolution process of trona.

In conclusion, the presence of nahcolite in the Beypazari basin is due to the dissolution process of trona, particularly during the last stage of evaporation, as a result of fresh water entering the basin. During that time, an increase in the HCO_3/CO_3 ratio resulted in nahcolite-trona phase transitions.

INTRODUCTION

Nahcolite and trona are rare minerals. Nahcolite has been found in primary inclusions in apatite crystals (Aspen, 1980), in organic-rich sediments (Reitsema, 1980), in volcanic environments (Keys, 1979), and in the Neogene Beypazari basin, Turkey (Suner, 1991 a, b) (figure 1). In the Beypazari deposits, nahcolite has formed with trona and other sodium and calcium carbonate-bicarbonates. Nahcolite has been deposited generally in nodular forms in clayey and dolomitic matrixes (Suner, 1989a; Reitsema, 1980). The most distinctive property of nahcolite, which has very similar macro-and microscopic features to those of trona, is the twinning structure (figure 2). This structure is easily observed in thin sections (Suner, 1989b).

The formation and precipitation of trona and nahcolite depend largely on temperature, as well as on the sodium, carbonate, and bicarbonate contents of brines. Trona and nahcolite can be deposited directly from brines, or as a secondary mineral as a result of transformation from other sodium carbonates. This paper discusses the process and physicochemical principles of the coexistence of trona – nahcolite based on the investigations of the Beypazari deposits (Suner 1989 a, b; 1991 a, b; 1992; 1994a; 1997).

REGIONAL GEOLOGY

The Beypazari basin is economically important because of the presence of industrial minerals. The minerals found within the Neogene volcano-sedimentary sequence are divided in two groups, one of which includes the second-largest natural sodium carbonate (trona) deposit in the world, while the other group consists of rare evaporite minerals that have accumulated within the same sequences in very small deposits (Suner, 1989a; 1993; 1994a).

Nahcolite and other rare evaporite minerals, such as thermonatrite, pirrsonite, and shortite, have been found interlayered within sequences of tuffs, tuffites, marlstones, claystones, and bituminous shale (figure 1). The rocks within the Beypazari basin are divided as follows: (a) a metamorphic basement; (b) a granodioritic intrusion; (c) Jurassic to Cretaceous carbonate rocks; (d) Cretaceous flysch and limestones; (e) Mesozoic ophiolitic rocks; (f) Eocene to Paleocene clastic sedimentary rocks; (g) Neogene volcanics; (h) Miocene lacustrine rocks; and (i) clastic sedimentary rocks

System	Period	Epoch	Formation	Thickn. (m)	LITHOLOGIC SUCCESSION	LITHOLOGIC DESCRIPTION
			Kara Doruk (M3)	40 - 80		claystone dolomites
T	N	Midd.				Claystone Bitum Shale
E	E	/ Upper	Hirka	250		Tuffite Marl
R	0	M I	(M2)	350	<u> </u>	Bitum.Shale Nahcolite
Т	G E	O C E				Trona Zone Claystone Tuffite
I	N	N E				Trona Zone Pirrsonite Gavlussite
A	E		Çoraklı	100		Tuffite Coal
R			(M1)			Claystone Conglomerate
Y	PA LE OG	EO CE NE		100 / 150		Volcanic bearing limestone
	ENE					Conglomerate
~_					<u> </u>	
			[b •••	
				Beypazari		المسس

Ankara

Figure 1. Location map and geologic columnar section of the Beypazari basin, Turkey (Suner, 1989a).



Study Area

Figure 2. Microscopic view of nahcolite (nh) and trona (tr), x 20 (Suner, 1994b).

Upper System

С

Ε

N

Ε

Ζ

0

I

С

(Suner, 1993). The Miocene sequence consists of six conformable units that range in thickness from 60 to 350 m (200 to 1,200 ft). Nahcolite was found in the upper part of the upper trona horizon within the Hirka Formation. Because of the progressive tectonism during the Miocene, all of the units have been subjected to extensional and compressional regimes; therefore, these accumulations are composed of many thin horizons or lenses. Obviously, tectonism affected the evaporite deposits resulting in their dissolution and redeposition. This process resulted in the modification of the volcano-sedimentary sequences, and the creation of mixed trona–nahcolite deposits.

FORMATION CONDITIONS OF TRONA AND NAHCOLITE

The mode of formation of trona and nahcolite can be deduced by understanding the geologic and physicochemical parameters at the time of deposition.

Geologic Conditions

In Turkey, trona and nahcolite formed in fault-related, closed lacustrine basins. These types of lacustrine basins often host other minerals such as pirssonite, gaylussite, halite, analcime, magnesite, and smectite-group minerals (Bradley and Eugster, 1969; Eugster, 1979; Suner, 1989a). In general, thin lenticular and nodular accumulations of the Beypazari basin evaporite minerals were deposited in alternating sequences of shales, claystones, volcanics, and limestones. Volcanic activity is an important depositional parameter because it contributes the necessary ions. In the Beypazari basin, nahcolite has been observed in the uppermost part of the trona strata, similar to its occurrence in the large Wyoming (USA) deposits.

Physicochemical Conditions

Nahcolite deposition depends largely on physicochemical factors. The main parameters are the activities of CO_2 , Na, H₂O, HCO₃, and temperature. These parameters can be illustrated on three- and four-component phase diagrams that are useful in understanding the formation paths of salt deposits (Eugster, 1979; Suner, 1992, 1997).

Coexistance of Trona and Nahcolite

Primary nahcolite is deposited from solutions containing Na and HCO_3 in appropriate proportions, or secondarily by alteration of trona (precipitated in an earlier stage), as a result of contact with solutions with increased HCO_3 activity. This second mode of formation is termed nahcolitization. Nahcolite found in the Beypazari deposits is mainly observed with trona, and more rarely in the form of separate and nodular accumulations, which were formed through nahcolitization.

Nahcolitization can be explained by the following reaction mechanisms:

$$CO_2 + H_2O + Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$$
 (trona)
 \rightarrow 3NaHCO₃ + 2H₂O (nahcolite)

In this process, CO_2 contributes to the production of HCO_3 as follows:

$$CO_2 + H_2O + CO_3 \longrightarrow 2HCO_3$$
$$CO_2 + H_2O \longrightarrow H + HCO_3$$

As a result of the above reactions, the amount of HCO_3 in the solution increases and alters trona to nahcolite. In this process, the most remarkable point is the incongruent dissolution of trona, which is the main reason for trona - nahcolite coexistence in evaporite basins. The assemblage of trona, nahcolite, and natron has been studied and some crystallization paths are plotted in figure 3. Three possible paths of sodium carbonate paragenesis are shown, based on observed stratigraphic relationships of nahcolites in the Beypazari deposits. The proposed origin of coexistant trona and nahcolite is shown in figure 4.



Figure 3. Nahcolite-natron- H_2O ternary diagram (Bradley and Eugster, 1969), nh: nahcolite, Tr: trona, and nt: natron.



Figure 4. The proposed physicochemical parameters (T, carbonate coefficient, and water activity) (Suner, 1989b).

During these various formation steps, nahcolitization is largely dependent on the first crystallization point. In other words, the composition of the solutions from which the first nahcolite formation is observed, is important (figure 3). In this system, Y is a physicochemical triple point where trona and nahcolite crystallization exists. At this point, trona and nahcolite crystals are in equilibrium with the solution, and the composition of the system is 21.84 percent nahcolite, 44.82 percent natron, and 33.34 percent H₂O. Further crystallization is blocked unless all the crystallized nahcolite is converted to trona. This allows the system to continue developing trona crystals and decreasing in H₂O content.

During evaporation in the first equation, trona and nahcolite cannot crystallize from the same solution at the same time. Either trona or nahcolite may crystallize as long as evaporation continues. In some cases, as a result of a high concentration of NaHCO₃, the composition of the solution cannot reach the Y point and trona cannot form. In the second process, an influx of sedimentary materials into the basin interrupts the crystallization of sodium carbonates. An increase of H₂O in the system accompanies the influx of sedimentary materials resulting in a higher activity of H₂O, that shifts the composition of the system from point Y to the higher point X. This process creates favorable conditions for the conversion of trona to nahcolite.

In my opinion, nahcolite formed by the second process in the Beypazari basin. This conclusion is supported by petrographical data, chemical analyses, and geochemical observations. Nahcolite is found in the upper parts of trona seams, and mostly together with trona instead of as separate nodular deposits or individual seams. Nahcolite in nodular form only occurs in the uppermost part of the seam. The observed petrographical and geochemical similarities between trona and nahcolite are shown in figures 2 and 5, and in table 1. The elementary contents of both trona and nahcolite are compared to evaluate the probable similarities of their formation conditions. These minerals show radial, acicular, and rosette crystal structures depending on the formation period. Their colors are always white or whitish gray. Furthermore, their trace element contents are similar, and they exhibit wellcrystallized forms, making it difficult to distinguish the two minerals.



Figure 5. Trace element relations in trona and nahcolite. S: standard deviation, r: regression value, ppm: parts per million.

Table 1.The average major and trace element contents (ppm) in nahcolite and trona (Suner, 1989; 1991; 1992).								
Major elements	Al	Mg	Ca	K	Sr	Cs	B	
Trona Nahcolite	266 118	7859 7410	1172 1110	19 23	214 198	631 576	18 9	
Trace elements	Rb	Fe	F	Ti	Ba	As	Li	
Trona Nahcolite	11 16	65 61	4875 3075	3	575 538	284 180	3 5	

It is noteworthy that nahcolite cannot form under atmospheric conditions; only trona, natron, and thermonatrite, depending on the temperature, can form under the effect of atmospheric CO₂, (300-400 ppm), as shown in figure 6. The necessary CO₂ content in solution for the formation of nahcolite is more than 1,700 ppm. This concentration level requires the presence of very high amounts of CO₂ within the basin, probably from several different sources. Most of the CO₂ was likely provided by rivers at the closing of the Neogene period of Beypazari basin deposition. As illustrated in figure 4, the increase of CO₂ in solution results in an increase of the bicarbonate ratio (HCO₃/HCO₃+CO₃). The higher CO₂ composition of the solution favors the formation of nah-



Figure 6. Trona (tr) - nahcolite (nh) - natron (nt) - thermonatrite (tm) stability as a function of temperature and CO_2 content (Bradley and Eugster, 1969).

colite. Nahcolite crystallization requires an increase in temperature or trona, as a more stable phase, will crystallize instead of nahcolite (figure 4). On the other hand, most rivers and other meteoric sources of fluids lower the solution temperature. Therefore, in the formation of nahcolite, the temperature and CO_2 content of the solution are inversely related. For this reason, nahcolitization is the most likely way for nahcolite to form. In other words, nahcolite occurrences are mainly the result of the nahcolitization process, which starts as a result of a sudden increase in the HCO₃ content of the solutions under the effects of the sedimentary burial processes.

Because of the entrance of volcano-sedimentary material into the Beypazari basin at the end of the evaporation period, favorable conditions were created for trona-nahcolite conversion. Under these geologic conditions, the solutions circulating in the buried sediments caused the conversion of trona to nahcolite to begin. Therefore, this conversion mechanism began after fresh waters and sedimentary materials covered the trona beds. Pore solutions in contact with organic material were also partly responsible for the nahcolization because of the presence of these conditions, along with bacterial fermentation, produce ¹³C-rich carbon dioxide which favors the formation of nahcolite rather than trona (Reitsema, 1980). Trona-nahcolite coexistence can be observed in pore solutions. The increase in HCO₃ content of pore solutions results in the dissolution of trona and the crystallization of nahcolite in the buried trona beds. The last trona beds deposited in the Beypazari basin were mostly converted to nahcolite, although, in some cases, the HCO₃ content of the solution, was not high enough to permit the total conversion, as shown in figure 2.

CONCLUSIONS

Nahcolite and trona are two rare minerals, and their deposition is largely dependent on physicochemical conditions. Trona–nahcolite coexistence is a result of the incongruent dissolution of the trona. A decrease in temperature and an increase in HCO_3 and H_2O content in the solution favors nahcolite formation. The solutions within the buried sediments are largely responsible for the incongruent process and consequently the coexistence. An active tectonic regime creates more favorable conditions for nahcolite-trona coexistance. Under atmospheric conditions, with trona being the most stable sodium-carbonate phase, nahcolite crystallization is very limited.

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STATISTICAL ANALYSIS OF SAND AND GRAVEL AGGREGATE DEPOSITS OF LATE PLEISTOCENE LAKE BONNEVILLE, UTAH

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ABSTRACT

Sedimentary deposits of pluvial Lake Bonneville are an important source of sand and gravel suitable for aggregate and construction in Utah. Data on Lake Bonneville basin sand and gravel deposit thickness, volume, grain size, percent of fines, and durability were statistically analyzed to detect variations associated with geologic domains, geographic location, Lake Bonneville shorelines, and sand and gravel deposit type, and to construct quantitative deposit models. Analysis showed several trends; (1) sand and gravel in younger shorelines was slightly more durable and the deposits considerably larger in volume, (2) younger shorelines are also more likely to contain more than one genetic deposit type, (3) the volume of terrace deposits is larger than beach deposits, (4) terraces and beaches are generally thicker than spits and bars, (5) the northern part of the Bonneville Basin contains slightly more durable sand and gravel than the southern part of the basin and is more likely to contain deposits composed of more than one genetic deposit type, and (6) the Wasatch domain deposits are composed of more than one genetic deposit type more often than deposits of the Basin and Range domain.

Three additional conclusions with immediate economic significance are; (1) the median sand and gravel deposit in the Wasatch domain, $360,000 \text{ m}^3$ (275,000 yd³), is three times larger than that of the Basin and Range domain (120,000 m³ [90,000 yd³]), (2) the median deposit thickness in the Wasatch domain, 5.8 m (19.0 ft), is nearly twice that of the Basin and Range domain (3 m [10 ft]), and (3) the Wasatch domain also contains slightly larger diameter gravel. These three conclusions are significant because the trend for sand and gravel development in the Bonneville Basin is to move from the Wasatch domain to the Basin and Range domain. Smaller, thinner deposits with smaller diameter gravel will require more surface area to mine than would have been necessary in the Wasatch domain. The result is a higher cost for sand and gravel in construction projects in the Salt Lake City area, especially since the gravel must also be hauled farther.

INTRODUCTION

Sand and gravel, along with crushed stone, are natural aggregate, a fundamental ingredient in the construction of buildings and roads. Aggregate processing is commonly lim-

ited to crushing, washing, and sizing (Langer, 1998). How much sand and gravel is likely to be needed at any given time in a region is dependent on several factors. Demand increases for sand and gravel in response to new real estate and infrastructure development. However, the sprawl of urban areas into rural and undeveloped areas prevents future development of sand and gravel deposits because housing and infrastructure developments cover the resource. People often resist the development of new aggregate production pits and quarries, particularly those near populated areas. Aggregate sources may also be eliminated due to stricter specifications on the type and characteristics of aggregate that can be used. Stricter specifications are set by governments to insure better performing, safer, and longer lasting roads and other structures. Most of these factors increase the likelihood that future aggregate production sites will be located greater distances from where the materials will be used. Because much of the cost of aggregate is in its transportation, this will make aggregate more expensive in the future.

Most of the sand and gravel produced in Utah comes from deposits of Lake Bonneville, a large, late Pleistocene lake that, at its maximum, extended from central Utah into Idaho and Nevada (figure 1). Some of the largest Lake Bonneville sand and gravel deposits are located in Salt Lake County, which has been in an extended building boom (Bryce Tripp, Utah Geological Survey, written communication, 1999). Isaacson (this volume) reported that rapid economic growth in Salt Lake County, which includes Salt Lake City (figure 1), will likely displace local sand and gravel production (including production from Lake Bonneville sediments) to deposits outside the county. The population in Salt Lake County is projected to increase by 54 percent over the next 20 years (and at even higher rates in the surrounding counties). Real estate development, spurred by the strong economy, is rapidly expanding into areas outside of established cities and towns. Future sand and gravel development will likely be located in the Basin and Range domain west of the urbanized Wasatch domain corridor (figure 1). Basin and Range production still will be largely from Lake Bonneville deposits. Are sand and gravel in these deposits comparable to those located in the Wasatch domain?

Both graphical and statistical tools were used to analyze data on Lake Bonneville sand and gravel deposits. Geotechnical characteristics studied included deposit thickness, deposit volume, percent of sand and gravel greater than 2.54 cm (1.0 in) in maximum diameter, percent of fines, and Los Angeles durability test results. Statistical analysis was used to determine whether these characteristics differ in sand and



Figure 1. Outline of Lake Bonneville at maximum size (after Gilbert, 1890). Discontinuous water pattern is for Lake Bonneville and solid gray patterns with imbedded letters is for current lakes. GSL—Great Salt Lake, UL—Utah Lake, SL—Sevier Lake, and T—Tule Valley.

gravel from different regional geologic settings, lake shoreline levels, or in different sand and gravel deposit types located in Lake Bonneville sediments. Regional geologic settings, lake shoreline levels, and deposit type are called "classification variables" in this study.

OBJECTIVES

The objectives of the study are twofold. The first is to show how statistical methods can be used to examine how geologic classification of sand and gravel deposits is also relevant to geotechnical characteristics. These "geotechnical" characteristics are important to those who produce sand and gravel, and those who use sand and gravel as aggregate in construction. Second, we show how statistical analyses can be used to prepare models for forecasting the nature of undeveloped sand and gravel resources. These models are also useful to government planners and economists.

THE STUDY AREA

Lake Bonneville was a large, pluvial lake present from about 17,000 to 15,000 years ago, which had a maximum size of about 51,700 km² (39,500 mi²). The lake was comparable in size to Lake Michigan (Morrison, 1991). Remnants of that once-large body of water include the Great Salt Lake, Utah Lake, and Sevier Lake (figure 1). While the northern part of the lake was, more or less, one continuous body of water, the southern part was a network of bays and channels. The lake left behind a complex system of terraces, beaches, spits and bars, deltas, and other fluvial-lacustrine deposits, that are being successfully exploited for sand and gravel for use in aggregate and construction. Only Utah Lake Bonneville sand and gravel deposits suitable for use as aggregate were addressed in this study. Within the study area, sand and gravel sites were grouped using the more obvious geomorphic features.

PREVIOUS STUDIES

Lake Bonneville has been the subject of considerable interest to many geologists, starting with Gilbert (1890). A sampling of some of the studies or reviews containing information on Lake Bonneville include an overview by Hintze (1988); discussion on isostatic deformation by Crittenden (1963); a report on the paleoclimatic implications of late Pleistocene sediment yield rates for the Lake Bonneville basin by Lemons and others (1996); an overview of the Quaternary stratigraphic, hydrologic, and climatic history of the Great Basin including information on Lakes Bonneville, Lahontan, and Tecopa by Morrison (1991); and a report on Lake Bonneville fluctuations and global climate changes by Oviatt (1997). Some catastrophic out flows from Lake Bonneville into the Snake River Valley of Idaho were described by Trimble and Carr (1961), Stearns (1962), and Malde (1968).

Lake Bonneville lacustrine deposits on the east and northeast areas of the lake basin have been the most thoroughly studied. Some of these studies include the geology of southern Cache Valley by Bissell (1961a) and Williams (1962); southern Utah Valley by Bissell (1961b); petrology of Bonneville gravels in Salt Lake County by Vlam (1963); the Bear River delta, Cache Valley, Idaho, by Anderson and Link (1998); geology of northern Utah Valley (Hunt and others, 1961); petrography and lithology of the Lake Bonneville sand and gravel deposits of Davis County (Kopp, 1987); and an overview of sandy and gravely lacustrine delta deposits along the eastern margin of Lake Bonneville by Milligan and Lemons (1998). Davis and Meyer (1972) reported on the friction between sand and gravel production and urban development along the Wasatch Front.

Two reports by Sack (1990, 1992) contain the results of

investigations of the Quaternary geology of Tule Valley (figure 1), including shoreline sediments of Lake Bonneville found in southwest Utah. The Tule Valley below the Lake Bonneville shoreline has an area of 1,193 km² (461 mi²) (Sack, 1992), of which 43 percent is covered with relict lacustrine deposits of all types. Of those sedimentary deposits, just 6 percent were reported to be lacustrine gravels.

Controversy about Lake Bonneville's stratigraphic and geologic history exists because the lake expanded and contracted in size a number of times, and these fluctuations destroyed, obscured, or modified the unconsolidated physical records of previous levels. Morrison (1991) suggested that this controversy can also be expected since the sediments deposited by each lake level are similar in appearance, and key beds are often absent. While delta complexes might have been large for a given shoreline level, these complexes were also easily and rapidly eroded when lake levels dropped. Morrison (1991, p. 302) also notes a lack of "adequate type locations" and that Gilbert's study (1890) was geomorphic, not stratigraphic. The detailed geologic history for Lake Bonneville developed by Morrison (1991) used a full spectrum of geologic data.

SAND AND GRAVEL DEPOSIT TYPES

Classification of Lake Bonneville sand and gravel deposits can be very arbitrary, and might be incorrect due to incomplete preservation or overprinting of the characteristics of one deposit type on another. Some of the more important depositional features recognized in Lake Bonneville deposits are discussed below.

Spits and bars are notable for their linear form (figure 2). They are deposited in lacustrine environments by long-shore currents moving parallel to the coast line, as well as by processes related to wave action. Bars in the Lake Bonneville basin are described in the Utah Highway Department (UHD) reports as forming parallel to the paleoshoreline and include barrier beaches that develop above lake level, and bars that form at or below lake level. The bar shown in figure 2 is attached at both ends to the coast line, but that is not a necessary condition. Bars in Lake Bonneville include a family of features having a linear form parallel to the paleoshoreline, and simply include all such features not recognized as spits.

A lacustrine beach is a depositional feature that, simply defined, is that area located on the lake margin as a gentle sloping surface, typically concave, that formed by wave action, and that includes areas both above and below lake level (Gary and others, 1972). Materials in a beach can include clay, sand, pebbles, and boulders. Defining the boundaries of the beach can be very complex. Beaches can be bounded by cliffs or vegetation. Beach geometry is the product of grain sizes, slope, and exposure to wave action (Reineck and Singh, 1980).

Terraces are geomorphic features that consist of long, narrow, low-angle ribbon surfaces bounded above by steep descending slopes and below by ascending slopes (Gary and others, 1972). Wave-built terraces of Lake Bonneville contain eroded lake sediments that extended lakeward from the shoreline. The distinction between terrace and beach deposits is simply one of focus. Beaches might be located on



Figure 2. Simplified examples of sand and gravel deposit-types located in the Lake Bonneville basin in map view showing spit, bar, beach, and delta.

terraces, but can also develop on bedrock or other surficial sediments. All terrace deposits could conceivably be classified as beach deposits but not vice-versa (figure 3).

Deltas develop where streams and rivers enter lakes (figure 2), particularly where long-shore currents are weak or absent, so that river sediments are deposited and not dispersed, and reworked. The shape and form of delta deposits are a composite of both river discharge and sediment load, and wave action.

Embankment gravel deposits are described in the UHD reports. They are related to delta deposits, and are recognized in Lake Bonneville sediments. These gravels were deposited during catastrophic floods in creeks flowing into the lake where the lake bottom was steeply dipping.



Figure 3. Simplified cross section showing typical location and relationship of beach and terrace deposit types.

DATA: SOURCES, TYPES, AND HANDLING

Data used in this report come from two primary sources; the Mineral Resources Data System (MRDS), a minerals database operated by the U.S. Geological Survey (USGS) with cooperation from state geological surveys; and a series of unpublished inventories of aggregate sites prepared by the UHD now called the Utah Department of Transportation (UDOT). A separate UHD inventory was prepared for each county. The unpublished inventories were also used to prepare most of the MRDS records that contain both original and revised data about each sand and gravel site. Some sites were found in the UHD inventories but not in MRDS, and vice versa. MRDS data on sand and gravel in Utah were supplied by different government agencies, but the vast majority of the data was from the Utah Geological Survey (UGS). The unpublished UHD inventories have limited distribution, but copies are maintained at the UGS library in Salt Lake City.

Data available for the sand and gravel sites used in this study represent a variable mix of data in that some resource records contained only estimates of volume and thickness, while records of other sites contained measured thicknesses and volumes. Thickness reports may only apply to specific exposures, and some data are from partially mined sites where only the amount of remaining material was reported. In some cases, geotechnical data are probably not representative of all material at the site.

Some data important to characterizing the suitability of sand and gravel are not available. Lithology is an important factor in aggregate suitability; however, data on that parameter was insufficient for inclusion in this analysis. For example, some gravels in Salt Lake County contained extrusive volcanic rocks. UHD inventories report cherts, some of which have deleterious reactions with alkali cement. Some of the volcanic rocks are porous, and may readily break down during freeze-thaw. Quartz monzonite clasts in some sand and gravel deposits along the Wasatch Mountain front are extensively weathered, rendering the sand and gravel unsuitable for use. Other deposits contain highly cleavable schist that can be problematic when used as aggregate.

Data integrity is an extremely important precondition to statistical analysis. Unfortunately, all data contain some errors. It is important to identify as many sources of errors as possible so that corrections can be made. All conclusions made in this study are qualified by some of the problems noted here. Unfortunately, correcting errors creates new errors. Geologic data are often the product of field interpretations that are dependent on both the quality of the exposure, and the expertise of the reporter--hence, more uncertainty. Unfortunately, data in this study were collected by a number of people over an extended period of time with no commonly agreed upon methodology.

The definition of deposits used in this study involved grouping sand and gravel sites; however, there is no general agreement on how close sand and gravel bodies must be to be considered part of the same deposit. Inspection of the MRDS location plots at 1:250,000 scale suggested that sites exhibited considerable variability in spacing. In order to standardize deposit definition, an arbitrary distance of 1.6 km (1.0 mi) was selected as the criteria for grouping, and the results of this grouping were defined as "deposits." In clusters that contained several deposit types, an average value was calculated for geotechnical characteristics reported for individual deposit sites. Thus, a series of sites along a shoreline might be grouped to form a chain that became a single deposit, and sites of different genetic types were grouped as one deposit. This was done to provide consistent characteristics that sand and gravel companies might expect of material they extract. However, the classification of individual sites was retained to allow for certain types of statistical analysis.

Sand and gravel deposits used in the analysis were lacustrine terraces, beaches, spits, bars, and sedimentary beds. Some complications in classification were present as some sites have either unknown deposit types or have a mixture of two or more deposit types. Other deposits were modified by fluvial and colluvial processes. Some sites might have been suitable only for use as fill, and would not be considered a viable source of aggregate. This was not always recognizable from the available data.

Another complication was that some stream terraces might have been misclassified as lake terraces. The UHD inventory for Salt Lake County suggested that there are questionable areas in the lower Jordan River Valley where terraces are high above the stream, and might contain considerable reworked lake terrace material. The UHD inventory for Juab County noted that alluvial fans coalesce to form alluvial plains extending to the shores of Lake Bonneville, a condition that made distinguishing between lake and alluvial sediments difficult. Reports in UHD inventories suggest that some gravels from Lake Bonneville have undergone repeated or long distance transport, or both, that destroyed most of the less mechanically durable rock types. This resulted in a high quality aggregate, and was confirmed in this study.

Grouping of sites reported in MRDS resulted in 382 deposits. Of these, 317 deposits were described by one MRDS record for each deposit, and seven deposits were described by two or more MRDS records where all sites had identical depositional types. These 324 sites were classified as being a single deposit type. An additional 49 deposits contained two deposit types, eight deposits contained three deposit types, and one deposit contained seven deposit types. Combining numerical data on sites into a single deposit was simple if both were of the same deposit type. For example, data from two or more adjacent sites all classified as terraces were combined simply by calculating an average. Note that data for some sites was limited to just one variable. No attempt was made to weight the value averages by volume. Deposits that contained a mix of different deposits types were also combined but were limited in use. In addition, sites that were sufficiently close to be combined as a deposit retained their deposit type classification. This made for complex data handling, but it was important for deposit type analysis. Most of the statistical analyses used in this study were from the subset of 324 deposits that were a single deposit type.

The 382 sand and gravel deposits used in this study were classified and grouped using: (1) deposit genetics, (2) Lake Bonneville shoreline levels, (3) regional geology, and (4) lake geography. All groupings are discussed in detail below. Not all sites could be readily classified without some ambiguity, and it is likely that this has led to some misclassification.

In summary, sand and gravel deposits in Lake Bonneville basin were the products of fluvial processes, lacustrine processes, or both. Most sand and gravel deposits formed within Lake Bonneville have been modified by streams and other surface processes since the disappearance of the lake. Classification for most deposits was made using deposit types reflecting lake depositional environment. The primary depositional types are: (1) terraces, (2) beaches, (3) lake bars and spits, (4) mixed lake types, (5) mixed lake and fluvial deposit types, (6) mixed lake and colluvial types, and (7) deposits in lake sediments of unknown types.

Three main databases were created for this study. Database A contains a compilation of all sand and gravel deposits in Lake Bonneville basin that were located during data compilation. These data contain formal sand and gravel deposits developed without regard to deposit types or shoreline designations among the clustered sites. Database A was used to assess the possibility of deposit properties being different in the two domains within the lake as defined below, and to develop a comprehensive statistical distribution for all of the Lake Bonneville sand and gravel deposits.

Database B contains a compilation of selected data for sand and gravel deposits in Lake Bonneville basin that were defined by one or more MRDS sites, all of the same deposit

type. Deposits with two or more deposit types were not included. This database was used extensively in the analysis that follows.

Database C contains a compilation of selected data for sand and gravel deposits in the Lake Bonneville basin that were defined by one MRDS site or multiple sites that were of the same deposit type. Also included, were data from parts of deposits broken out by genetic types. Therefore, this database was a mixture of deposits and parts of deposits defined and recorded in a way so that sand and gravel bodies of the same genetic type were recognizable. This database was used to analyze the effect of deposit-type-classification on sand and gravel geotechnical characteristics.

STATISTICAL ANALYTICAL METHODS

In the course of this study, both graphic and tabular methods were used to analyze the data. A generalized flow diagram in figure 4 gives an overview of how this study was conducted. Graphic and tabular presentation included the boxplot and contingency tables for Chisquare testing. Statistical distributions like the one shown in figure 5C were identified as models, and were comparable to those described by Singer (1993a, b). The Appendix provides a more detailed discussion of these tools.

As stated previously, geotechnical characteristics include the following: (1) sand and gravel deposit thickness, (2) deposit volume, (3) percent of sand and gravel greater than 2.54 cm (1.0 in), (4) percent of fines or percent of material less than 200-mesh (0.074 mm) sieve,

and (5) Los Angeles durability test results. Classification variables include regional geologic settings, lake shoreline levels, and genetic sand and gravel deposit types. We examined each geotechnical characteristic as it related to each classification variable, and attempted to determine whether it was different or comparable within the groups of classification variables. For example, we compared the thickness of deposits within the various deposit types. Steps 1 through 4 on figure 4 explain this part of the study.

The sections of the report that follow are organized by classification variable. All geotechnical characteristics were examined for each classification variable. Boxplots were prepared, and paired sets of them compared (figure 4, step 3). A detailed description of the process is found in the Appendix. Figure 5B is an example of a boxplot, a device useful in detecting asymmetry and identifying the presence of extreme values (Rock, 1988). In figure 5B, the 95 percent confidence limits of the median for each boxplot are shown as two



*Classification variables include regional geologic settings (domains), lake shoreline levels, shoreline configuration, and genetic classification of sand and gravel deposits.

**Geotechnical characteristics include deposit thickness, deposit volume, percent of sand and gravel greater than 2.54 cm, percent of fines or percent of material less than 200-mesh (0.074 mm) sieve, and Los Angeles durability test results.

Figure 4. Generalized flow diagram showing the steps in this study.



Figure 5. Three different diagrams showing the same data as a histogram (with fitted lognormal distribution curve--see text) (A), boxplot (B), and as a model (C). See text on discussion of a model. Data are volumes of Lake Bonneville sand and gravel deposits. Volumes are scaled in logarithm base 10.

opposing "V"-shaped notches on both sides of the box. The width of the "V" at the top is the 95 percent confidence limit. Boxplots with notches or confidence limits that did not overlap (as shown in figure 6) suggested that the medians may not be significantly different, and might also suggest that the data come from two populations. Comparisons of two or more boxplots were extensively used in this study to investigate whether the geotechnical characteristics of sand and gravel deposits were different or comparable between members of a classification variable (figure 4, step 3).

Data were combined if alignment of the boxplots and the 95 percent confidence limit of the medians suggested that the geotechnical characteristics were comparable for the classification variable under investigation (figure 4, steps 3 and 4). Evaluation of the combined data then proceeded to determine if the data could be described using either the normal or lognormal distribution (figure 4, steps 6a and 6b). The Lilliefors' test, a special form of the Kolmogorov-Smirov test (Rock, 1988) was used for checking data, with and without transformation, to see if one of these distribution types was appropriate. The test uses the maximum distance of the biggest gap between the observed distribution and a standard distribution. The size of the gap has an associated probability. If the size of the gap between the observed distribution and a standard distribution was found to be significant at the 5-percent confidence level, the assumption that the distribution was normal or lognormal was rejected (go to step 7, figure 4). If a distribution was not rejected, the data were prepared as a model (go to step 6c, figure 4) like the one shown in figure 5C, and as described in the Appendix.

While normal and lognormal distributions can be used to describe geotechnical data, some data sets could not be described using statistical distributions found in this study. Data that have a large number of values either approaching zero, or zero, where zero is a valid value, will likely not be successfully described with a standard distribution. Other data that could not be described include data that are actually describable by other statistical distributions not considered, data that are a mixture of two or more populations, or simply data that are of poor quality. However, data that could not be described using the normal or lognormal distribution can be described using a distribution-free model (ending at step 7, figure 4) where data like that shown in figure 5C would not include a statistical distribution, and the 10th, 50th, and 90th percentiles are calculated directly from the data and not a statistical distribution. Figure 13 is a good example of a distribution-free model.

Data were not combined if alignment of the boxplots and the 95 percent confidence limit of the medians suggested that the geotechnical characteristics were not comparable for the classification variable under investigation (figure 4, step 3). To determine whether or not the data sets were actually different (figure 4, step 4), testing of the two data sets used for the boxplots was conducted utilizing the nonparametric Mann-Whitney U test (Gibbons, 1976). Nonparametric methods were used because some data sets in this study departed from both the normal and lognormal distributions. Nonparametric tests do not require data normality as in parametric testing. The Mann-Whitney U test was used to determine if the null hypothesis that two data sets are actually the same can be rejected.

Nonparametric tests use ranks rather than values so the effect of extremely small or large values is also greatly reduced. The hypothesis tested is that the two data sets of the geotechnical characteristic under investigation are equal. As the difference between the data sets increases, the Mann-Whitney U test variable U increases in value as well. Higher values have a smaller probability of being due to chance. When U in the study had a probability that was less than 0.05, the hypothesis that the two data sets were part of the

same population was rejected. The alternative hypotheses(that the data sets were from different populations(was accepted. Therefore, two models would be needed, and each data set was separately evaluated in the same way discussed above for combined data sets. In figure 4, this involves steps 5a and 5b ending at either step 5c or 7. If three or more groupings were studied, the nonparametric Kruskal-Wallis test was used (figure 4, step 4). See Gibbons (1976) or Conover (1999) about nonparametric statistics for additional details.

LAKE BONNEVILLE

Regional Physiographic Setting (Domains)

Lake Bonneville occupied parts of three physiographic regions; the Basin and Range region, the Colorado Plateau region, and the Central Rocky Mountains region. The latter is a part of the Western Mountain Ranges aggregate region of Langer and Glanzman (1993), who delineated comprehensive national aggregate regions. They grouped some standard physiographic regions that contained similar types and sources of sand and gravel, and crushed stone. The Western Mountain Ranges aggregate region, or more specifically the Wasatch Range, bounds the Lake Bonneville basin on the east. The range lies east of Logan, Salt Lake City, and Provo (figure 1), and has higher relief than the mountain ranges of the Basin and Range or Colorado Plateau regions in the Lake Bonneville basin. High relief promoted high erosion rates, resulting in large quantities of material reaching Lake Bonneville. In addition, glaciation of the Wasatch Range generated considerable sand, gravel, and silt that were later carried down slope in melt water by rivers and streams. The Colorado Plateau region comprises only a small part of the study area along the east side of the lake. For study purposes, it was combined with the Basin and Range region because the two have comparable geology and topographic relief within the study area.

Sand and gravel deposits were classified by location as either Wasatch domain or Basin and Range domain (figure 1) in order to determine whether sand and gravel deposits adjacent to the Wasatch Range differ from the deposits in the rest of the lake basin. The data used in this analysis were for sand and gravel deposits that included all adjacent sites (database A) without regard to deposit type.

Data for 106 deposits in the Wasatch domain, and 143 deposits in the Basin and Range domain are shown as volume boxplots in figure 6. The medians and associated 5-percent confidence intervals of volume of the two domains were not aligned (figure 6). The Mann-Whitney Test gave a U value of -4.42. A test result of this size has an associated probability of less than 0.0001 that the difference in median volumes was due to chance. In other words, there is less than one chance out of 10,000 of having a U value of this size given the differences in deposit volumes between the two groups. This is less than 0.05 confidence level set for the study. Therefore, we rejected the hypothesis that the data sets were equivalent, and accepted the alternative hypothesis that the volume of deposits in the Wasatch domain are larger.

The median of Wasatch domain sand and gravel deposits was 360,000 m³ (280,000 yd³), three times larger than the



Figure 6. Boxplots of sand and gravel deposits of the two geologic domains in the Lake Bonneville basin. Volumes are scaled in logarithm base 10.

median of 120,000 m³ (90,000 yd³) for deposits located elsewhere in the Lake Bonneville basin. The results of the analysis suggested; (1) that the presence of the Wasatch Range adjacent to Lake Bonneville likely affected deposit volume, and (2) that two volume models (figures 7 and 8) were needed to describe the volumes of sand and gravel deposits located within the two domains of the Lake Bonneville basin.

The assumption that the lognormal distribution could be used to describe both volume models was not rejected when tested using the Lilliefors' test at the 5-percent confidence



Volume, in cubic meters

Figure 7. Model of volume of sand and gravel deposits located in the Wasatch domain as shown on figure 1. Volumes are scaled in logarithm base 10.


Volume, in cubic meters

Figure 8. Model of volume of sand and gravel deposits located in the Basin and Range domain as shown on figure 1. Volumes are scaled in logarithm base 10.



Thickness, in meters

Figure 9. Boxplots of sand and gravel deposits of the two geologic domains in Lake Bonneville basin. Thicknesses are scaled in logarithm base 10.

level. For the Wasatch domain, the test statistic, maxdif, was 0.063 for the data, and had an associated probability of 0.334. However, for the data from the Basin and Range domain, the test statistic, maxdif, was 0.057, and had an associated probability of 0.277. The normal distributions were shown in both models (figures 7 and 8) as lines, each with their associated 90, 50, and 10 percentile values given below each plot.

These volume models suggest that displacement of the aggregate industry outside of the Salt Lake County and surrounding area (Isaacson, this volume)--herein considered approximately equivalent to the Wasatch domain--into the Basin and Range domain means that the sources of sand and gravel would be much smaller. More Basin and Range deposits would need to be developed to meet the same level of demand than if deposits in the Wasatch domain were used. Economy of scale would be less for these smaller deposits, and it would cost more to extract their sand and gravel.

Not only are the sand and gravel deposits located in the Wasatch domain likely to have larger volumes, they are also likely to be thicker as suggested by thickness boxplots (figure 9). Comparison of the two thickness data sets for the two domains was accomplished using the Mann-Whitney test that gave a U value of -6.92. A test result of this magnitude had an associated probability of less than 0.0001 of the difference being due to chance. Therefore, we rejected the hypothesis that the two data set were equivalent, and accepted the alternative hypothesis that the thickness of deposits in the Wasatch domain are larger than those in the Basin and Range domain. The median thickness of the 111 Wasatch domain sand and gravel deposits was 5.8 m (19.0 ft), 70 percent larger than the median of 3.0 m (10 ft) for 216 deposits located elsewhere in the Lake Bonneville basin.

The results of the analysis suggest that the presence of the Wasatch Range adjacent to Lake Bonneville also affected deposit thickness, and that two thickness models (figures 10 and 11) were needed to describe the thickness of sand and gravel deposits located within these two domains of the Lake Bonneville basin. The assumption that the lognormal distribution could be used to describe both thickness models was rejected when tested using the Lilliefors' test at the 5-percent confidence level. For the Wasatch domain, the test statistic, maxdif, was 0.095 and had an associated probability of 0.016. Therefore, the assumption that a lognormal distribution can be used was rejected. For the Basin and Range domain, the test statistic, maxdif, was 0.097 for the data and had an associated probability of less than 0.001. Therefore, the assumption that a lognormal distribution can be used was rejected. The distributions of thickness values are shown in two empirical models (figures 10 and 11) where values were 90, 50, and 10 percentiles of the data.



Figure 10. Empirical models of thickness of sand and gravel deposits located in the Wasatch domain of the Lake Bonneville basin as shown on figure 1. Thicknesses are scaled in logarithm base 10.



Figure 11. Empirical model of thickness of sand and gravel deposits located in the Basin and Range domain of the Lake Bonneville basin as shown on figure 1. Thicknesses are scaled in logarithm base 10.

These thickness models suggest that displacement of the aggregate industry outside of the Wasatch domain into the Basin and Range domain would limit sources of sand and gravel to thinner deposits. As a result, more surface area would need to be obtained and mined to extract an equivalent amount of sand and gravel from the Basin and Range domain deposits compared to deposits from the Wasatch domain. Additional land acquisition and reclamation costs would also likely increase the cost of sand and gravel production.

In addition to being larger and thicker, boxplots show that the Wasatch domain deposits were also likely to have a greater percentage of gravel with a diameter greater than 2.54 cm (1.0 in) (figure 12). These percentages were reported from uncrushed samples. Mann-Whitney test analysis gave a U value of -2.13, with an associated probability of less than 0.032 that the difference is due to chance. That is less than the 5-percent level of significance set for this study. Therefore, we reject the hypothesis that the two data sets were equivalent and accept the alternative hypothesis that deposits in the Wasatch domain have larger percentages of gravel with a diameter greater than 2.54 cm (1.0 in) than those in the Basin and Range domain. The median percent of gravel with a diameter greater than 2.54 cm (1.0 in) for the 81 Wasatch domain sand and gravel deposits is 19 percent, and is only slightly larger than the median of 15 percent for 134 deposits located elsewhere in the Lake Bonneville basin. The results of the analysis suggest that the presence of the Wasatch Range adjacent to Lake Bonneville might have had a slight effect on the percent of gravel greater than 2.54 cm (1.0 in) in sand and gravel deposits. Some possible reasons for this difference include: (1) higher stream gradients in the Wasatch domain as compared to streams in the Basin and Range domain, (2) transportation distances shorter in the Wasatch domain as compared to streams in the Basin and Range domain, and (3) differences in durability for different types of bedrock in the two domains (Phil Moyle, USGS, written communication, 1999).



Figure 12. Boxplots of percent of material greater than 2.54 cm (1.0 in) in diameter for sand and gravel deposits of the Lake Bonneville basin.



Figure 13. Empirical model of percent of gravel larger than 2.54 cm (1.0 in) in diameter in sand and gravel deposits of the Lake Bonneville basin.

As the difference between the median values of the domains was small, modeling the domains separately was not done. A single model (figure 13) was prepared for the lake as a whole. Note that the model is empirical--no distribution is given, as 8 percent of the data have zero values, and many values approach zero. Some deposits also have an unusually large percentage of material that is greater than 2.54 cm (1.0 in); one over 90 percent (figure 12).

Boxplots suggested that fines, the percent of material less than the 200-mesh (0.074 mm) sieve, were comparable (figure 14) between deposits in the Wasatch domain and those in the Basin and Range domain. Analysis using the Mann-Whitney test gave a U value of -1.38. A test result of



Figure 14. Boxplots of percent of material smaller than the 200-mesh (0.074 mm) sieve for sand and gravel deposits of the Lake Bonneville basin. The dashed line identified as "A" is at 15 percent and is the common maximum fines accepted in U.S. aggregate operations.

this size has an associated probability of 0.17 of the difference being due to chance. This value is not less than the 5percent level of significance set for this study. Therefore, the hypothesis that the percent of fines in the data sets for the two domains were equivalent was not rejected. Note that fines had two sources in each sample: (1) the original fines present in the samples before crushing, and (2) those fines produced and added to the sample after it was crushed to a maximum size of a 2.54 cm (1.0 in).

A single model for fines is applicable to all sand and gravel deposits in Lake Bonneville (figure 15). Note that the model is empirical--no distribution is given as many values were approaching zero. Some deposits also had an unusually large percent of fines, values that were greater than the 15 percent usually reported in sand and gravel operations in the United States (dashed line at A, figures 14 and 15). Some of these sites may be sources of fill rather than aggregate.

Boxplots (figure 16) suggest that the data sets of the results of the Los Angeles durability test were comparable for deposits in the Wasatch domain and those in the Basin and Range domain. Analysis using the Mann-Whitney test gave a U value of -1.10. A test result of this size has an associated probability of 0.27 that the difference was due to chance. This value is not significant at the 5-percent level of significance set for this study. Therefore, the hypothesis that the results of the Los Angeles durability test for the two domains were equivalent was not rejected.

A single distribution model for Los Angeles durability test results was applicable to nearly all sand and gravel deposits in Lake Bonneville (figure 17). The assumption that the normal distribution could be used to describe Los Angeles durability was not rejected when analyzed using the Lilliefors' test at the 5-percent confidence level, particularly when the three outliers greater than 35 percent were excluded from the analysis (figure 17). For the remaining 169 values, the test statistic, maxdif, was 0.047 with an associated



Material less than the 200-mesh sieve, in percent

Figure 15. Empirical model of percent of material smaller than the 200-mesh (0.074 mm) sieve in sand and gravel deposits of the Lake Bonneville basin. The dashed line identified as "A" is at 15 percent and is the common maximum amount of fines accepted in U.S. aggregate operations.

probability of 0.441. The three values excluded from the analysis were only 1.7 percent of the data. One site contained colluvium, and was included in the sample. Arbitrary exclusion of values simply because they were unusually high is generally not desirable. Users of the model shown in figure 14 need to be aware that the data suggested that there was a probability of 0.017 that larger Los Angeles durability values not described by the model might be present, assuming that the original values in the data used were not in error.



Figure 16. Boxplots of Los Angeles durability test results for sand and gravel deposits of the Lake Bonneville basin. Higher percentages indicate less durable material.





Figure 17. Model of Los Angeles durability test for sand and gravel deposits of the Lake Bonneville basin. Higher percentages indicate less durable material. The three highest values were not used in fitted distribution (see text).

Northern and Southern Bonneville Basin

As noted in the introduction, Lake Bonneville covered an area of about 51,700 km² (20,000 mi²); its maximum depth was on the order of 300 m (1,000 ft). The northern part of the lake was characterized by one large relatively uninterrupted body of water extending from the vicinity of the current Great Salt Lake to the Nevada border (figure 1). In contrast, the southern half of the lake consisted of a complex system of channels and bays (figure 1). The southern part of the lake was not as deep as the basins to the north, and did not always contain water during some of the lower shoreline levels (Curry and others, 1984). It is assumed that lake dynamics were different, and that sediments were reworked more in the northern basin. Do the sand and gravel deposits of the northern basin have different characteristics than those in the southern bays when comparing deposits located in the Basin and Range domain? These sand and gravel deposits were compared and divided into two groups--those north of latitude 40°N (figure 1) were designated as being "main body" and those south of latitude 40°N as belonging to "south bays." Data used in the analysis were for those deposits with a single deposit type.

Boxplots (not shown) for volume, thickness, percent of gravel greater than 2.54 cm (1.0 in), and fines suggested that there was no difference between the northern basin and south bays for these variables. However, boxplots of Los Angeles durability test results (figure 18) suggested that main body deposits had higher durability values than those in the south bays. Comparison of the data sets using the Mann-Whitney test gave a U value of -4.19 with an associated probability of less than 0.0001 of being due to chance. Therefore, the assumption that data sets with Los Angeles durability test results are equivalent was rejected, and the hypothesis was accepted that the test results were lower (and therefore, better quality) in the main body compared to those in the south bays. The median test result from the main lake body sand



Loss in Los Angeles durability test, in percent

Figure 18. Boxplots of Los Angeles durability tests of deposits classified by geographic area. Higher percentages indicate less durable material.

and gravel deposits was 22 percent loss, compared to 26 percent loss for the median result from deposits located in the south bays. Both median values were well within acceptable values for quality aggregate. Stronger and longer exposure to lake currents more prevalent in the main body of Lake Bonneville may have improved sand and gravel durability, or perhaps better quality material was present in the bedrock and sediments in the area of the main body. More volcanic rocks, that are usually less durable, are recognized in the bedrock in the region of the south bays (Bryce Tripp, UGS, written communication, 1999). While the data sets were different, the magnitude of the difference was too small to justify separate models for deposits in the main body and the south bays. The distribution of Los Angeles durability test values for single-style deposits used in this part of the study had essentially the same form and distribution as those for deposits that were prepared without considering whether multiple deposit forms were present or not. Therefore, the model given in figure 17 is applicable.

Lake Bonneville Shorelines

The evidence of two opposite processes--erosion and deposition--can be recognized in the shorelines of Lake Bonneville. Evidence left by waves and currents eroding competent rocks can be observed as lake cliffs and benches; the most common lake erosional features. Depositional features include terraces, beaches, and other lacustrine features composed of sand and gravel. Classification of shorelines was complex due to multiple overprinting events of Lake Bonneville elevation oscillations. In order to complete the analysis, sand and gravel deposits were grouped using elevations of the major shorelines of Lake Bonneville (and of the Great Salt Lake) as given by Currey and others (1984). Because sand and gravel deposits were located at all elevations (figure 19), deposits were grouped using shoreline assignments employing the midpoint between standard shorelines identified below (table 1).



Figure 19. Histogram showing the distribution of sand and gravel deposits by elevation in the Lake Bonneville basin. Deposits are classified into the three groups named above using the minimum and maximum boundary elevations given in table 1.

Table 1.

Significant shorelines, lake levels, and shoreline groups of Lake Bonneville and Great Salt Lake (after Currey and others, 1984).

Shoreline Name (Group)	Midpoint Elevation (m)	Max. (m)	Min. (m)
High Terraces (N/A)	_	—	GT 1610
Bonneville (same name)	1550	1610	1497
Provo (same name)	1440	1497	1408
Stansbury (SGGSL)	1370	1408	1333
Gilbert (SGGSL)	1295	1333	1290
GSL (SGGSL)	1282	1290	1277

Notes: (1) Shorelines are listed by elevation; in meters above sea level where group names are in parenthesis; (2) Abbreviation uses: GSL -- Great Salt Lake, SGGSL -- Stansbury-Gilbert-GSL; Max. is upper elevation for deposits to be classified with a given shoreline; Min. is the minimum elevation.; GT -- greater than. Midpoint for GSL computed stands noted at 1285 m, 1284 m, 1280 m, and 1277 m.

Sand and gravel deposits were located at the Stansbury and Gilbert shorelines, and at all levels of the Great Salt Lake (GSL). However, only a few shorelines are still present, and they were grouped and designated as SGGSL in this study. A number of terraces observed in the data were above the maximum elevation of the highest level of Lake Bonneville. They were classified as high terraces and not used in this analysis. One complication in using elevation for distinguishing between various lake levels was that rebound of the crust occurred as a result of removal of the massive weight of the water once present in Lake Bonneville. Crittenden (1963) located a maximum rebound of 64 m (210 ft) in sections of the Bonneville shoreline. The rebound was greatest on the west side of Great Salt Lake (Crittenden, 1963, figure 3). Elevation is an imperfect proxy for age. Given the complex geologic history of the lake, a number of higher elevation deposits could be younger than some of the lower ones.

The Lake Bonneville Group contains two formations; the oldest is the Little Cottonwood Formation which contains three members and the youngest is the Draper Formation. The Alpine Member of the Little Cottonwood Formation is the oldest and thickest unit of the Lake Bonneville Group and ranges from 15 to 30 m (50 to 100 ft) in thickness (Morrison, 1965). The Provo and Bonneville Members are the other units in the Little Cottonwood Formation that overlie the Alpine Member.

In the Draper $7^{1/2}$ minute quadrangle located between Salt Lake and Provo (figure 1), Morrison (1965, table 4) estimates that the Alpine Member likely contained 68 percent of the original volume of the Lake Bonneville Group. In the UHD material inventory, the Alpine is identified as the more important depositional unit of Lake Bonneville at 1,538 m (5,046 ft) than the highest stand of Bonneville shoreline (1,564 to 1,584 m) (5,131 to 5,197 ft) as described by Curry and others (1984). Deposits found at the two elevation bands can be combined using the maximum and minimum intervals given in table 1. Morrison (1965) divides the Alpine Member into two facies. One is a gravel facies with abundant cobble- and boulder-sized material with some coarse gravel. The sand facies contains thin, parallel interbeds of granular to pebbly sand with local ripple marks and with variable levels of sorting (Morrison, 1965). Transition between the two facies is described as usually abrupt (UHD material inventory). Along the Wasatch Mountains, much of the gravel facies of the Alpine Member was derived from the Big Cottonwood, Mutual, Mineral Fork, Tintic, Woodside, Thaynes and Ankareh Formations and less from the Nugget Sandstone (Morrison, 1965). Lithologies include quartzite, quartz monzonite, and argillites initially thought to be a product of glaciation as reported by the UHD inventory. Most material in the Alpine Member in Salt Lake County is in beach and spit gravels. According to the UHD, these deposits have grain distributions with very small median sizes, and considerable variability in rounding. Well-rounded pebbles were likely derived from either the Cretaceous Echo Canyon Conglomerate or the Tertiary Wasatch Formation. Contamination of the gravels by numerous mud-rock flows was reported. Gravel layers ranging up to 15 m (50 ft) in thickness were found in the Alpine Member (UHD inventory).

Sediments of the Provo shoreline band include the Provo Member of Little Cottonwood Formation (Morrison, 1965). Both this and the Bonneville Member are younger than the Alpine Member discussed above. The Provo shoreline, proper, was reported at an elevation of 1,460 m (4,790 ft) in Salt Lake County. Both the onshore and offshore facies are similar to those seen in the Alpine Member deposits described above. However, here, the transition from onshore to offshore materials was less dramatic. Sand and gravel were deposited in beaches, spits, and deltas. The amount of materials present appears to be substantially greater than in the Alpine Member; at least in Salt Lake County, where total thickness reached 24 m (79 ft). Pebbles are also larger, averaging just over 5 cm (2.0 in) in maximum diameter. Parts of the Provo Member sediments were derived from reworking of the Alpine Member, particularly, sand and gravel deposits at Point-of-the-Mountain spit (UHD Material Inventory). Delta deposits associated with the Provo Member can be seen north of the Utah State Capitol.

A number of Lake Bonneville (Stansbury, Gilbert shorelines) and GSL shorelines are found at lower elevations (figure 19). As noted previously, they are all treated in one group identified as "SGGSL." Beach and embankment gravel were minor where the shore had low relief; however, larger deposits did develop along steeper mountain fronts including those along the Wasatch Range and the north end of the Oquirrh Mountains (UHD Material Inventory). Spits might be an important local source of sand and gravel. Contribution of material from higher shoreline deposits to these deposits was often significant.

All sand and gravel deposits located in the Lake Bonneville basin were used in this part of the study to determine whether sand and gravel deposit characteristics differ in the three shoreline groups identified above.

The boxplots for deposit thickness, percent of gravel greater than 2.54 cm (1.0 in) in diameter, and percent of fines (not shown) suggest that these characteristics were not statistically different among shoreline groupings. The non-alignment of boxplot medians (and the associated 5-percent confidence interval) of volumes of sand and gravel deposits suggest that there might be significant differences in volumes of sand and gravel deposits, as classified by shoreline group (figure 20). Analysis using the Kruskal-Wallis test gave an H value of 7.33 with associated probability of 0.026, less than the previously set 5-percent confidence level. The alternative hypothesis that there were differences among the groups was accepted. The median volume of the 90 Bonneville sand and gravel deposits was 160,000 m³ (122,000 yd³), very comparable to that of the 56 Provo sand and gravel deposits at 200,000 m³ (150,000 yd³). In contrast, the median volume for the 59 SGGSL deposits was twice as



Volume, in cubic meters

Figure 20. Boxplots of volume of deposits classified by shoreline groups. Volumes are scaled in logarithm base 10.

large at 400,000 m³ (300,000 yd³).

One possible explanation is that the older the deposits, the greater the likelihood that subsequent erosion had reduced deposit volume. Sack (1992) reported that 53 percent of the Bonneville shoreline had been obliterated by erosion in the Tule Valley (figure 1). This is comparable to 43 percent for the Provo shoreline (Sack, 1992). However, the youngest shoreline, from a lake local to the Tule Valley, and identified as the Lake Tule shoreline, had been extensively eroded, with 77 percent obliteration. The reasons this may have happened appear to be related to several local conditions that are discussed in detail by Sack (1992). Note that these erosion estimates are for specific shorelines, not shoreline groups as used in the study. One factor possibly contributing to the pattern observed in this study is that younger deposits often contain reworked contributions of material from older deposits, possibly accounting for their greater volume.

Two volume models were developed. One model combined data from the 90 Bonneville and 56 Provo sand and gravel deposits (figure 21). The assumption that the normal distribution could be used to describe the data was not rejected when tested using the Lilliefors' test at the 5-percent confidence level. The test statistic, maxdif, was 0.076 with an associated probability of 0.065.

For the 59 SGGSL deposits that served as the volume model (figure 22), the assumption that the normal distribution could be used to describe the data was not rejected when tested using the Lilliefors' test at the 5-percent confidence level. The test statistic, maxdif, was 0.076 with an associated probability of 0.515.

The boxplot medians (and the associated 5-percent confidence interval) for results of the Los Angeles durability test are not aligned, suggesting that there might be differences in deposits located in the Bonneville, Provo, and the combined Stansbury-Gilbert-Great Salt Lake (SGGSL) shoreline groups (figure 23). Analysis using the Kruskal-Wallis test



Volume, in cubic meters

Figure 21. Volume model of sand and gravel deposits in the Lake Bonneville and Provo shoreline groups. Volumes are scaled in logarithm base 10.



Volume, in cubic meters

Figure 22. Volume model of sand and gravel deposits in the combined Stansbury, Gilbert, and Great Salt Lake (SGGSL) group. Volumes are scaled in logarithm base 10.



Figure 23. Boxplots of Los Angeles durability tests of deposits classified by shoreline groups. Higher percentages indicate less durable material.

gave an H value of 21.4, with an associated probability of less than 0.0001 of the differences being due to chance. The hypothesis that the Los Angeles durability tests are comparable for the three groups was rejected. The median result of the Los Angeles durability test for the 62 Bonneville shoreline deposits was 26 percent. Medians were 24 percent for the 52 Provo shoreline deposits, and 21 percent for the 58 SGGSL deposits respectively. The results of the analysis suggested that there is a gradual, and relatively small, decline in aggregate quality with increased age of the deposits as expressed by Los Angeles durability test results. It should be noted that nearly all of the results were well within usual acceptable values for quality aggregate. Therefore, test results of the shoreline groups need not be separately modeled and are represented in figure 17.

GENETIC CLASSIFICATION OF SAND AND GRAVEL DEPOSIT TYPES

Each deposit can consist of one or more types of sand and gravel. Because of infrequent reporting, several deposit types were not considered. These included sites in lake beds located at a distance from the shore and usually recognized by their sheet or blanket geometry. Only 3.3 percent of sites were identified as lake beds. These sites also tend to be fine grained, and a less promising source of sand and gravel. Colluvium was noted in some lacustrine deposits. This reflected modification of deposits once exposed. Slightly more than 1 percent of the sites were in colluvium or in lacustrine material with colluvium. All these sites were excluded from the following analysis.

The majority (56 percent) of the 575 sand and gravel sites (grouped to form formal deposits) were identified as lake terraces. Terrace or embankment deposits were located on steeply inclined slopes adjacent to water that was comparatively deeper than water near other deposit types, and they occurred as a depositional feature extending outward from the slope (figure 2).

The second largest group (15 percent) of the sand and gravel sites, were located in lake spits and bars. Two examples of spits in Lake Bonneville basin are the Cottonwood-Draper spit and the Point-of-the-Mountain spit. Sorting is usually good in spits and bars, and fine materials are absent; however, excessive sorting can be detrimental since most specifications for construction aggregate require a range of grain sizes.

Sand and gravel sites can have a mix of lacustrine deposit types as well as fluvial and lacustrine types. Delta deposits are a good example of this. Eleven percent of the data on sand and gravel deposits in the Lake Bonneville basin were of this mixed type.

The fourth most prevalent deposit type identified in the study were beaches. In Salt Lake County, clasts from beach gravels were reported by the UHD to be well rounded with a discoidal shape, and were well sorted.

Preliminary data evaluation suggested that it would be best if some deposit types were dropped from the analysis. These included sites classified as lake bed, unknown, or mixed. Therefore, the focus of the analysis was on lake terraces, beaches, spits, and bars. Data from deposits consisting of only one deposit type were used for analysis. These types represent 79 percent of sites used to develop the data in this study.

The boxplots for volume, percent of gravel greater than 2.54 cm (1.0 in), fines, and Los Angeles durability test results (not shown) suggested that sand and gravel deposits located in spits and bars were not statistically different. However, statistical analysis did suggest that thickness might be different between spits and bars, The limited number of thickness observations for eight spits might not be representative, and more data is needed before a successful analysis can be completed.

The boxplots for thickness, percent of gravel greater than 2.54 cm (1.0 in), fines, and Los Angeles durability test results were statistically comparable (not shown) for sand and gravel deposits located in beaches and in terraces. However, the absence of alignment of boxplot medians (and the associated 5-percent confidence interval) of volume (figure 24) suggests that there might be significant differences

Terraces (n=136) Beaches (n=19) 10⁵ 10⁹ 10³ 10⁷ 10¹ Volume, in cubic meters

Figure 24. Boxplots of sand and gravel terrace and beach deposits of the Lake Bonneville basin. Volumes are scaled in logarithm base 10.

between the volume data sets of beaches and terraces. Analysis using the Mann-Whitney test gave a U value of -2.15 with an associated probability of 0.032, that was less than the previously set 5-percent confidence level. The alternative hypothesis that the volume of terraces is larger than the volume of beaches was accepted. The median of the 19 sand and gravel observations in beaches was 100,000 m³ (76,000 vd³) as compared to that of 250,000 m³ (190,000 yd³) in the 136 terraces. The limited number of beaches in the data render this analysis preliminary. Perhaps one reason that beach volumes were smaller was that nine of the observations were from the Bonneville shoreline group that had smaller deposits of all types (see above). The balance of the beach deposits were from the Provo shoreline group. No observations were reported from the SGGSL group. Given the relatively small difference between the medians for the two data sets, the data for beaches was combined with data for terraces.

The boxplots for volume, percent of gravel greater than 2.54 cm (1.0 in), fines, and Los Angeles durability test results (not shown) suggests that these characteristics were not statistically different between the spit-bar and terrace-beach groups. However, the absence of alignment of boxplot medians (and the associated 5-percent confidence interval) of thickness (figure 25) suggests that there might be significant differences in thickness of sand and gravel deposits between the spit-bar group and the terrace-beach group. Analysis using the Mann-Whitney test gave a U value of -3.48 with an associated probability of 0.0005, that was less than the previously set 5-percent confidence level. Therefore, equivalency of the two data sets was rejected, and the alternative hypothesis that the terrace-beach group were thicker than the spit-bar group was accepted. The median thickness of the 47 sand and gravel observations in the spit-bar group was 2.4 m (7.9 ft), as compared to that of the 210 observations in the terrace-beach group of 4.6 m (15.1 ft).

The results of the analysis suggested that thickness models were needed for the two groups. The assumption that the

Figure 25. Boxplots of sand and gravel deposits in terraces and beaches and in spits and bars of the Lake Bonneville basin. Thicknesses are scaled in logarithm base 10.

10

Thickness, in meters

0.1

1

lognormal distribution could be used to describe both volume models was rejected for both groups when tested using the Lilliefors' test at the 5-percent confidence level. The test statistic, maxdif, was 0.104 for the data from the 210 deposits in terraces and beaches and had an associated probability of less than 0.001. Figure 26 shows an empirical thickness model for sand and gravel deposits in terraces and beaches.



Figure 26. Empirical model of thickness of sand and gravel deposits located in terraces and beaches. Thicknesses are scaled in logarithm base 10.

The test statistic, maxdif, was 0.14 for the data from 47 deposits in bars and spits and had an associated probability of 0.003. Therefore, both thickness models were empirical (figure 27).

100

209

1000





Thickness, in meters

Figure 27. Empirical models of thickness of sand and gravel deposits located in spits or bars. Thicknesses are scaled in logarithm base 10.

DEPOSITS WITH ONE, AND WITH MULTIPLE DEPOSIT TYPES

Most sand and gravel deposits in this study were dominated by only one deposit type. A few contained two or three, and one had seven. For analytical purposes, two groups were adopted. One group contains only those deposits with just one deposit type. The second group contains deposits with two or more deposit types, and was identified as the multiple-deposit-type group below. For purpose of the discussion that follows, there were now two new groupings or "styles" of deposits--those consisting of a single deposit type, and those consisting of multiple deposit types-identified as hybrid. Were deposits classified using these two styles preferentially distributed in the Lake Bonneville basin? Analysis suggested that deposit style was dependent on the geologic situation (domain, shoreline, and so on) in which they were found. Deposit styles were appraised using the Chi-square test of independence.

Previous analysis demonstrated that the Wasatch domain sand and gravel deposits differed in a number of deposit characteristics from those in the Basin and Range domain. How did the two domains compare in terms of deposit styles? Table 2 shows the distribution of deposits by group. Also shown are number of deposits by group if domain and deposit styles are independent. The Chi-square value in table 2, comparing the difference between the expected number of deposits and the observed number of deposits in each classification, is 7.67. This has an associated probability of 0.0056, considerably less than the previously set 5-percent confidence level. The hypothesis that style and domain were independent was rejected. The alternative hypothesis that style and domain were dependent was accepted. Table 2 suggests that the Wasatch domain contains more hybrid deposits than the Basin and Range domain. This likely reflects the greater complexity and closer spacing of deposit sites located in the Wasatch domain.

Table 2.
Distribution of sand and gravel deposits classified by domain
and number of deposit types. Expected deposit numbers are
given in parentheses and are rounded to integers.

Domains	One deposit type	Hybrid deposit type
Wasatch	110 (119	31 (22)
Basin and Range	204 (195)	26 (35)

Did shoreline groupings have different sand and gravel deposit styles? Table 3 shows the distribution of the number of deposits observed, and the expected number of deposits if shoreline groups and deposit styles were independent. The Chi-square value for table 3 is 7.84 and has an associated probability of 0.02, less than the previously set 5-percent confidence level. The hypothesis that shoreline groups and deposit styles are independent was rejected. The alternative hypothesis is that shoreline group and deposit style are dependent. Table 3 indicates that the Bonneville shoreline group contains too many single-type deposits compared to those that were hybrid deposits. Data on both the Provo and SGGSL shoreline groups exhibit the opposite pattern--hybrid deposits were too common. These patterns might have resulted from better opportunities for preservation in lower shoreline groups. The lower group also had a greater likelihood of having been repeatedly reworked thus promoting development of more complex deposits including development of hybrid deposits.

Table 3. Distribution of sand and gravel deposits classified by shoreline group and number of deposit types. Expected deposit numbers are given in parentheses and are rounded to integers.					
Shoreline Group type	One deposit type	Hybrid deposit			
Bonneville	122 (113)	12 (21)			
Provo	91 (98)	25 (18)			
SGGSL	97 20	(99) (18)			

Did the geography of Lake Bonneville basin affect deposit style? Only sand and gravel deposits located in the Basin and Range domain were examined. Sand and gravel deposits were classified into two groups--those north of latitude 40° N (figure 1) were designated as being "main body," and those south of latitude 40° N as belonging to "south bays." Table 4 shows the distribution of the number of deposits observed, and the expected number of deposits if geography and deposit styles were independent. The Chisquare value for table 4 is 4.07 with an associated probability of 0.04, just slightly less than the previously set 5-percent confidence level. The hypothesis that lake geography and deposit style are independent was rejected. The alternative hypothesis is that deposit style is affected by geography. Table 4 suggests that the main body of Lake Bonneville contains more hybrid deposits than did the south bays. Perhaps this reflects the greater complexity of lacustrine processes, and a greater number of young sand and gravel deposits present in the main body of the lake (see section on shoreline groups).

Table 4. Distribution of sand and gravel deposits classified by geography and number of deposit types. Expected deposit numbers are given in parentheses and are rounded to integers.					
Area	One deposit type	Hybrid deposit type			
Main body	193 (200)	43 (36)			
South bays	121 (114)	14 (21)			

INCLUSIVE VOLUME MODEL FOR LAKE BONNEVILLE

All volume data on sand and gravel deposits of Lake Bonneville were used together to prepare a single distribution-type model (figure 5C), and were used as the example (see appendix) to explain the figures in this report. The data were also given as a histogram with a fitted lognormal distribution curve (figure 5A), and as a boxplot (figure 5B). As shown above, better volume models for deposits in Lake Bonneville are also available given additional details about the geology and geography of sand and gravel deposits. The inclusive volume model (figure 5C) suggested that 90 percent of the 249 sand and gravel deposits in Lake Bonneville had a volume of 30,000 m³ (23,000 yd³) or greater; that half had a volume of 250,000 m³ (190,000 yd³) or greater; and that 10 percent of the deposits had a volume of 2.3 million m³ (1.8 million yd³) or greater.

The Lake Bonneville volume model can be used to compare the volume of sand and gravel deposits located in the Lake Bonneville basin to those associated with other lakes and other sand and gravel depositional processes. Are sand and gravel deposits bigger and better if deposited by rivers as opposed to lakes? How do these lacustrine sand and gravel deposits compare to those formed along the ocean? For example, Bobrowsky and Manson (1998) reported that the volume of 14 sand and gravel deposits located in marine sedimentary landforms on Vancouver Island, British Columbia, had a probability of 0.8 of being between 15,000 m³ (11,000 yd³) and 780,000 m³ (600,000 yd³). That is within the same order of magnitude or one order of magnitude smaller than the comparable limits at the same probabilities for Lake Bonneville sand and gravel deposits, (figure 3C)--between 30,000 m³ (23,000 yd³) and 2.3 million m³ (1.8 million yd³). However, spatial definition of deposits is probably different. How data were collected and reported is always an issue in

this kind of comparison and might account for the distinction. The size of the Bobrowsky and Manson (1998) database was also fairly small.

Bobrowsky and Manson (1998) also conducted a detailed evaluation of sand and gravel deposits located in 11 different geomorphic landform families on Vancouver Island. For all 144 sand and gravel deposits, without regard to landform, the median volume was $76,000 \text{ m}^3$ (58,000 yd³). That was an order of magnitude smaller than the median of 250,000 m³ (190,000 yd³) for those found in the Lake Bonneville basin. On the other hand, the median Lake Bonneville deposit was also an order of magnitude smaller than the median (5.4 million m³) (4.1 million yd³) of a volume model developed by Bliss and Page (1994, figure 4) for 275 fluvial and other types of sand and gravel deposits. Data for deposits also included sites in glacial terraces, outwash plains, modern and raised beaches, and others. Most of the data were from the United Kingdom and California. Sand and gravel deposits in alluvial fans were excluded due to their obviously larger volumes. A very generous definition of what constituted a sand and gravel deposit was used during data compilation.

How did calculated reserves of sand and gravel deposits in 26 sites in England (Wardrop, 1999) compare to Lake Bonneville deposits? The median volume of the Wardrop data was 500,000 m³ (380,000 yd³), twice as large, but within the same order of magnitude, as the Lake Bonneville median volume of 250,000 m³ (190,000 yd³). The similarity is remarkable, considering all the variability involved in developing these types of data. However, the Mann-Whitney U test, suggesting the hypothesis that the data sets are equivalent, would be rejected at the 5-percent confidence level. The sites in the Wardrop data were located in fluvial and glacial-fluvial deposits, and no information was given on how close the sites were to one another. Wardrop (1999) also gave a number of other qualifications to his data.

FUTURE USE OF QUANTITATIVE AGGRE-GATE MODELS

Models like the ones developed in this study can be used in quantitative mineral resource assessments of aggregate as described by Singer (1993a, b). He and others have applied models to the evaluation of resources in over 5 million km² (2 million mi²) in various parts of the Western Hemisphere. In fact, models for about 85 deposit types, predominantly for metallic minerals (but also for some industrial minerals), have been developed (Cox and Singer, 1986; Bliss, 1992; Orris and Bliss, 1992). For some assessments, Monte Carlo simulations are run using some of these models and other data to produce probability distributions of quantities of undiscovered metals (Root and others, 1992).

Perhaps similar forecasts can be made for aggregate if appropriate models are available. Most engineers, geologists, and others involved in providing natural aggregate for construction projects are aware that in the future, aggregate, particularly that suitable for high-end uses at an affordable price, may not be available either in the quantity, quality, or near the location needed. Forecasting how much quality aggregate may be within a region will be useful for all types of planning including planning by highway departments and by managers of state and federal lands. Quantitative aggregate assessment is a logical extension of the type of studies made by engineers who already use probabilistic and statistical methods to solve a wide range of problems (Li and Lo, 1993.)

CONCLUSIONS

Statistical analysis of sand and gravel deposits of pluvial Lake Bonneville demonstrated differences in some geotechnical data related to geology. Geotechnical data analyzed included deposit volume, deposit thickness, percent of sand and gravel greater than 2.54 cm (1.0 in) in maximum diameter, percent of fines (material less than 200-mesh [0.074 mm] sieve), and Los Angeles durability test results. For example, the median volume of sand and gravel in the Wasatch domain was three times larger than that of the Basin and Range domain (figure 1). Another difference was that deposits located in the younger shoreline sediments had a median volume nearly twice that identified in the older shorelines.

Deposit thicknesses, like volume, were greater (by 40 percent) in sand and gravel deposits of the Wasatch domain compared to those in the Basin and Range domain. The only other likely difference in thickness relating to geology was among some sand and gravel deposit types. Thickness of deposits in beaches and terraces was a third larger than those located in spits and bars.

Sand and gravel in Lake Bonneville sediments in the Wasatch domain were also found to be slightly coarser, based on the percentage of gravel within deposits larger than 2.54 cm (1.0 in) in maximum diameter. The same pattern was also found when comparing Basin and Range domain deposits north and south of latitude 40°N (figure 1). Those in the north were coarser.

Percent of fines in sand and gravel deposits were indistinguishable among the various groups of deposits for the geologic variables considered in the study. However, sand and gravel durability as measured by the Los Angeles durability test was slightly better north of latitude 40° N (figure 1) and increased in quality as shoreline deposits became younger.

Statistical analysis also discovered that hybrid deposits (ones with two or more different deposits types) were more likely to be located in the Wasatch domain. They also were more likely north of latitude 40°N, and in younger shorelines.

The median volume of all sand and gravel deposits located in Lake Bonneville sediments was 250,000 m³ (190,000 yd³). This was an order of magnitude greater than the volume of marine deposits reported on Vancouver Island, but within the same order of magnitude for nonmarine deposits in the United Kingdom.

In summary, the important discoveries made in this study were that the sand and gravel deposits located in the Bonneville Lake basin adjacent to the Wasatch Mountains were likely to be larger, thicker, and more coarse than elsewhere in the Bonneville basin.

ACKNOWLEDGMENTS

The authors thank the UDOT staff for identifying and locating the material inventories that were vital to this inves-

tigation, and to the UGS library for providing copies of county inventories that we needed. A special thanks to the reporters and organizations that contributed data to MRDS from which we developed the initial databases used in the study. Thanks also to Phil Moyle for his review, and who recognized what the objectives of the study were and suggested that we include an objectives section in the report. Lastly, thanks to Bryce Tripp (UGS) for his review, and providing valuable insight to the historical circumstance of data collection.

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APPENDIX

Introduction

This appendix provides some additional information about some of the graphics and statistical tests used in this study. The histogram is given in the example as it is a familiar way to present data, and provides a reference to boxplots, statistical distributions, and models developed from the same data as used for the histogram. It was also used to show numbers of deposits found by elevation in Lake Bonneville sediments (figure 19).

Histogram, Transformation, and Distributions

One of the simplest diagrams used to illustrate data is the histogram. It is prepared using a table of frequency distributions where data are grouped into several defined intervals. Each interval is depicted as a bar in the histogram the height of which is proportional to the number of observations (or counts) in the interval (figure 5A).

Also shown on the histogram is the outline of the normal distribution (figure 5A) that is fitted to the same data that make the histogram. The normal distribution is one of the best-known and most often observed frequency distributions in geology (Krumbein and Graybill, 1965). Also commonly found is the lognormal distribution. Log normal distributions are used to describe concentrations of trace elements in rocks, thicknesses of sedimentary beds, and particle-size distributions of some sediments (Krumbein and Graybill, 1965).

Data that fit a normal distribution have a predictable bell-shaped curve, the outline of which is commonly suggested by the histogram (figure 5A). However, the curve in this example is for a lognormal distribution. The sand and gravel deposit volume data have a normal distribution only after the values are transformed into base logarithm 10. Transformation is a common procedure in statistics and includes, among others, taking the square root of the values. It is not uncommon for transformed values to follow a normal distribution. Thus, the data are transformed as logarithms in the example, and the curve is identified as a lognormal distribution in figure 5A. To make the values easily understood, volume is reported in exponential form on the x axis.

Boxplots

Another way to portray data is with the boxplot (figure 5B). Examination of data in this study begins with the creation of boxplots. The same data used to prepare the histogram in figure 5A are used in the boxplot of figure 5B. Note the x axes on both diagrams are identical (figures 5A and 5B). Construction of a boxplot is straightforward. As an example, consider constructing the boxplot shown in figure 5B for volumes of sand and gravel of Lake Bonneville. Values of sand and gravels are ranked from smallest to largest. The midpoint in the ranked data is the median, that defines the internal line. The data are then divided into an upper half and a lower half by the median. Each half is again divided in half. The midpoint in the lower half is used to locate the left edge of the box. A quarter of the data is located between the median and the left edge of the box. The midpoint in the upper half is used to locate the right edge of the box. A quarter of the data is located between the median and the right edge of the box. Whiskers extend out from the box on both sides to vertical lines that are called fences which are identified on figure 5B. The fences bound 40 percent of the values above, and 40 percent below, the median. Data beyond the fences are shown as points and account for the lowest 10 percent of the values and the highest 10 percent of the values in the data. Eighty percent of the data is found between the fences.

Modeling

Models follow the procedure outlined by Singer (1993b), who was concerned about finding ways to use grade and tonnage data of mineral deposits (predominantly metallic types) in quantitative resource assessment and exploration planning. Models used in this report are simply a graphical way to present data (figure 5C). Both the data and the statistical distribution that can be used to describe the data are shown in figure 5C. The distribution line is obscured in figure 5C but is visible in figures 7 and 8. The horizontal axis shows the geotechnical characteristic being modeled, and the vertical axis shows the cumulative proportion of deposits (Singer, 1993b). The geotechnical characteristic in this example is deposit volume. The data are cumulated in figure 5C so that larger sand and gravel volumes are at lowest percentages, the smallest at higher percentages. For example, 90 percent of the sand and gravel volumes have a value of $30,000 \text{ m}^3$ (23,000 yd³) or greater, 50 percent of the variables have a value of 250,000 m³ (190,000 yd³) or greater, and 10 percent of the variables have a value of 2.3 million m³ (1.8 million yd³) or greater. These three percentiles are from the statistical distribution used to describe the data.

Chi-Square Test

Another statistical test employed in this study was the Chi-square test. The test is used to determine if two nominal variables are independent. An example of a nominal variable is the classification of the outcome of a coin toss as heads or tails. A comparable nominal classification in this study would be categorizing sand and gravel deposits by types such as terrace or beach. Classification of ancient shorelines of Lake Bonneville as the Bonneville shoreline or the Provo shoreline is also a nominal variable. Therefore, in this example, each sand and gravel deposit has two nominal assignments--deposit type and shoreline. This information can be organized into a table (also called a contingency table). Tables 2, 3, and 4 are examples. Is there an association between sand and gravel deposit types and the shorelines where they are located? More exactly, do the counts of observed members in the cells of the tables depart significantly for the Chi-square test from the expected counts of members given the nominal variables are independent? The expected count of members in each cell is the total deposit count times cell probability. For example, in table 3, there is a total of 367 deposits, including those with one deposit type and hybrid deposit type (these characteristics are called deposit styles) among the three shoreline groups. Since the probabilities are unknown for each cell, an estimate is made from the observed results. An estimate of the expected number of one-deposit types in the Bonneville shoreline group (table 3) is made by first determining the proportion of all deposits that belong to the Bonneville shoreline group, which is 134 deposits (the total for the second row in table 3). Therefore, 134 of the 367 deposits found in table 3 or 36.5 percent of all deposits used are from the Bonneville shoreline group. Next, consider the total of 310 one deposit-type members in table 3. Of these deposits, 36.5 percent or 113 deposits, are expected to be in the Bonneville shoreline group. Note, this is the value in parentheses in table 3. The expected values for all other cells in table 3 are calculated in a similar fashion.

If shoreline groups and deposits styles are not independent, the Chi-square test statistic that compares the numbers of observed and expected members in the cells would be too large to be due to chance. If the variables are dependent, then deposit style may be dependent upon the shoreline in which the deposit is located. When the probability is less than the 5-percent confidence level, the assumption of independence of the nominal variables in Chi-square testing is rejected.

ECONOMIC GEOLOGY OF MANGANESE

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ABSTRACT

Ninety percent of manganese is used as an alloying element in steel. Smaller amounts are used in dry-cell batteries, in aluminum and bronze alloys, and many other uses. The element has several oxidation states, and oxidation-reduction reactions control its chemical behavior. Manganese, in primary minerals such as rhodochrosite, rhodonite, and braunite, is in a divalent oxidation state, and manganese in secondary minerals, such as pyrolusite and cryptomelane, is in a quadrivalent state.

Virtually all manganese ore production comes from three types of sedimentary manganese deposits. First, lenticular beds of manganese carbonate or carbonate-silicate rock in Early Precambrian volcano-sedimentary complexes in South America and Africa have been major sources of manganese ore. Second, laterally extensive beds of mangano-silicate and manganiferous carbonate minerals in certain banded iron formations are major sources of commercial ore and constitute the largest resource of manganese. Finally, manganese accumulations deposited in marginal to epicontinental basins are the largest source of current manganese ore production. Residual deposits resulting from the destructive weathering of rocks with a low manganese content have been, but are no longer, important sources of manganese ore.

Most deposits have been altered to some extent by supergene oxidative processes, and are economic because of that alteration. Outcrops of manganese ores are invariably oxidized and can be very deceiving as to the character of the underlying material. Nearshore facies of epicontinental basins, and nearshore age-equivalents of metalliferous black shales are among the targets for new manganese exploration. Very high-grade manganese occurs in sedimentary deposits altered by metamorphic and metasomatic processes.

INTRODUCTION

This paper discusses the chemistry and industrial specifications of manganese ores, and describes and classifies those types of manganese deposits from which ores meeting industrial specifications have been produced economically. Excluded from the discussion are manganiferous veins and precious/base metal-bearing gossans, for which methods to produce usable manganese concentrates have not been developed; and deep-sea manganese nodules, for which economic and environmentally acceptable recovery systems have not been developed. For a discussion on the economics of manganese, including resources, historical market requirements, and projected supply and demand, see Machamer (in press).

CHEMISTRY AND MINERALOGY

Manganese, atomic number 25, is a hard, brittle, grey metal with oxidation states of +2, +4, and +7 being the most common (Laubengayer, 1949). In aqueous solution, the behavior of manganese is similar to that of iron: the divalent form is relatively soluble, and thus mobile, whereas the higher valence states (quadrivalent, in the case of manganese) are highly insoluble, and thus immobile. In primary minerals, manganese is generally in the divalent or trivalent state, occurring in minerals such as rhodochrosite (MnCO₃), rhodonite (MnSiO₃) and variations thereof, braunite $(Mn^2Mn_6^3SiO_{12})$, and hausmannite $(Mn^2Mn_2^3O_4)$. These minerals alter readily and yield manganous ions to ground water; when the ground water reaches an oxidizing environment, or becomes oxidizing, the lower valence ions are rapidly oxidized to the quadrivalent manganic state and immediately precipitate as manganese dioxide/hydroxide or variations thereof. The common manganese minerals in the supergene or surficial environment are pyrolusite (MnO₂) and its polymorphs, and the cryptomelane/psilomelane series $[(K, Ba)1-xMn^3xMn^4_7O_{16}]$. Iron has a much greater affinity for oxygen than does manganese (Garrels and Christ, 1965): thus, when both manganous and ferrous ions are present, the iron will oxidize and precipitate almost quantitatively before manganese begins to oxidize and precipitate (Krauskopf, 1957).

The importance of recognizing the effects of supergene processes in the evaluation of manganese ores cannot be overemphasized. Outcrops are always oxidized, and can be very deceiving as to the character of the underlying material. Vertical or steeply dipping manganese deposits are almost universally oxidized to a depth of 90 meters (300 feet); shallow-dipping deposits may be oxidized for a horizontal distance of more than 200 meters (600 feet) from the outcrop. Manganese content is usually increased (enriched) by weathering, whereas silica is usually depleted (leached). Elevated values of potassium (in cryptomelane), and phosphorus, can render a manganese ore unusable. The manganese to iron ratios may also have changed due to weathering. Many manganese ores are of value only because of supergene enhancement of both ore chemistry and physical structure.

USES OF MANGANESE

The uses of manganese are reviewed in Mineral Facts and Problems (Jones, 1985). Approximately 90 percent of manganese is consumed as ferro manganese or silicomanganese in the iron and steel industry, where the manganese acts as a deoxidizer and desulphurizer and imparts specific metallurgical properties to finished steels. Manganese dioxide, either natural or manufactured, is an essential component of dry-cells, where it is one of the chemical reactants, and serves as a depolarizing agent. Metallic manganese is used in aluminum and bronze alloys. Various manganese compounds are used as coloring agents in ceramics, as oxidizing agents in chemical plants and water treatment facilities, as animal feed supplements, as fungicides, and for other uses.

Manganese ores for metallurgical use have rigid specifications with respect to the content of base metals (cumulatively less than 0.1 percent), sulphur (as low as possible; maximum about 0.03 percent), and phosphorus (again, as low as possible, maximum 0.15 percent). The ratio of manganese to iron is also important, with the preferred ratio being 7.5:1, but no less than 6:1. For use in dry-cells, manganese dioxide content must be as high as possible, with an absolute minimum of 70 percent, and base metal content cannot exceed a cumulative total of .005 percent (50 ppm). Metallurgical grade manganese ores are also used for a variety of other purposes, including as a coloring agent in the ceramics industry. The ceramics industry demands specific ores from specific deposits in order to guarantee consistent hues in their finished products.

CLASSIFICATION OF DEPOSITS

Manganese ores which are, or have been, of industrial importance fall into one of two broad groups: residual deposits, resulting from the destructive weathering of sedimentary or metasedimentary rocks with low manganese content; and sedimentary rocks (lithostratigraphic units) with a high primary manganese content. Many of the sedimentary deposits have been more or less altered and enriched by supergene processes. A subset of the sedimentary type are those which have been modified and/or enriched by metamorphic or metasomatic processes.

Residual Deposits

The source rocks for most residual manganese deposits are primarily dolomite, dolomitic limestone, and manganiferous shale (or their metamorphic equivalents) containing a few percent divalent manganese in carbonate and silicate minerals. The manganese is released by the breakdown of the primary minerals, transported in ground water to the site of accumulation, and precipitated and/or concentrated by oxidation. The same processes also concentrate iron and phosphorus. The resultant deposits tend to be small and discontinuous, and to have variable, but relatively high, iron and phosphorus contents.

Although historically important, residual manganese deposits are of limited present significance. Perhaps the most important residual deposits were those of the Postmasburg district in the former Cape Province of South Africa (Grobbelaar and Beukes, 1986). Other relatively important residual manganese deposits occur in India, Brazil, Zambia (Fort Rosebery), and the Philippine Islands. In the United States, residual deposits were mined in the Appalachian states and in Arkansas in the early part of this century (Harder, 1910).

Sedimentary Deposits

Sedimentary deposits are divided into three groups, each with a distinctive geological setting and character. The first group is comprised of lenticular beds of manganese carbonate or carbonate/silicate in metamorphosed Early Precambrian volcano-sedimentary complexes (greenstone belts). The second group is comprised of beds of braunite and manganiferous carbonate minerals in certain distinctive units of banded iron formations. The third group includes basin-margin deposits associated with epicontinental sedimentary systems. These deposits may be endogenic, with the manganese oxides, carbonates, and silicates having been derived from within the basin; or exogenic, with the manganese having been derived from sources external to the basin. All of the deposits have been modified to a greater or lesser extent by post depositional supergene processes, and some of the older deposits have been metamorphosed. The sedimentary deposits are, and will continue to be for the foreseeable future, the principal source of economic manganese ore.

Volcano-Sedimentary Deposits

Volcano-sedimentary deposits are composed of lenticular beds of manganese carbonate or manganese carbonate/silicate protore intercalated with submarine (pillowed) basic volcanic rocks and carbonaceous shale, and their metamorphic equivalents (orthoamphibolite [Herz and Banerjee, 1973] and graphitic schist). Near-surface protore is always oxidized and enriched to a high-grade oxide ore; oxidation and enrichment typically extend to a depth of 90 meters (300 ft). The unoxidized protore resembles grey, fine-grained, dirty limestone, and is remarkable only for its relatively high specific gravity. The oxidized ore forms hard, dense to vuggy, commonly botryoidal, masses of black manganese dioxide minerals.

These deposits occur in clusters or belts of lenses, with the horizontal dimensions of an individual lens on the order of a few tens of meters by a few hundreds of meters. There may be only one individual lens in a deposit, or several, as at Serra do Navio (Scarpelli, 1973). Because the manganese oxide ores are both physically and chemically resistant, deposits of this type form prominent topographic features which typically stand out above the surrounding countryside.

The known deposits of the volcano-sedimentary type occur in older terranes in those portions of the Precambrian shield areas of South America and Africa that border the South Atlantic Ocean (ancient Gondwana). In Nsuta, Ghana the host rocks for the protores are unconformably overlain by the auriferous quartz-pebble conglomerates of the Tarkwa gold field. Deposits included in the volcano-sedimentary group are the Morro da Mina (Lafaiete), Jacobina, and Serra do Navio deposits in Brazil; probably the Matthews Ridge deposit in Guyana; Tambao deposit in Burkina Faso; Nsuta deposit in Ghana (Service, 1943); Grand Lahou in the Ivory Coast (Peccia-Galleto, 1960); and Kisenge in Zaire (Pelletier, 1964). Other than at Tambao and Kisenge, the enriched oxide ores that capped the deposits of the volcano-sedimentary type have now been depleted; carbonate protore is now being produced from Morro da Mina and Nsuta.

Deposits in Banded Iron Formations

The manganese deposits in banded iron formations are distinct, discrete, laterally extensive beds comprised principally of braunite and manganiferous carbonate minerals, within jaspilitic iron formations. The host iron formations are distinct in that the bedding is quite irregular and all of the iron is present as hematite. Iron and manganese are mutually exclusive, with essentially no manganese in the jaspilite and no iron in the manganese beds. Although the manganese beds have been extensively modified by supergene processes, the highly oxidized state of the iron formation is a primary feature and not the result of post-depositional oxidation.

The known examples of this class of deposits are in the Hotazel Formation of the Kalahari district of South Africa (Black Rock, Hotazel, Mamatwan, Middleplaats, N'chwaning, Wessels, and others mines) (Cairncross and others, 1997) and the Band' Alta Formation of Mato Grosso Sul, Brazil (Santana and Urucum deposits) and Santa Cruz, Bolivia (Mutun) (Dorr, 1945; Haralyi and Walde, 1986). The Hotazel Formation underlies an area of about 300 square kilometers (120 square miles), under cover of younger rocks. The Band' Alta Formation, on the other hand, caps a group of prominent, irregular mesas within an area of several hundred square kilometers in the area south of Corumba, Brazil and Puerto Suarez, Bolivia. The age of the Hotazel Formation is reported to be between 2,200 to 2,300 ma (Cairneross and others, 1997), whereas the age of the Band' Alta Formation has not been definitively determined.

The manganese beds in both the Hotazel and Band' Alta Formations have been materially altered, with very important economic consequences in both cases. It appears that the primary ore (protore) in both formations is a braunite/manganiferous carbonate rock containing about 35 percent manganese, and a relatively low iron content. In the Kalahari district, the protore has been metasomatically altered along faults and fracture zones, giving rise to the premium, very high manganese, low iron lump ores of the Wessels (+50 percent Mn) and Hotazel (up to 60 percent Mn) types for which the district is famous. In the case of the Band' Alta Formation, supergene alteration, extending inward from the outcrop in some places for more than 200 meters (600 feet), converted the protore into high-iron (about 10 percent), high- potash (2.5 percent) cryptomelane, which has a significant negative impact on the smelting characteristics of the ore. Similar alteration has affected some near surface parts of the Hotazel Formation in South Africa.

A minor subset of this deposit type is the group of residual deposits formed by the supergene alteration of manganese carbonate-rich, siliceous iron formations of India, Brazil (Miguel Burnier, Miguel Congo), and the North Range of the Cuyuna district of Minnesota, United States.

Manganese deposits in units of banded iron formations support about 20 percent of current manganese ore production, and constitute the largest known manganese resource, although by no means, all of that resource meets current industrial specifications. This type of deposit may also hold the highest potential for the discovery of new deposits.

Endogenic Basin-Margin Deposits

Endogenic basin-margin deposits formed in the marginal areas of anoxic/euxinic epicontinental basins, where the supply of manganese to depositional sites was almost certainly from within the basin. In this situation, iron and base metals are precipitated by reaction with hydrogen sulphide in the anoxic portions of the basin. This, in turn, leads to the relative concentration of manganese in the seawater, which is then precipitated by oxidative processes where upwelling currents carry the manganese-enriched waters to oxidizing sites (Weber, 1968, 1973; Force and Cannon, 1988). A "living" example of this type of deposit is the group of Oligocene deposits that border the Black Sea (Varna in Bulgaria, Nikopol in Ukraine, and Tchiatura in Georgia). The Black Sea deposits have a well-developed updip (nearshore) oxide facies (Nikopol and Chiatura), a mixed oxide carbonate facies, and a downdip (offshore) silicate-carbonate facies (Varna and Bolshoi Tokmak) (Varentsov and Rakhmanov, 1977). The oxide facies has been the principal source of economic ore. Facies relations may be obscured somewhat by syndepositional oxidation and erosion, as well as by postdepositional oxidation.

Examples of endogenic basin-margin deposits are found in the Proterozoic Francevillien Series in Gabon and Rio Fresco Series in Para, Brazil. The Gabon deposits are the result of in situ oxidation and surficial enrichment (by concentration of manganese and leaching of silica) of a flat lying, carbon-rich black shale with a high primary manganese carbonate content. The deposits cap a series of prominent plateaus (Bangombe, Okouma, and others) in the Franceville region, although not all of the plateaus contain ore of the quality presently being mined. The Azul deposit in the Rio Fresco Series of the Carajas region of northern Brazil is almost identical to the Gabonese deposits (Coelho and Rodrigues, 1986), although Azul shows evidence of some post-weathering redistribution of the ore.

Large parts of Central Africa (UNESCO, 1985), and the Amazon Basin (Departamento Nacional de Producao Mineral, 1995) appear to be underlain by rocks equivalent to the Francevillien and Rio Fresco Series, suggesting that these areas may be prospective for deposits similar to the Gabonese and Azul deposits. Nearshore facies of rocks that are age equivalent to the "black shale" metal deposits (Nonesuch Shale of Michigan, United States; Zechstein of Europe), and nearshore facies of basins such as the Athabasca Basin in Canada, are also prospective for manganese deposits of this type.

A subtype of the endogenic basin-margin type of deposit occurs near Molango, Hidalgo, Mexico, on the eastern margin of the great carbonate platform that forms the Mesa Central physiographic province of Mexico (Okita, 1992). Here, the basal portion of the Jurassic Taman Formation (silty limestone) contains a laterally extensive manganiferous zone containing up to 28 percent manganese. The higher grade portions of the zone are mined by both open pit and underground methods, and the ore is calcined to produce a 38 to 40 percent manganese sinter. Oxidized outcrops of the manganiferous zone are an important source of high grade battery-active manganese ore.

Exogenic Basin-Margin Deposits

Exogenic basin-margin deposits are thought to have formed where the source of the manganese was external to the basin within which the deposit formed. The best known example of this deposit type is the Cretaceous Groote Eylandt deposit on the island of that name in the Northern Territory of Australia. The deposit consists of a discontinuous bed of pisolitic manganese oxide overlying and wedging out against a Precambrian quartzite. The bed is reported to grade downdip into "manganiferous calcareous siltstone" (Pracejus and Bolton, 1992). The manganese bed occurs on the landward side of the island, and, from informal comments by geologists working in the area, also on the adjoining mainland, but does not occur in age-equivalent rocks on the seaward side of the island.

The Groote Eylandt deposit has been modified by secondary solution and redeposition of manganese, giving rise to very high grade lump ores, as well as to underlying siliceous ore (sand and disaggregated quartzite cemented by manganese oxides).

Metamorphic and Metasomatic Deposits

Metamorphic and metasomatic deposits are formed from sedimentary manganese-rich rocks that have been altered by postdepositional processes not necessarily related to surficial weathering. The principal metamorphic deposits are those of the Mansar Schist Belt north and northeast of Nagpur, in the states of Maharashtra and Madhya Pradesh, India (Balaghat, Dongri Buzurg, Mansar, Tirodi, and other deposits). These deposits consist of a series of isolated, steeply dipping bodies of braunite with quartz and manganese silicates ("gondite") in a high-grade metasedimentary terrane. The deposits all had higher-grade supergene caps, which have been largely depleted. Only one mine (Dongri Buzurg) still produces high-grade supergene ore, while the Balaghat mine produces high-grade primary ore.

The principal metasomatic deposits are those of the Black

Rock, Hotazel, N'chwaning, and Wessels mines, in the northern portion of the Kalahari district in South Africa (Cairncross and others, 1997). Metasomatism occurred where the braunite protore of the district is cut by thrust and normal faults, and caused a differential migration of iron and manganese within the manganese beds, such that iron moved towards, and manganese away from, the fault zones (Gutzmer and Beukes, 1995). The results are the high-grade Wessels-type, and super high-grade Hotazel-type ores of the Kalahari district.

ACKNOWLEDGMENTS

Particular thanks are due the management and staffs of Associated Manganese Mines of South Africa, Limited; SAMANCOR (South Africa); Cie. Miniere de l'Ogooue (Gabon); Groote Eylandt Mining Company (Australia); the former African Manganese Company Ltd. (Ghana); ICOMI (Brazil); Cia. Minera Autlan, S.A. (Mexico); Manganese Ore India Ltd.; Cia. Vale do Rio Doce (Brazil); the former Cia. Meridional de Mineracao (Brazil); Mangan, Inc. (Bulgaria); Mysore Minerals Ltd. (India); and Sandur Manganese and Iron Ore Ltd. (India); each of whom received the author with great hospitality and provided valuable insights into its operations. Elkem ASA supported much of the compilation and analysis of data upon which this review is based, and has concurred in the presentation of this review. Mr. Trond Veisal of Elkem assisted the author in all phases of the Elkem project. Dr. Thomas S. Jones of the U.S. Geological Survey provided much valuable information. Drs. Nicolas Beukes of Rand Afrikaans University and Arno Kleyenstuber of Mintek, both in South Africa, organized an outstanding field trip in that country and provided much fruitful discussion. Dr. Somnath Dasgupta of Jadavpur University did the same for the Mansar Schist Belt of India.

This paper was reviewed by Glenn B. Morey and G. Robert Ganis, both of whom provided critical comment and valuable suggestions.

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THE INFLUENCE OF GEOLOGY ON THE QUALITY OF FELDSPAR PRODUCTS

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ABSTRACT

Feldspars have major uses in glass manufacture and in ceramic products. About 6 million metric tons (6.6 million short tons) are used annually. Feldspars are desirable because of their high aluminum and alkali contents. Na feldspars are favored for glass, while K feldspar is often preferred in the pottery and tile industries. Economic deposits occur in a variety of geological environments. Most are in granites or granite-like bodies, pegmatites being a common source worldwide. Alkali granites, particularly those sometimes called alaskites, are mined directly as a source of feldspar and associated minerals. Some other igneous bodies, such as aplites, rhyolites, and partly altered granites (for example china stone) provide alternative feldspar-rich products. Nepheline syenites and phonolites are other sources of feldspar and contain higher amounts of alkalis. Feldspar-rich (arkosic) sediments derived from the weathering of pegmatites and granites are widely extracted and processed for use in ceramics. The present study reviewed the various sources of feldspars throughout the world. Data on the quality of products has been taken from literature, and samples have been obtained from a large number of producers. The mineralogy and chemistry of the samples has been determined and, as far as possible, have been related to the geology of the source area.

Feldspar products show a wide range of chemical and mineralogical compositions. Some are pure Na feldspar (albite), others are made up entirely of K feldspar (microline and orthoclase), but many are mixtures of Na and K feldspars. Significant quantities of quartz are often present, and many products contain mica and kaolinite. Fe₂O₃ contents are very low, typically less than 0.1 percent. Detailed mineralogical studies show that four groups of products can be recognized on the basis of feldspar mineralogy. These are albite, albite with microcline, microcline with orthoclase, and orthoclase with albite. Products containing microcline and orthoclase together are mostly sedimentary in origin. Those with albite only, or albite with microcline have a pegmatitic or granite origin. Those containing orthoclase as the dominant K feldspar are derived from aplites or rhyolites. There does not appear to be any relationship between the feldspar mineralogy and the quartz content. Peraluminous Stype granites and pelite-dominated high-grade metamorphic rocks, in which there is a significant volatile component, are likely to be the most important feldspar sources. Partial kaolinization of feldspar-containing rocks often improves minability, decreases crushing costs, reduces iron content, and increases the K₂O/Na₂O ratio.

INTRODUCTION

Around 6 million metric tons (6.6 million short tons) of feldspar products are consumed worldwide annually (Harben, 1995; Bolger, 1995). These products come from a variety of sources, including pegmatites, aplites, rhyolites, alkali granites, especially those known as alaskites, and partly altered granites, such as china stone. Another major source is from feldspathic sands. In some products, the raw material is highly processed to remove impurities. Others are sold virtually in the unprocessed state, apart from size reduction, and contain feldspar along with significant amounts of other minerals, notably quartz.

Feldspars are exploited in numerous countries for internal consumption, but there is also a substantial amount of international trade in the mineral. By far the largest markets are the glass (approximately 60 percent of consumption) and ceramic (35 percent) industries (Harben and Bates, 1990; Collenette and Grainger, 1994). In glass, feldspar provides a source of aluminum along with some alkalis, and in ceramics feldspar provides a low melting or fluxing constituent (Bolger, 1995). Generally, Na-rich feldspars are used in the glass industry, whereas K-rich feldspar is preferred for the manufacture of ceramics (Harben and Bates, 1984; Harben, 1995). The remaining 5 percent of feldspar production is used in the manufacture of abrasives and fillers (Harben and Bates, 1990; Collenette and Grainger, 1994). Apart from the high alkali and aluminum contents required in feldspar products, the only other chemical requirement is for a low amount of coloring oxides, such as Fe_2O_3 and TiO_2 , and volatile elements, such as F. A lot has been written of the main markets and uses of feldspars (Harben and Bates, 1990; Kauffmann and Van Dyk, 1994; Bolger, 1995; Harben and Kuzvart, 1996), therefore, these subjects are not addressed here.

The scope of this paper is to evaluate the geological origin of existing commercial feldspar deposits, so producers can optimize their product to market requirements, and focus their exploration for new deposits on specific geological environments. This is accomplished by relating the composition and mineralogy of feldspar products to their geology. A knowledge of the mineralogy and petrology of feldspars, especially their crystallization dynamics in a granitic melt, is used to explain the diversity observed.

The work has involved a worldwide research of feldspar products, both from literature and from data provided by producers. Useful sources of information were found in "Industrial Minerals" and other journals, both in individual articles and in advertisements. Several companies provided a large number of samples to support the literature study. The samples were final products in powder form. These samples were analyzed chemically for major and minor elements by X-ray fluorescence spectrometry. Detailed mineralogy was determined by X-ray diffraction. Distinction between orthoclase and microcline was made using the data in Ribbe (1983a).

For some of the data, the geological setting of the feldspar product is known. In other cases, limited or no information is available, and assumptions were made based on the regional geology of the source area. Industrial mineral merchants, in particular, were unaware of the geological setting of the minerals they were selling. This is unfortunate, because with geological knowledge of their products, they could better suit a particular product to a market, and could easily decide on the market potential and quality for new sources of feldspar. The research also goes part way to enabling users of feldspar products to gain some knowledge of the geological source of their feldspar product based on its chemical and mineralogical properties. All of the information has been compiled into a database. Individual companies are not identified as samples were supplied in confidence, and it is not the purpose of this paper to comment on the relative quality of individual products.

MINERALOGY AND PETROLOGY OF FELDSPARS

Feldspars are framework silicates made up of interlinking SiO₄ and AlO₄ tetrahedra with alkali (usually Na and K) or alkaline earth (usually Ca) elements occupying the available voids in the atomic structure (Ribbe, 1983b, 1983c; Klein and Hurlbut, 1993). There are three main end members, NaAlSi₃O₈, KAlSi₃O₈, and CaAl₂Si₂O₈, but, varying degrees of solid solution and disorder in the Si-Al distribution give rise to many different feldspar compositions, crystal morphologies, and intergrowths. In Na-K, or alkali feldspars, the Al-Si distribution varies from complete disorder, as in sanidine (KAlSi₃O₈) and high albite (NaAlSi₃O₈), through some degree of order, as in orthoclase (KAlSi₃O₈), to complete order as in microcline (KAlSi₃O₈) and low albite (NaAlSi₃O₈). There is almost complete solid solution between Na and Ca end-member compositions (the plagioclase series). A complete solid solution also exists between the Na-K, or alkali feldspars, at high temperatures, but this breaks down at lower temperatures (figure 1), producing Narich (low albite) and K-rich feldspars (orthoclase or microcline). These can occur as entirely separate crystals or are intimately intergrown as an 'apparent' single mineral, known as perthite. The separate Na and K feldspars in perthite are only visible at high magnifications under a microscope. Whether separate Na and K feldspars or a perthite occurs depends on the mode of formation. Minor amounts of Ca are usually present in the Na-rich end-member feldspars.

The crystallization of alkali feldspars in granites and related acid igneous rocks is strongly controlled by temperature, and by the pressure of coexisting volatile components such as water (H₂O), carbon dioxide (CO₂), chlorine (Cl), boron (B), and fluorine (F). In the absence of volatiles, the lowest temperature K feldspar (microcline) is only stable at temperatures well below the solidus (figure 2), the curve under which the system is completely solid. Therefore,



Figure 1. Binary diagram summarizing subsolidus phase relationships in the alkali feldspars. Based on Barth (1969) and Smith and Brown (1988).

under "dry" conditions, microcline can only form by solid state reordering from a higher temperature phase (for example, orthoclase). The point of final crystallization, or eutectic, of a typical granite magma, in the absence of volatile components, lies approximately midway between the main components (for example, modally 33 percent albite, 33 percent K feldspar, and 33 percent quartz); many granites reflect this composition. Water pressure has a major effect on the crystallization of the alkali feldspars (Bowen and Tuttle, 1950; Morse 1970). At low water pressures, only one alkali feldspar can crystallize (figure 2), although it can undergo solid-state reordering to give perthite intergrowths in which the two feldspars remain intimately mixed. Increasing volatile water pressure progressively depresses the solidus until, at high volatile pressures, typically in excess of 5,000 bars (Morse, 1970), the solidus cuts the solvus (figure 2), and two separate feldspars (one K-rich and one Na-rich) can crystallize simultaneously. The degree of depression of the solidus is also dependent on the chemistry of the volatile component. Fluorine- and boron-rich volatiles are more active and depress the solidus to a greater extent than water alone (Manning and Pichavant, 1983; London, 1990), but these elements normally only form minor constituents of volatile fluids. In addition to lowering the solidus, high volatile pressures also cause the eutectic point of the granite system to move towards the albite end member (Luth and others, 1964). Therefore, at water pressures of 5,000 bars, ideal crystallization of a granitic magma yields 50 percent albite, 30 percent quartz, and 20 percent microcline (Luth and others, 1964). Volatiles may also cause Na and K to become strongly partitioned. In particular, Na preferentially partitions into the volatile-rich melt phase (London, 1990). Thus, further separation of Na- and K-rich feldspars can occur in pegmatites.



Figure 2. Binary diagrams showing the effect of increasing H_2O pressure on the system KAlSi₃O₈-NaAlSi₃O₈. Diagrams after Bowen and Tuttle (1950) and Morse (1970).

GEOLOGY OF FELDSPAR DEPOSITS

The five main deposit types from which feldspar products are obtained are: (1) pegmatites, (2) aplites, (3) rhyolites, (4) granites, and (5) feldspathic sands. The geology for these types of deposits is reviewed in Bates (1969), Harben and Bates (1984; 1990), Kauffmann and Van Dyk (1994), and Harben and Kuzvart (1996). Brief summaries of each deposit type are given below.

Pegmatites

Pegmatites are very coarse-grained rocks of which there are two types. The first are of igneous origin related to granites. They constitute the last derivatives of magmatic fractionation, and consequently are rich in volatile components and other elements which are incompatible in magmatic minerals (for example Li, F, B, and Be). A second type of pegmatite, of metamorphic origin, can be produced as initial liquid fractions under conditions of progressive partial melting during regional metamorphism in orogenic areas. Both types of pegmatites are mined for feldspars in many parts of the world. They constitute the main source of feldspar for internal use in less developed countries. Small scale operations are common where individual pegmatites a few meters wide are exploited. Both Na- and K-rich feldspars can be present in a single pegmatite, although perthites are very common. Individual Na- and or K-rich feldspar products are sometimes selectively mined. If the individual minerals are present in very large crystal sizes, they are separated into different feldspar types by hand. Large pegmatites are often zoned so that different mineral assemblages are found in different parts of the pegmatite, enabling further selective mining. Mica, quartz, and Li-bearing and other rare lithophile element minerals are sometimes exploited from pegmatites simultaneously with feldspars. In finer grained pegmatites, and in larger scale operations, the separation of feldspar from quartz, and from mica, some of which is often enclosed within feldspar crystals, is made using froth flotation. In France,

bodies of albitite are exploited as a source of feldspar (Harben and Kuzvart, 1996). They are similar to pegmatites, but are of metasomatic origin.

Aplites

Aplites are fine grained rocks with a similar chemical composition and mineralogy to granite, usually being made up of one or more alkali feldspars plus quartz and mica. Aplites are often associated with pegmatites, and may represent the product of a residual magma similar to one which would form pegmatites, except that an aqueous fluid phase was absent. When Fe_2O_3 amounts are low (for example, biotite or Fe oxide minerals are absent), aplites can be a source of feldspar. Aplites are used in their crushed form without further processing. Commonly, they have a high Na₂O/K₂O ratio. Aplites are exploited commercially in Italy and the United States. They were formerly exploited in the United Kingdom (UK).

Rhyolites

Rhyolites are the volcanic equivalent of granites and are, therefore, similar chemically. Thus, they have potential as a source of high alkali material for glass or ceramic uses. Although originally mostly glassy, rhyolites often remain at least partly vitreous, or contain extremely fine-grained devitrified quartz and feldspar, occasionally with quartz or feldspar phenocrysts. Rhyolites appear to be rarely exploited as a source of feldspar, except where they have been hydrothermally leached of mafic (Fe-rich) components. Even then, the frequent presence of alunite restricts their use as a source of feldspar. Rhyolite deposits are mined in Germany, and similar altered dacitic rocks are exploited in Russia (Harben and Kuzvart, 1996).

Granites

Granites contain about 60 to 70 percent alkali feldspar,

either as perthite, or two separate alkali feldspars (albite or oligoclase, and orthoclase or microcline). Because of their abundance, they could provide the world with an unlimited supply of feldspar. However, only alkali-rich granites, with few or no ferromagnesian or other dark minerals, are currently used as a source of feldspar. These granites are classified as leucocratic, two feldspar granites, such as the alaskites in the Spruce Pine area of North Carolina (Olsen, 1944; Brobst, 1962; Harben, 1978), where grain sizes range up to pegmatitic in size. The whole rock is crushed and separated by froth flotation and other methods to yield feldspar products as well as quartz and mica (Hill and others, 1969). Potentially, many other low-Fe₂O₃, alkali-rich granites could be sources of feldspar. One advantage of extracting feldspar from a large uniform body of granite is that a consistent product can be made. This may be preferable to a smaller, more variable pegmatite source of feldspar, even though the pegmatite has a higher chemical purity.

A relatively small source of feldspar in the UK is a partially kaolinized leucocratic granite in south-west England, which is known as china stone. Traditionally, this material has been the principal flux in high quality bone china. The granite is selectively mined and lumps are further hand selected and used without further processing other than size reduction.

Nepheline Syenites and Phonolites

Nepheline syenites and phonolites are also sources of feldspar. They are quartz deficient and feldspathoid rich, and therefore, have a greater Na₂O content and an overall greater alkali content than other igneous feldspar products. The syenites and phonolites are processed using magnetic separation to remove ferromagnesian and iron oxide minerals, and compete with other feldspar products in glass, ceramic, and other markets. A comprehensive review of the geology of these type of deposits is found in Guillet (1994). Two deposits, one in Canada, and the other in Norway, dominate the western world's production of around one million metric tons (1.1 million short tons) per annum.

Feldspathic Sands

Some beach and alluvial sands are worked commercially for feldspars in several European countries, the United States, and Japan. Most of these sands are Pleistocene or Holocene deposits. The sediments are derived from nearby granitic bodies or feldspathic metamorphic rocks. They contain much quartz, and froth flotation and magnetic separation are used to separate the feldspars. Products ranging from relatively pure feldspars to feldspars mixed with quartz are often marketed from a single deposit.

CHEMISTRY AND MINERALOGY OF FELDSPAR PRODUCTS

Representative chemical analyses of feldspar products from different sources are given in table 1, along with the mineralogy determined by X-ray diffraction. Idealized endmember mineralogical compositions are calculated assuming a four-component system (albite, K feldspar, anorthite, and quartz), and perfect stoichiometry. The complete data are plotted in figures 3a and 3b, 4a and 4b, and 5a and 5b to illustrate the range of compositions found in company data sheets (43 products), published literature, and in the analyses of samples obtained from producers (53 samples). Although the two data sets show similar results, it would not be appropriate to combine them, as the former relates to typical compositions or maximum/minimum values for elements, whereas the latter is specific to the samples obtained. Nepheline syenite products are excluded from the data set.

A wide spectrum of feldspar compositions is shown, although feldspar products in which anorthite is the major component are absent (figure 3). Many are mixed Na and K feldspar products. Some are almost pure albite with very minor amounts of the anorthite component. A few are made up entirely of K feldspar apart from minor amounts of albite. Virtually all of the feldspars have a low CaO content (table 1, figure 3), reflected by the anorthite component almost always being less than 10 percent. Na-rich feldspars tend to



Figure 3. Ternary diagram showing the calculated feldspar mineralogy (modal percent) of (a) data from samples and (b) company data sheets and other published sources.

contain more Ca than K-rich products. Quartz is present in virtually all of the products. It is a major constituent in many (figure 4), and in a few it is dominant. All of the samples have low concentrations of impurities, such as Fe₂O₃, which would impart color to glass or ceramics at a higher level of concentration. This is to be expected as there would be no market for a feldspar product which contained a significant amount of impurities. Apart from rhyolites and aplites, which sometimes contain up to 1.0 percent Fe₂O₃, amounts of this oxide are mostly less than 0.1 percent. Some aplites contain a significant amount of MgO (0.5 percent). The Fe₂O₃ content does not appear increased preferentially in either albite or K feldspar products (figure 5); rather, our analyses show higher amounts of Fe₂O₃ than the published company analytical data sheets, indicating that the latter may not always fully reflect the composition of the product. TiO_2 is generally less than 0.5 percent. In many feldspar products, and especially feldspathic sands, this element occurs in amounts up to 0.25 percent, but is often less than 0.1 percent. However, in many pegmatites from different countries, and in aplite, TiO_2 is present in amounts around 0.2 to 0.3 percent. Small amounts of mica and or kaolinite are found in some samples, notably those where the loss on ignition is more than 2 percent.

The detailed study of the mineralogy (figure 6; table 1) shows that all products containing significant amounts of both Na₂O and K₂O are made up of at least two separate feldspar phases; no homogeneous Na/K feldspars, or sanidine, have been found. Four groups are recognised: (1) albite (\pm quartz), (2) albite with microcline (\pm quartz), (3) microcline with orthoclase (\pm albite and quartz), and (4) orthoclase (\pm albite and quartz), microcline always occurs with at least a small amount of other alkali feldspars, either orthoclase and or albite. There does not appear to be any relationship between the feldspar mineralogy and the quartz content (figure 6b). Although there are K feldspar-



Figure 4. Ternary diagram showing the calculated alkali feldspar – quartz mineralogy (modal percent) of (a) data from samples and (b) company data sheets and other published sources.



Figure 5. Ternary diagram showing the relationship of Fe_2O_3 to the feldspar chemistry (relative weight percent) of (a) data from samples and (b) company data sheets and other published sources. Note: Fe_2O_3 relative proportion is multiplied by 10.



Figure 6. Ternary diagram showing (a) the calculated feldspar mineralogy (modal percent) and (b) the calculated alkali feldspar – quartz mineralogy (modal percent) of samples with separation of mineral assemblage as identified by X-ray diffraction. Symbols: Δ = orthoclase plus albite; X = microcline plus orthoclase, with or without albite; O = albite plus microcline; + = albite only.

rich products with high amounts of quartz, the most albiterich products always have low quartz contents. Overall, there are relatively few pure, single feldspar products.

Muscovite and or kaolinite are found in many feldspar products. Muscovite accounts for the small amount of K_2O in some products which are dominantly albite. Kaolinite is present mostly in K_2O -rich feldspars. Its presence may be a consequence of the source rock being altered by weathering or hydrothermal activity, resulting in the selective removal of the Na feldspar component.

DISCUSSION

The mineralogical groupings described above reflect the source geology. All of the K feldspar-rich products containing both microcline and orthoclase are sedimentary in origin, derived from feldspathic sands. Those dominated by albite, and albite with microcline, appear igneous in origin, coming from granite or pegmatite. The products in which orthoclase is the dominant K feldspar are primary igneous rocks (aplites and rhyolites), apart from one group of samples of feldspathic sands from Japan.

Sedimentary feldspar deposits can give rise to relatively pure K feldspar products, albeit mixed microcline and orthoclase, with quartz contents are typically greater than 5 percent. There are few albite-dominant, sedimentary feldspar products. This most likely reflects the high susceptibility of albite to chemical and mechanical weathering compared to K feldspars. Orthoclase occurs, in addition to microcline, in many of the sedimentary feldspar products, but not in others. This probably indicates that the sediments have more than one granitic source, and or diagenetic growth of secondary K feldspar has also occurred within the sediment. The presence of orthoclase as the sole K feldspar phase in one set of sedimentary samples from Japan may indicate a different type of granite source from the other (mostly European) sedimentary feldspar products and may reflect a different tectonic setting.

Many pegmatite-derived feldspar products are albite rich (with little or no microcline). This is somewhat unexpected as pegmatites are commonly enriched in K feldspar (Hall, 1996). This may reflect the selective mining of albite-dominated pegmatites to accommodate market requirements. Mixed albite and microcline products, which often contain significant amounts of quartz, probably represent perthitic or antiperthitic feldspar intergrowths or mixed whole rock compositions, where no mineral separation has been attempted. Indeed, a number of the samples have chemical and mineralogical compositions approaching that of a typical granite.

The presence of microcline as the dominant K feldspar in the bulk of the samples indicates that the crystallization history of the source rock is critical in the development of feldspar products. Microcline can only form by subsolidus reordering or by crystallizing directly from granitic magma under high fluid pressures (Marmo, 1971). These processes require a significant degree of volatile activity. High volatile pressure is also important in enabling albite to be dominant in pegmatites, the eutectic of the granite system (K feldsparquartz-albite) shifts towards more albite-rich compositions under high volatile pressures (especially F and B) (Manning and Pichavant, 1983). In addition, Na preferentially partitions into the volatile-rich magmatic phase (London, 1990). Hence, during crystallization of granitic (microcline-albitequartz) pegmatites, the residual volatile pressure increases. This may shift the eutectic of the system towards albite, simultaneously lowering the viscosity of the melt (Hannah and Stein, 1990) and causing quartz and microcline to crystallize (London, 1990). The lowered viscosity of the melt allows the magma (Na, F, B enriched) to migrate (London, 1990) and form albite-rich pegmatites.

Peraluminous S-type granites (Chappell and White, 1974), typical of collisional and post-collisional orogenic zones, are commonly alkali rich, and Fe, Mg, and Mn poor (Barbarin, 1990). These granites predominantly comprise pelitic, crustal-derived material, but may contain a small mantle component (Barbarin, 1990). They may also contain a significant volatile content derived from the dehydration of

Table 1.

Summary of feldspar product chemistry and mineralogy. Major and minor refer to the relative abundance of the mineral phases microcline (Mc), orthoclase (Or), albite (Ab), quartz (Qz), mica (Mi), and kaolinite (Ka). * = calculated end-member composition assuming perfect stoichiometry. Percent feldspar values were calculated by assigning all K₂O to K feldspar (K-spar), Na₂O to albite (Na-spar), and CaO to anorthite (Ca-spar). Surplus SiO₂ is calculated as free quartz. \dagger = Total includes 0.25 percent F. LOI = loss on ignition. Data are in weight percent.

Source	*K-feldspar	*Albite	Pegmatites			Granite		
Major			Ab	Ab	Ab, Mc	Qz, Mc	Mc, Ab	Ab, Mc
Minor			Qz, Mi	Qz	Qz, Mi	Mi, Ka		Qz
SiO ₂	64.77	68.74	70.02	68.22	67.43	74.37	66.06	68.66
TiO ₂			0.11	0.03	0.25	0.14	0.00	0.02
Al_2O_3	18.31	19.44	17.66	18.46	19.34	14.20	18.61	18.12
Fe ₂ O ₃			0.06	0.13	0.18	0.71	0.05	0.07
MnO			0.00	0.00	0.00	0.03	0.00	0.00
MgO			0.08	0.00	0.01	0.15	0.00	0.00
BaO			0.00	0.01	0.06	0.01	0.04	0.09
CaO			0.49	0.38	1.52	0.00	0.08	1.31
Na ₂ O		11.82	9.53	11.45	7.76	0.22	2.38	6.62
K ₂ O	16.92		0.40	0.14	2.73	5.74	13.15	4.67
P_2O_5			0.20	0.03	0.27	0.02	0.00	0.01
S			0.00	0.02	0.00	0.00	0.00	0.00
LOI			0.65	0.65	0.28	4.08	0.42	0.30
Total	100	100	99.20	99.52	99.83	99.67	100.79	99.87
%K-spar	100		2.4	0.8	16.1	33.9	77.7	27.6
%Na-spar		100	80.6	96.9	65.7	1.9	20.1	56.0
%Ca-spar			2.4	1.9	7.5	0.0	0.4	6.5
%Quartz			12.0	0.3	8.6	51.1	1.7	9.5
Total			97.4	99.9	97.9	86.9	99.9	99.6
Source	China Stone	Aplite	Rhyolite		Fel	dspathic Sa	nds	
Source Major	China Stone Qz	Aplite Or, Qz	Rhyolite Qz, Or	Mc	Fel Mc, Ab	dspathic Sa Or	nds Qz, Or, Mc	Ab, Mc, Or
Source Major Minor	China Stone Qz Ab, Mc, Mi, Ka	Aplite Or, Qz Ab, Mi	Rhyolite Qz, Or Mi, Ka	Mc Qz, Or, Ka	Fel Mc, Ab Or, Mi	dspathic Sa Or Qz	nds Qz, Or, Mc Ka	Ab, Mc, Or Qz
Source Major Minor SiO ₂	China Stone Qz Ab, Mc, Mi, Ka 71.31	Aplite Or, Qz Ab, Mi 70.43	Rhyolite Qz, Or Mi, Ka 75.63	 Мс Qz, Or, Ka 66.24	Fel Mc, Ab Or, Mi 67.39	dspathic Sa Or Qz 66.88	nds Qz, Or, Mc Ka 85.45	Ab, Mc, Or Qz 67.56
Source Major Minor SiO ₂ TiO ₂	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06	Aplite Or, Qz Ab, Mi 70.43 0.29	Rhyolite Qz, Or Mi, Ka 75.63 0.07	Mc Qz, Or, Ka 66.24 0.25	Fel Mc, Ab Or, Mi 67.39 0.00	dspathic Sa Or Qz 66.88 0.07	nds Qz, Or, Mc Ka 85.45 0.12	Ab, Mc, Or Qz 67.56 0.01
SourceMajorMinorSiO2TiO2Al2O3	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20	Mc Qz, Or, Ka 66.24 0.25 17.34	Fel Mc, Ab Or, Mi 67.39 0.00 17.64	dspathic Sa Or Qz 66.88 0.07 17.34	nds Qz, Or, Mc Ka 85.45 0.12 8.29	Ab, Mc, Or Qz 67.56 0.01 18.81
$\begin{tabular}{ c c c c c }\hline Source & \\ \hline Major & \\ \hline Minor & \\ SiO_2 & \\ TiO_2 & \\ Al_2O_3 & \\ Fe_2O_3 & \\ \hline \end{tabular}$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09	dspathic Sa Or Qz 66.88 0.07 17.34 0.26	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04
SourceMajorMinorSiO2TiO2Al2O3Fe2O3MnO	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00
SourceMajorMinorSiO2TiO2Al2O3Fe2O3MnOMgO	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00
Source Major Minor SiO ₂ TiO ₂ Al ₂ O ₃ Fe ₂ O ₃ MnO MgO BaO	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.00 0.31	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16
Source Major Minor SiO ₂ TiO ₂ Al ₂ O ₃ Fe ₂ O ₃ MnO MgO BaO CaO	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05 0.03	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10
Source Major Minor SiO ₂ TiO ₂ Al ₂ O ₃ Fe ₂ O ₃ MnO MgO BaO CaO Na ₂ O	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09
$\begin{tabular}{ c c c c }\hline Source & \hline Major & \\ \hline Major & \\ \hline Major & \\ \hline Minor & \\ SiO_2 & \\ TiO_2 & \\ Al_2O_3 & \\ Fe_2O_3 & \\ Fe_2O_3 & \\ MnO & \\ MgO & \\ BaO & \\ CaO & \\ Na_2O & \\ K_2O & \\ \hline \end{tabular}$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13 7.41	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04
$\begin{tabular}{ c c c c }\hline Source & \hline Major & \\ \hline Major & \\ \hline Major & \\ \hline Minor & \\ SiO_2 & \\ TiO_2 & \\ Al_2O_3 & \\ Fe_2O_3 & \\ MnO & \\ MgO & \\ MgO & \\ BaO & \\ CaO & \\ Na_2O & \\ K_2O & \\ P_2O_5 & \\ \hline \end{tabular}$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13 7.41 0.01	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04
$\begin{tabular}{ c c c c }\hline Source & \hline Major & \\ \hline Major & \\ \hline Major & \\ \hline Minor & \\ SiO_2 & \\ TiO_2 & \\ Al_2O_3 & \\ Fe_2O_3 & \\ MnO & \\ MgO & \\ BaO & \\ CaO & \\ Na_2O & \\ K_2O & \\ P_2O_5 & \\ S & \\ \hline \end{tabular}$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13 7.41 0.01	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00
$\begin{tabular}{lllllllllllllllllllllllllllllllllll$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00 3.07	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05 0.03 0.13 7.41 0.00 2.81	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00 1.14	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00 0.38
$\begin{tabular}{lllllllllllllllllllllllllllllllllll$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00 3.07 98.99 [†]	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00 100.01	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05 0.03 0.13 7.41 0.01 0.00 2.81 100.44	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54 99.60	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68 100.21	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00 1.14 99.93	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40 100.12	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00 0.38 100.23
$\begin{tabular}{ c c c c c }\hline Source & \hline Major & \hline Minor & \\ \hline Minor & \hline SiO_2 & \\ TiO_2 & & \\ Al_2O_3 & & \\ Fe_2O_3 & & \\ MnO & & \\ MgO & & \\ BaO & & \\ CaO & & \\ MgO & & \\ BaO & & \\ CaO & & \\ CaO & & \\ Na_2O & & \\ CaO & & \\ Na_2O & & \\ CaO & & \\ CaO & & \\ Na_2O & & \\ CaO & & \\ S & & \\ LOI & & \\ \hline Total & & \\ \hline \% K-spar & \\ \end{tabular}$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00 3.07 98.99 [†] 26.9	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00 100.01 45.6	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05 0.03 0.13 7.41 0.01 0.00 2.81 100.44 43.8	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54 99.60 84.1	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68 100.21 64.2	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.00 1.14 99.93 77.7	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40 100.12 26.1	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.04 0.00 0.38 100.23 41.6
$\begin{tabular}{lllllllllllllllllllllllllllllllllll$	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00 3.07 98.99 [†] 26.9 18.2	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00 100.01 45.6 14.2	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13 7.41 0.01 0.00 2.81 100.44 43.8 1.1	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54 99.60 84.1 3.9	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68 100.21 64.2 24.1	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00 1.14 99.93 77.7 5.8	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40 100.12 26.1 1.5	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00 0.38 100.23 41.6 43.1
Source Major Minor SiO ₂ TiO ₂ Al ₂ O ₃ Fe ₂ O ₃ MnO MgO BaO CaO Na ₂ O K ₂ O P ₂ O ₅ S LOI Total %K-spar %Ca-spar	$\begin{array}{r} \mbox{China Stone} \\ \mbox{Qz} \\ \mbox{Ab, Mc, Mi, Ka} \\ \mbox{71.31} \\ \mbox{0.06} \\ \mbox{16.09} \\ \mbox{0.16} \\ \mbox{0.01} \\ \mbox{0.01} \\ \mbox{0.00} \\ \mbox{0.77} \\ \mbox{2.15} \\ \mbox{4.55} \\ \mbox{0.46} \\ \mbox{0.00} \\ \mbox{3.07} \\ \mbox{98.99}^{\dagger} \\ \mbox{26.9} \\ \mbox{18.2} \\ \mbox{3.8} \end{array}$	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00 100.01 45.6 14.2 6.4	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.05 0.03 0.13 7.41 0.01 0.00 2.81 100.44 43.8 1.1 0.1	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54 99.60 84.1 3.9 0.2	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68 100.21 64.2 24.1 1.0	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00 1.14 99.93 77.7 5.8 0.2	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40 100.12 26.1 1.5 0.1	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00 0.38 100.23 41.6 43.1 5.5
Source Major Minor SiO ₂ TiO ₂ Al ₂ O ₃ Fe ₂ O ₃ MnO MgO BaO CaO Na ₂ O K ₂ O P ₂ O ₅ S LOI Total %K-spar %Ca-spar %Quartz	China Stone Qz Ab, Mc, Mi, Ka 71.31 0.06 16.09 0.16 0.01 0.11 0.00 0.77 2.15 4.55 0.46 0.00 3.07 98.99 [†] 26.9 18.2 3.8 39.7	Aplite Or, Qz Ab, Mi 70.43 0.29 14.73 0.86 0.06 0.68 0.09 1.30 1.67 7.71 0.16 0.03 2.00 100.01 45.6 14.2 6.4 28.4	Rhyolite Qz, Or Mi, Ka 75.63 0.07 13.20 1.07 0.03 0.00 0.05 0.03 0.13 7.41 0.01 0.00 2.81 100.44 43.8 1.1 0.1 46.5	Mc Qz, Or, Ka 66.24 0.25 17.34 0.10 0.00 0.00 0.31 0.04 0.46 14.23 0.08 0.01 0.54 99.60 84.1 3.9 0.2 9.0	Fel Mc, Ab Or, Mi 67.39 0.00 17.64 0.09 0.01 0.02 0.00 0.20 2.85 10.87 0.46 0.00 0.68 100.21 64.2 24.1 1.0 8.8	dspathic Sa Or Qz 66.88 0.07 17.34 0.26 0.01 0.00 0.34 0.04 0.68 13.14 0.03 0.00 1.14 99.93 77.7 5.8 0.2 12.5	nds Qz, Or, Mc Ka 85.45 0.12 8.29 0.06 0.00 0.05 0.10 0.02 0.18 4.41 0.04 0.00 1.40 100.12 26.1 1.5 0.1 67.5	Ab, Mc, Or Qz 67.56 0.01 18.81 0.04 0.00 0.00 0.16 1.10 5.09 7.04 0.04 0.00 0.38 100.23 41.6 43.1 5.5 8.7

pelites. Hence, the chemistry of the magma and the presence of substantial volatiles in these granites are likely to produce the correct conditions to provide a suitable source for commercial feldspars, either from the granite itself or in associated pegmatites. Similarly, pegmatite feldspar deposits may also develop in pelite-dominated high-grade metamorphic terrains. Sedimentary feldspar deposits are dominated by microcline, indicating that they are derived from similar granite types to primary igneous feldspar deposits. Using these arguments, it is possible to define suitable exploration targets for feldspar deposits (both primary igneous and sedimentary) using tectonic setting.

Partial kaolinization of a source rock is often advantageous in the extraction of feldspar for both practical and commercial reasons. Firstly, this process softens the rock so that it can be extracted more easily, sometimes without the use of explosives. Secondly, less energy is consumed in subsequent crushing. Albite and other plagioclase minerals are more susceptible to kaolinization than K feldspars. Even the exsolved albite within perthites is preferentially kaolinized. Thus partial kaolinization can give rise to feldspar products in which the K₂O/Na₂O ratio is significantly increased. After separation of quartz by froth flotation from partly kaolinized granites, pegmatites, or feldspathic sands, virtually pure K feldspar products can be produced. A further benefit from kaolinization can be the removal of Fe from biotite. This is a well-known effect of the kaolinization of the granites in south-west England (Bristow and Exley, 1994; Mueller and others, 1999) which gave rise to the major china clay (kaolin) deposits of that region. Feldspar products from partly kaolinized granites, pegmatites, or feldspathic sands, therefore, have less potential for contamination from minor amounts of Fe-rich minerals. Feldspars can also constitute a potential by-product from kaolin operations where the alteration process is incomplete.

The significance of the presence of either orthoclase or microcline, or both, in feldspar products, and their relationship to the relative suitability for use of the different raw materials does not appear to have been addressed in the technical literature on feldspar products. There may be no significance, as differences in the bulk chemistry, nature of impurities, and particle-size distribution between feldspar products in themselves are likely to be sufficient to create differences in behavior in glass and ceramic processes. However, as the two phases have different crystal structures, their heat capacity and their rates of dissolution and consumption of energy in glass and ceramic melting processes, at the atomic scale, will be different. It may be worthy of investigation.

CONCLUSIONS

A survey of published literature and product data sheets, supplemented by determination of the mineralogy and chemistry of samples of feldspar industrial mineral products from throughout the world, has shown that there is a relationship between the geological setting of the source material and the properties of the products. Many feldspar products are mixed Na and K feldspars containing albite with microcline and or orthoclase, often as perthites, along with varying amounts of quartz. Occasionally quartz dominates the mineralogy. These mixed feldspar products are exploited from granites, pegmatites, aplites, rhyolites, and feldspathic sands. Mica and kaolinite are common impurities in some products. Pure albite feldspars are sourced from pegmatites, but relatively pure K feldspar products are mainly sourced from feldspathic sands. Peraluminous S-type granites and pelitedominated, high-grade metamorphic rocks, in which there is a significant volatile component in the fluid phase, are likely to be the most important sources for feldspars, whether in the granite itself, in albite-rich pegmatites, or in adjacent feldspathic sediments derived from the granite by partial weathering. Partial kaolinization of the source rock often improves minability, decreases crushing costs, reduces iron content, and increases the K₂O/Na₂O ratio.

ACKNOWLEDGMENTS

The authors are grateful to all the companies who supplied samples and analytical data sheets. The chemical analyses were made at the Camborne School of Mines (CSM) by Fiona Thomas. The authors also thank Jens Andersen and Colin Bristow for suggesting improvements to the text. CSM Trustees are thanked for providing partial funding for the research.

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APPENDIX 1

ABSTRACTS-ORAL PRESENTATIONS

Listed by principal author in alphabetical order

FGD POWER PLANTS IN THE OHIO RIVER VALLEY – USE OF LIMESTONE RESOURCES AND GENERATION OF WASTE

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Coal-fired electrical power plants are increasing their efforts to meet new Federal Clean Air Act standards. In the six-state Ohio River Valley region, this increased effort is demonstrated by the increasing number of power plants that are using flue-gas desulfurization (FGD) units to remove sulfur from their emissions. In 1989, 22 plants used FGD units, in 1997, 33 of the 156 coal-fired electrical power plants in the Ohio River Valley used FGD units. This increase has been accompanied by a 65 percent increase in demand for sorbent from 3,146,100 short tons in 1991 to 5,192,940 short tons in 1997, with the sharpest increase in demand occurring between 1994 and 1995. Abundant limestone resources exist in the Ohio River Valley to supply this sorbent material. However, of the more than 975 limestone or dolomite quarries in the Ohio River Valley, only about 35 are believed to have supplied limestone for use as a sorbent. The locations of these limestone suppliers do not show a simple spatial correlation with FGD facilities. In most cases, quarries which provide sorbent are more than 30 miles from the nearest FGD utility, suggesting that in some cases, reduction in transportation costs may be possible.

FGD-generated waste has also increased through time, with a large increase again occurring between 1994 and 1995. Most of this waste is not recycled; before 1995, recycling accounted for less than 1 percent of the waste generated by FGD units. However, many FGD sites are relatively close to gypsum producers that may be able to process some of their waste. In the Ohio River Valley, seven of the FGD units are within 50 miles of a gypsum operation, and 24 are within 100 miles. The recent announcement that six new wallboard plants will be built within this six-state region indicates new opportunities for recycling FGD waste.

ECONOMIC INCENTIVES TO WORK ON ANNETTE ISLAND RESERVE, AK

BOOTH, Terrance, Metlakatla Indian Community, Metlakatla, Alaska, USA Contact Stephen Manydeeds, U.S. Bureau of Indian Affairs, 12136 W. Bayaud, Ste. 300, Lakewood, Colorado, 80228, USA

The Tsimshian Tribe of the Annette Islands Reserve in extreme southeastern Alaska is interested in exploiting their crushed rock resources. The federal government has designated the Reserve an Economic Development Zone, which offers specific economic and tax incentives for investment. Mining agreements involving Indian lands enjoy exclusive economic privileges. The Indian Mineral Development Act of 1982 allows negotiable forms of agreement, term, and acreage, resulting in infinite and unique possibilities. There are many economic advantages of working on the Annette Islands Reserve.

CHARACTERISTICS OF WYOMING BENTONITE AND THEIR COMMERCIAL APPLICATIONS

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Bentonite mining in Wyoming occurs almost exclusively in the Upper Cretaceous Frontier Formation, and the Lower Cretaceous Mowry Shale and Thermopolis Shale. These formations contain numerous beds of sodium bentonite, of which over a dozen are of commercial significance. The physio-chemical properties of these beds vary considerably, both between beds, as well as vertically and horizontally within each bed. These variations yield a wide range of functional characteristics with commercial applications. This paper discusses the relationship between these characteristics and the products produced from Wyoming bentonite. A discussion of new and innovative applications for Wyoming bentonite is included.

THE ECONOMIC SIGNIFICANCE OF THE FELDSPAR DEPOSITS IN TURKEY

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This presentation's objective is to exhibit the geology, current reserves, annual production, and exports of Turkey's feldspar deposits. Turkey, with its very complex geology, has large reserves of a variety of industrial minerals. Feldspar constitutes the majority of these reserves, exceeding 150 million metric tons in a number of locations including Aydin, Kutahya, Manisa, Balikesir, Bilecik, Ankara, Kirsehir, Kayseri, Artvin, and Bitlis regions within the Menderes, Kirsehir, and Bitlis massifs. The deposits mainly occur as pegmatites, granites, syenite, and nepheline-syenites. At present, the feldspar deposits in Turkey are being operated as open-pit mines using conventional methods. Contaminants such as iron and titanium oxide are removed by mineral processing procedures.

Turkey, with approximately one million metric tons of annual production, produces nine percent of the world feldspar. Furthermore, production can increase sharply depending on increasing world demand. For example, the total amount of feldspar exported increased from just 100,000 metric tons in 1989 to 750,000 metric tons in 1995. The total feldspar production of Turkey reached 1 million metric tons in 1997, ranking Turkey second in world production following Italy. In addition to the export market, feldspar has a wide spectrum of applications in a variety of domestic industries ranging from ceramics to plastics.

BASICS OF EXTRACTING AND PROCESSING MINERALS FROM THE GREAT SALT LAKE

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All processes to extract minerals from the Great Salt Lake presently employ solar evaporating ponds. There are over 65,000 acres of solar ponds around the Great Salt Lake, and hundreds of miles of operating roads and dikes bordering these ponds. Concentrated liquid and crystallized minerals are removed from solar ponds and further purified in processing plants to produce sodium chloride, sodium sulfate, potassium sulfate, and magnesium chloride. These minerals are used in literally thousands of commercial applications. Pond operation and management have brought some unique challenges resulting in innovative solutions. The author discusses the basic processes used, and also comments on associated problems and solutions encountered during process development.

THE WESTERN U.S. LIME INDUSTRY -- A SNAPSHOT

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(Greater Volumes x More Markets)/Fewer Producers = Lower Prices.

What's wrong with this equation?

The lime industry in the western United States has steadily expanded capacity for years. Traditional customers are cyclical, though with different cycle lengths. Changes in the marketplace require constant adjustments to remain competitive. This oldest manufactured chemical is changing in response to customer demands. Competition has stiffened as the number of producers has dropped. Though some costs have increased (labor rates, equipment, permitting, and regulatory compliance), other factors (labor and equipment productivity, and energy) permitted a low cost of production. With a high capital investment and decreasing prices, what does the future hold for the western lime industry?

UPDATE ON IDAHO'S INDUSTRIAL MINERAL OPERATIONS

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Industrial minerals comprise an important and stable part of Idaho's mining industry. In 1997, the value of nonfuel mineral production in Idaho was \$477 million according to statistics compiled by the U.S. Geological Survey. If one includes the estimated value of in-state processing of Idaho's phosphate ore, the value of Idaho's mineral production was over \$1 billion in 1997, with approximately half the value attributable to southeast Idaho's phosphate industry. Though phosphate is the largest segment of the mineral industry in the state, other industrial mineral commodities are well represented, a consequence of Idaho's diverse geology.

Phosphate ore is mined from the Permian Phosphoria Formation by four companies. FMC and Solutia (formerly Monsanto) operate the only elemental, phosphorus plants in the United States. Agrium and J.R. Simplot produce phosphoric acid fertilizer from their plants in Soda Springs and Pocatello. Until recently, phosphate markets have been thriving, but a negative factor for the industry is the recently studied, environmental effect of selenium which is naturally concentrated in black phosphatic shales. Studies are ongoing for ways to minimize the selenium hazard.

Sand and gravel producers, as well as cement, crushed stone, and dimension stone producers, have benefitted from Idaho's growing population and a healthy construction industry, particularly in the Boise and Coeur d'Alene areas. Idaho is the nation's leading producer of industrial grade garnets, mostly from Emerald Creek Garnet Company, which mines over 25,000 tons of placer garnets a year. These garnets are used for filters, abrasives, and water jet cutting media. Other specialty product operations include Hess Pumice in Malad, Unimin Corporation's silica sand pit near Emmett, Chemical Lime's plant at Bancroft, and Teague Mineral's zeolite pits in southwestern Idaho. Gemstones such as Spencer opal, Bruneau jasper, and Idaho's famed star garnets also delight mineral collectors.

INDUSTRIAL MINERALS OF BRITISH COLUMBIA - SITE OF THE 2001 MEETING OF THE FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

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The 37th Forum on the Geology of Industrial Minerals will be held in Victoria, British Columbia, Canada. The area of southwestern British Columbia has been an important source of industrial minerals for more than a hundred years. Bricks and dimension stone were first produced in the 1850s. In 1873, the San Francisco Mint was built using sandstone from Newcastle Island near Nanaimo. Granite from Nelson Island has been exported since 1887; it has been used in many buildings in Portland and Seattle, and even exported as far as Hawaii and Australia. Roofing slate from Jervis Inlet, produced between 1890 and 1920, was primarily used locally. Limestone on Texada Island, Todd Inlet, and several other sites has been quarried since the 1880s for lime and cement, which was shipped to users in Vancouver, Seattle, Tacoma, and many other destinations along the coast. Low refractory "firebricks" for steamship boilers have been produced in Victoria and Nanaimo since 1890, and since 1905, high PCE (pyrometric cone equivalent) fireclay products from Sumas Mt. Claystone have been made in Abbotsford, and are being sold worldwide. The area has also produced alunite, jade, manganese oxide, pyrophyllite, rhodonite, and lightweight aggregate. Southwestern British Columbia has established itself as a major production center of limestone, cement, and lime for the Pacific Northwest, and is also an important distributor of white calcium carbonate, granite, marble, and a variety of clay products. Bulk transportation systems have been developed by the industry to ship construction aggregate from pits on the coast to construction sites in the Vancouver area and elsewhere in the Strait of Georgia and Puget Sound. It is anticipated that British Columbia will ship increasing amounts of crushed rock to the United States and to off-shore destinations within the next ten years. You are invited to come and see these operations at the Industrial Minerals Forum in 2001 to be held in Victoria, B.C.

ORIGIN OF SODIUM SULPHATE DEPOSITS OF SOUTHERN SASKATCHEWAN, CANADA: I. STABLE ISOTOPE AND CHEMICAL COMPOSITION OF GROUNDWATER

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Sodium sulphate is used in the manufacture of powdered detergents, carpet fresheners, plate (float) glass, kraft paper, and textiles. Sodium sulphate is also reacted with potash (potassium chloride) to produce potassium sulphate. It has been mined from lacustrine evaporite deposits in southern Saskatchewan since 1918. In 1997, three companies operated four sodium sulphate operations, and two other companies extracted sodium sulphate for potassium sulphate production. The total value of sodium sulphate and potassium sulphate produced in Saskatchewan in 1997 was approximately \$CDN 40 million.

The sulphate deposits occupy post-glacial endorheic (closed) lake basins in a belt that stretches from northwestern North Dakota and northeastern Montana across southern Saskatchewan to east central Alberta. Previous workers generally acknowledge the empirical relationship between evaporitic mineralization and the presence of active lake-bottom or peripheral springs. Groundwater discharging into the lake basins contains 1,000 to 5,000 ppm of total dissolved solids (TDS). Most of the TDS load is Na+ and SO₄=. Groundwater is viewed as a causative agent, but workers disagree on the ultimate origin of the groundwater (for example, connate water, deeply circulating brines, or recent meteoric water) and the source of dissolved ions (such as, Paleozoic evaporites deep in the sedimentary section, bentonite in Cretaceous mudstones, or till). None of the previous workers tested their hypotheses.

Hydrogen and oxygen isotope results for groundwater sampled from six sodium sulphate deposits suggest that the spring systems that currently supply ions to alkali lakes in southern Saskatchewan are not hydraulically connected to Paleozoic saline aquifers. Ion chemistry suggests that the groundwater may be at least partly from a pre-Wisconsinan aquifer, perhaps mixed with shallow groundwater during ascent.

NEAR-SURFACE BRINE RESOURCES IN THE GREAT SALT LAKE DESERT, UTAH

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The Great Salt Lake Desert contains over 2,000 square miles of barren salt and mud flats in northwestern Utah. Although the Great Salt Lake Desert is generally thought of as a single basin, at least three subbasins have been identified, which are known to contain potentially significant resources of sodium, potassium, and magnesium salts in near-surface brines. The most well known and developed area surrounds the Bonneville Salt Flats, where Reilly-Wendover, Inc. produces potash and magnesium chloride brine. Other areas that have been explored include Pilot Valley, located north of the Bonneville Salt Flats, and the Newfoundland Basin, west of the Newfoundland Mountains.

The near-surface brine resources of the Great Salt Lake Desert were initially explored by the U.S. Geological Survey in 1925. A total of 405 shallow test holes were drilled, and brine samples were recovered and analyzed. From this exploration, an area of about 1,300 square miles was identified with shallow brines containing over 100 grams of chloride per liter. This area includes the three subbasins where the brines have been better defined.

The area of the Bonneville Salt Flats has been extensively explored, and the brine composition and the aquifer characteristics are relatively well known. A typical brine contains 21 percent sodium chloride, 0.9 percent potassium chloride, and 1.3 percent magnesium chloride by weight. Pilot Valley to the north of the Bonneville Salt Flats has been less extensively studied, but a number of studies on the Bonneville Salt Flats have used the Pilot Valley subbasin as a control area to address the impacts of potash production on the shallow brine aquifer. In the 1960s, 42 test holes were drilled to characterize and estimate the potash resources in this subbasin. The Pilot Valley brines are similar to brines being produced near the Bonneville Salt Flats. The Newfoundland Basin occurs east of Pilot Valley and contains the lowest surface elevations in the Great Salt Lake Desert. The Newfoundland Basin was explored in the mid-1960s by Reynolds Metals Company. Reynolds drilled 92 test holes in the shallow brine aquifer. There is no indication that any tests were made on the hydrologic characteristics of the aquifer, but brine samples were collected and analyzed. The brines were somewhat less concentrated than the brines at Bonneville or Pilot Valley, with about 14 percent sodium chloride by weight. However, the brine samples collected during this exploration contained an average of 0.8 percent potassium chloride and 1 percent magnesium chloride by weight.

Development of potash-bearing brines from Pilot Valley and Newfoundland Basin is impeded by difficult access to the areas, a lack of understanding of the hydrologic characteristics of the shallow-brine aquifer in these basins, and land ownership and land-use restrictions.

MARBLE IN THE LEADVILLE LIMESTONE NEAR MARBLE, COLORADO

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The resurgence in the use of dimension stone led to the successful reopening, in the early 1990s, of the Yule quarry near Marble, Colorado. The Yule quarry exploits a very thin unit of the Leadville Limestone that has been recrystallized into white marble. The marble occurs in an area with zinc, lead, copper, and silver associated with faults and fissures in the Paleozoic rocks surrounding Treasure Mountain dome. Marble deposits frequently occur in association with metallic mineralization, an example is the Big Cottonwood mining district in Utah.

The Yule deposit has gone from being economic (producing more than 1.5 million tons of marble in the early 1900s) to non-economic, and back to economic. An important factor keeping the deposit viable is delineation of high grade, low grade, and waste zones by the quarry geologist. In reality, others, such as sales and production staff, have a more important role in determining what is ore versus non-ore. The reopening of the Yule quarry can serve as a model for determining the viability of other industrial mineral deposits.

ASPHALT FROM UTAH'S ASPHALT RIDGE OIL SANDS: APPLYING NEW TECHNOLOGY

MEALEY, Jay, Crown Energy Corporation, 215 S. State St., Ste. 650, Salt Lake City, Utah, 84111, USA

The author presents a discussion of Crown's Asphalt Ridge oil sand extraction facility near Vernal, Utah, including a description of the facility

and extraction process. The primary product manufactured at the facility is a premium grade asphalt, and the presentation includes an overview of the product and its application in the changing asphalt market.

HALLOYSITE IN UTAH; THE DRAGON MINE, EUREKA, UT

NEWMAN, Thomas, and SANTOS, Vanessa, Holnam, Inc., P.O. Box 1468, LaPorte, Colorado, 80535, USA

Halloysite is an exotic; unique to clay mineralogy, and the science of mineralogy in general. Very little was known about halloysite until Xray diffraction and the Scanning Electron Microscope (SEM) were invented; attempts to identify the white clay were unsuccessful until the 1930s. What was found was a stunning clay mineral. Halloysite is a hydrated form of kaolinitic clay $(Al_2O_32SiO_2 \cdot 4H_2O)$; an even more hydrous form is known as endellite. Typical ore consists of nearly pure halloysite with finely disseminated pyrite, which when oxidized, can color the clay pink to reddish brown. What is spectacular about halloysite is its physical character. It has an extraordinarily high degree of crystallinity and stacking order. Under the SEM halloysite displays a unique tubular or hollow tube form. This is caused by curving layers of the crystal lattice that leads to "rolling" of the clay platelet structure.

At the turn of the century, the Dragon was mined for iron oxide for use in smelting gold and silver ores. At the time, it was noted, that the iron oxide bordered massive white "clay or talc". International Smelting and Refining Company acquired the deposit for its metals potential. Filtrol Corp. then bought the deposit and in 1949, discovered a profitable use of the clay as a petroleum cracking catalyst; approximately 500,000 short tons were mined for this use. Utah was the center of halloysite mining for most of the twentieth century, with the Dragon mine dominating the world's supply.

Today, clays are being modified and re-engineered. Halloysite's hollow tubular structure lends itself to this advanced technology. We suggest that the Dragon mine be re-evaluated for new uses in specialty clays.

THE EXPLORATION OF HALLOYSITE-RICH CLAYS AND THEIR POTENTIAL USE IN THE MANUFACTURING OF BRICK

NORTH, Jerry, Interstate Brick Company, 9780 S. 5200 W., West Jordan, Utah, 84088, USA

The Fox Hills deposit is located southwest of Soldier Pass in the area of Utah Lake, Utah County, Utah, approximately 45 miles south of the Interstate Brick Company plant site in West Jordan. Two hundred acres of patented mining lode claims and 1,500 acres of state leases cover the deposit.

The beds are found in an area three miles square, that contains three inactive open-pits. Filtrol Corp. actively mined this area until 1948, producing over 30,000 short tons of clay for oil filtration. Interstate Brick first sampled this deposit in 1994, in areas where the thickness ranges from two to four feet at the old mine sites. These deposits were thought to be composed of kaolin, halloysite, and alumina. Laboratory tests showed that samples had a high percent shrinkage, which is undesirable for brick manufacturing. However, it was discovered during further testing that this clay, when fired in some clay mixes, produced a product that met or exceeded ASTM standards.

RAILROAD BALLAST PRODUCTION AT THE MILFORD QUARRY

PFINGSTEN, Craig, Kiewit Mining Group, Inc., 1000 Kiewit Plaza, Omaha, Nebraska, 68131, USA

Twin Mountain Rock Company recently opened a quarry north of Milford, Utah, to supply ballast to the Union Pacific railroad. Crushed rock for ballast is an integral component of the overall track structure. The specifications for railroad ballast are stringent, and require a rock to possess several chemical and physical properties. To perform well in track, a rock must be hard, tough, dense, resistant to freeze-thaw, and free of cementing properties. Generally, most igneous rocks and some quartzites will meet these specifications. One economic requirement is that a rock source must be located close to the rail line in order to minimize the amount of track required from the main line to the quarry site. This requirement drastically limits the number of deposits suitable for railroad ballast. The rock at the Milford quarry meets all of the railroad's specifications. A petrographic examination of the quarry rock identified it as a quartz-hornblende, monzonite porphyry.

Mining and processing operations at Milford are typical of most quarries. The operation consists of four steps: (1) drill and blast, (2) load and haul to the plant, (3) crush and screen, and (4) loadout in railcars. Railroad ballast is generally produced in a 2-1/4 inch x 3/4 inch size. The ballast byproduct, which is smaller than 3/4 inch, is typically marketed for uses such as concrete aggregate, asphalt aggregate, and road base material. The amount of commercial aggregate sold can greatly affect the profitability of the operation.

AN UNUSUAL BENTONITE DEPOSIT IN NORTH OREGON

RALLS, Russell J., North Oregon Resources, Inc., P.O. Box 788, Madras, Oregon, 97741, USA, and REGIS, Andrew J., Arizona Resources, 3 Estambre Ct., Santa Fe, New Mexico, 87507, USA

A new discovery of bentonite in the John Day Formation in northern Oregon will help to shed light on the origin of smectite clays in Tertiaryaged sediments in Oregon. Early Oligocene volcanism in western Oregon deposited tuff and ash materials which were altered into a unique sequence of bentonite beds that in many respects resemble Wyoming-type bentonites.

Variations in the tuff chemistry, together with diagenesis of the sediments, yielded minable bentonite beds which vary from a high-sodium calcium bentonite, to an intermediate-sodium calcium bentonite, to a high-calcium sodium bentonite. These different bentonite compositions occur in multilayer sequences covering an area of up to two square miles.

Commercial development of this deposit is enhanced by thick bentonite beds. These thick beds enable the deposit to be selectively mined for a particular use, based on the physical and chemical properties of each bed.

INDUSTRIAL MINERALS ON FEDERAL LANDS-IMPACTS ON DEVELOPMENT

REGIS, Andrew J., Arizona Resources, 3 Estambre Ct., Santa Fe, New Mexico, 87507, USA

Aside from the moratorium currently blocking the issuance of new patents on mining claims on public domain lands, there are two other new regulations that will have severe impacts on the development of mining claims.

By far, the most important is the new rule defining the term "excess reserves," or those reserves which cannot be marketed within the reasonably foreseeable future. A 1996 Solicitor's Opinion noted that "excess reserves" by definition have no present value in the market place, and therefore cannot be said to be valuable mineral deposits within the meaning of the mining law. In response to this opinion, the U.S. Bureau of Land Management's (BLM) Director issued an Instruction Memorandum in 1998, authorizing BLM mineral examiners to invalidate or contest those mining claims that contain more than 40 years of reserves.

The other regulations affecting the development of mining claims are the proposed revisions of the 3809 Surface Management Regulations. These regulations govern the surface disturbance on mining claims on those lands where the BLM and USFS hold the mineral estate. The more important revisions to these regulations cover:

- changing the relationship between the states and the BLM on the enforcement and monitoring of Notice of Intent and Plan of Operations on mining claims,
- allowing mineral examinations to occur on mining claims within withdrawn areas to determine validity before the issuance of a Notice of Intent or a Plan of Operations,
- better definition of the bonding requirements for a Notice of Intent and/or Plan of Operations,
- allowing the BLM to designate more special resource areas,
- better defining of the civil and criminal regulations of 3809, and
- allowing public and private interest groups to accompany BLM inspectors on site visits at BLM discretion.

Mining claimants today must become aware of the new governmental evaluation methods that agencies are implementing to determine validity of industrial mineral mining claims on the public domain.

THE 36TH FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS, BATH, ENGLAND, UNITED KINGDOM

SCOTT, Peter W., and BRISTOW, Colin M., Camborne School of Mines, University of Exeter, Redruth Cornwall, TR15 3SE, UK

The 36th Forum on the Geology of Industrial Minerals will be held in Bath, England, United Kingdom (UK) on 7-12th May 2000. Bath is an outstandingly beautiful and interesting Georgian city, centered on a group of thermal springs, about 100 miles west of London, and with some of the most important Roman remains in Britain. It is England's only World Heritage City, and is popular for conferences. The main conference sessions will be in the 18th Century Assembly Rooms, where there will also be a trade exhibition. There will be an all-day field excursion on May 7, followed by two full days of papers covering all aspects of industrial minerals. This will be followed by a one-day field conference specifically devoted to limestones (including geology, mining, planning, and environmental issues), and will include oral presentations and local field excursions in the Mendip Hills near Bath. These deposits are a very important source of limestone for UK industry. Offers of papers for oral and poster presentations have already been received, and more are welcomed. There will be two, two-day field excursions: one to the kaolin and ball clay producing areas of southwest England and another to central/northwest England (sands, salt, structural clays, and others). The UK is an important producer of industrial minerals, worth in excess of \$3 billion annually before adding value through processing. The basic and other industries are supplied by its many indigenous industrial mineral raw materials. The UK is a major exporter of kaolin. The conference is combined with the 11th UK Extractive Industry Geology Conference to create a very special and unique event for the millennium. A separate leaflet giving much more detail is available. An ambitious social and spouse program is being organized. See you there!!

MAGNESIUM RECOVERY OPERATION, GREAT SALT LAKE, UTAH

TRIPP, Tom, Magnesium Corporation of America (MagCorp), 238 N. 2200 W., Salt Lake City, Utah, 84116, USA

Magnesium metal has been commercially produced from the waters of the Great Salt Lake for the past 27 years. Magnesium Corporation of America and its predecessors had to overcome various technical challenges, as well as political hurdles, climatic calamities, and unfair international competition to continue as a viable business. This discussion includes a basic technical description of the magnesium manufacturing process, an explanation of the operating history of the Rowley plant, and the current commercial uses of magnesium metal.

PHOSPHATE ORE PRODUCTION AND PROCESSING, SOLUTIA, INC., SODA SPRINGS, IDAHO

VICE, Michael J., and HART, Mitchell J., Monsanto, Inc., P.O. Box 816, Soda Springs, Idaho, 83276, USA

In September, 1997, Solutia, Inc. was formed as a spin-off of the chemical businesses of Monsanto. The Soda Springs, Idaho plant was a joint-venture operation, wholly owned by both Monsanto and Solutia, with Solutia operating the plant. As a result of several more mergers and reorganizations, Monsanto regained full ownership of the mine and plant in October, 2000. The Soda Springs elemental phosphorus plant has been operating since 1951.

The Enoch Valley mine, opened in 1989, is the third mine to supply phosphate ore to Solutia's Soda Springs plant. The mine is operated by mining contractor Dravo - Soda Springs. Solutia mines 1.0 to 1.5 million short tons of high-quality phosphate ore annually, which is hauled approximately 20 miles from the mine to the elemental phosphorus plant. For every ton of ore, 3.5 to 4.0 cubic yards of overburden material are removed. The ore contains, on average, over 26 percent phosphorus pentoxide (P_2O_5). Mining will continue at Enoch Valley until 2001, at which time operations will move to the southeast.

The Meade Peak Member of the Permian Phosphoria Formation is mined. About 250 million years ago, phosphorus-rich sediments were

deposited on the shallow edges of the Phosphoria Sea. Conditions were right to eventually form the high-quality phosphate-rich beds of the Phosphoria Formation in southeastern Idaho.

Solutia takes their stewardship over the land they mine very seriously. Comprehensive mine plans assure the land is reclaimed and returned to more productive uses. Solutia is very proud of the numerous state and federal awards received for their mining and reclamation efforts. Solutia's philosophy has always been, and will always be - "return the land to a better condition than we found it."

GILSONITE OPERATIONS-BONANZA, UTAH

WHITE, Earl, American Gilsonite Company, P.O. Box 28, Vernal, Utah, 84078, USA

American Gilsonite Company is the largest producer of a unique mineral which is produced solely in Utah. Gilsonite (Uintaite) is classified as an asphaltite, and is currently mined and processed on the eastern flank of the Uinta Basin in Uintah County, Utah. Gilsonite has been sold commercially since 1884. The industrial applications of gilsonite include use in floor tile, rubber compounds, automobile undercoating, asphalt pavement additive, electrical wire insulation, inks, japans, and acid resistant paints to name just a few. Today, the primary industries for gilsonite applications are ink, asphalt, foundry, and oil drilling fluids. This paper discusses the geologic occurrence, mining, processing, and markets for gilsonite and gilsonite-derived resins.

SALT LAYDOWN PROJECT - BONNEVILLE SALT FLATS: 1997-99 PROGRESS REPORT

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The U.S. Bureau of Land Management (BLM), Reilly Industries, Inc. (Reilly), and the racing community (represented by "Save the Salt" - STS) are concerned about the reported deterioration of the Bonneville Salt Flats, and through cooperative agreements are attempting to replenish salt to the Salt Flats.

In 1991, Reilly and STS jointly funded a salt-replenishment feasibility study that resulted in a Salt Laydown Facility plan. According to the plan, sodium chloride (NaCl) brine would be pumped onto the Salt Flats 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 anticipated to have an initial life of at least five years. Engineering estimates suggest that as-much-as 7.5 million short tons of salt could be deposited over a 28-square mile area during the 5-year period.

Based on the 1991 salt-replenishment feasibility study, BLM and Reilly entered into a Salt Laydown Agreement in 1995. Under this agreement, Reilly financed the installation and operation of the \$1,000,000 Salt Laydown Facility. The Salt Laydown Facility is comprised of brackish water supply wells, nearly 13 miles of collection ditches and associated pumps, a 921-acre bedded salt deposit (containing about eight million short tons of salt), and a brine-distribution manifold. Also, as part of the agreement, BLM and Reilly initiated a cooperative monitoring agreement to measure the amount of salt replenishment accomplished by the Salt Laydown project each year of the program.

The first year of the project commenced on November 1, 1997. Despite startup problems, 0.825 million short tons of salt (NaCl) were pumped as brine onto the Salt Flats by April 30, 1998. The 0.825 million short tons of salt delivered to the Salt Flats by the first year of the Laydown project closely matched the 0.85 million short tons estimated by the U.S. Geological Survey to be lost annually from the Salt Flats. As a result of improvements made to the Salt Laydown Facility during the summer and fall of 1998, the second year of the Salt Laydown project delivered nearly 1.63 million short tons of salt to the Salt Flats, or nearly 2 times first-year salt tonnage.

STAKER PAVING AND CONSTRUCTION COMPANY'S BECK STREET OPERATION

WORISCHECK, Mike, Staker Paving and Construction Company, 1000 W. Center, North Salt Lake, Utah, 84054, USA

The author presents a "start-to-finish" look at the Beck Street operation, including the mining operation, crushing, asphalt hot plant production, hauling, and placement. Recent exploration results involving some deep drilling are also presented.

The Beck Street operation, with 150 employees, produces approximately 3.5 million short tons of product annually, with hot plant production of about 1 million short tons. Production and sales of common fill material is also important. Fill is mostly produced from overlying alluvium. The reserves, totaling about 130 million short tons, are mostly Mississippian dolomites with minor amounts of Tertiary siltstone, and Devonian and Cambrian conglomerates.

The rocks are highly fractured due to the proximity of the Wasatch Fault, but some blasting is required due to calcite cementation. The quarry is worked in 70-foot faces with 20-foot-wide benches. Quarry-run material is trucked to a 50° x 42° jaw crusher for reduction and screening.

APPENDIX 2

ABSTRACTS-POSTER PRESENTATIONS

Listed by principal author in alphabetical order

A COMPARISON OF LANDSCAPE FORM AND CHANGE FROM ANTHROPOGENIC AND NATURAL EARTH MOVEMENT-UNDERSTANDING THE PUBLIC PERCEPTION

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Aggregate quarries and sand and gravel pits impose a common design form on the landscape which is unpopular with the public, while similar geometric patterns created by nature are not subject to public disapproval. In mined land analysis and reclamation, the aesthetic and cultural back-ground of people living in a mining area are as important as the geology, climate, flora and fauna, legal requirements, safety issues, and other factors. The visual impact of a reclaimed mining site can generate strong public opposition no matter how environmentally and technologically sound the operation may be.

With the increasing use of aggregate nationwide, it is useful to examine the visual and other attributes of hard rock quarries and sand and gravel pits as summarized in the following table:

NATURAL FORM	QUARRY	PIT
Space	Large-scale, deep	Medium-scale, shallow
Mass	Vertical	Curvilinear
Color	Light and shadow	Gray
Texture	Angular	Rounded
ENCLOSURE		
Perspective View	Perpendicular	Planar
Visual Zone	Shortened	Extended flowing lines
Configuration	ArealSingle large area	LinearNarrow strip
GEOLOGY		
Origin	Magmatic, metamorphic,	Stream valley and terrace, sedimentary glacial deposits, marine terrace
Slope	Steep	Gentle
Soil	Unstable Faster weathering	Rather stable Slower weathering
Water	Retentive floor surface Less infiltration on slopes	Permeable floor surface Greater infiltration on slopes
Scarcity	More plentiful in East	More plentiful in West
Wildlife Habitat	Moderately complex	Simpler
CULTURAL		
Metaphor	Mountain, creation	Water, entropy
Mining Impact	Blasting, highwalls, smaller quantity of waste	Settling ponds, sometimes significant quantity of waste
Longevity	Long-term	Short-term

The confusion surrounding what we expect "nature" to look like may lead to conflict. Public and scientific perception of design work for reclamation can be favorable when "aesthetics" is defined from a biological as well as philosophical view. Becoming familiar with the term "land-scape" from different perspectives allows industry, land planners, and designers to be more aware of the need to communicate in a language all understand. Ultimately, the end result of a final reclamation project will determine how acceptable that industry is in an area. People are more willing to accept the presence of mining from an industry responsive to aesthetic and sociocultural factors.
INDUSTRIAL MINERALS ON INDIAN LANDS

CHASTAIN², Lynne, MANYDEEDS¹, Stephen, and ZEISE³, John,

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This poster is a compilation of various industrial mineral information on tribal lands throughout the United States.

National Indian Land Aggregate Resources

The Colorado School of Mines and U.S. Bureau of Indian Affairs are currently studying potential aggregate resources on Tribal lands in the western United States. Summaries of geologic deposits with potential for use as aggregates are being prepared for each Tribal land. The summaries are available to the public through the U.S. Bureau of Indian Affairs' web site at: http://snake1.cr.usgs.gov/demr/index.htm.

Wind River Indian Reservation Gypsum Resources

The Shoshone and Arapaho tribes of the Wind River Reservation are interested in exploiting their gypsum resources. The Sweetwater Basin deposit, located in the northeastern corner of the reservation, occurs as an approximately 50-foot-thick bed at the base of the Gypsum Springs Formation. The estimated gypsum resource is about 13 million short tons.

Annette Islands Reserve Aggregate Resources

The Metlakatla Indian Community is conducting a crushed rock resource assessment on Annette Island, Alaska. Crushed rock from Annette Island has passed Federal Highway Administration standards for road base, asphalt, and concrete. Current efforts are focusing on crushed rock near the all-weather harbor on the island.

RECONNAISSANCE FOR INDUSTRIAL MINERALS AND MATERIALS USING 7.5- AND 30- BY 60-MINUTE GEOLOGIC MAPS

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Field geologic mapping in Utah, at 7.5-minute (1:24,000) scale, whether for publication at this scale or compilation into digital, 30-by 60minute (1:100,000 scale) maps, can improve reconnaissance for industrial minerals and materials. Such maps can show the extent, thickness, and dip of units that have been used historically, as well as units with mineral potential. Sampling can be better controlled, reducing the number of non-representative samples taken and increasing the chances of sampling the best, most representative outcrops, especially in structurally complex terrain.

One example from the area east of Ogden, Utah is shown (Ogden 30- by 60-minute quadrangle) with supporting, more-detailed mapping. This mapping was done by the Utah Geological Survey as part of three years of STATEMAP cooperative agreements with the U.S. Geological Survey. In this case, mapping of individual members of the Jurassic Twin Creek Limestone helped refine structural geology, and shows the Watton Canyon Member to be a source of feed for the Holnam, Inc. cement plant at Devils Slide. Similar mapping in Millard County, Utah could help in the search for feed for the Ash Grove Cement and Continental Lime plants in Leamington Canyon and near the Cricket Mountains, respectively.

GEOLOGY, GEOCHEMISTRY, AND INDUSTRIAL IMPORTANCE OF ALAYUNT DIATOMITE OCCURRENCE IN KUTAHYA, WESTERN TURKEY

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Diatomite, also named tripoli and kieselguhr, is formed by the accumulation and induration of diatoms, and has the chemical formula $SiO_2 \cdot nH_2O$. Diatomite has a variety of applications ranging from the filtration to insulation. At present, most diatomite is processed to improve its physical and chemical properties.

Turkey has approximately 125 million metric tons of diatomite reserves in different localities. The largest deposits are located in Hirka-Kayseri district (northeast Turkey) with reserves of 70 million metric tons. The total reserve of the Alayunt diatomite deposit in western Turkey is estimated to be in excess of 32 million metric tons, covering an area of about 4.5 square kilometers. The reserve is not currently being mined.

In this study, a detailed investigation of the Alayunt diatomite deposit using geological, mineralogical, and geochemical methods was undertaken. The geologic setting comprises a volcano-sedimentary sequence of Paleogene-Neogene age in a lacustrine basin that consists mainly of chert, tuffite, conglomerate, diatomite, and tuffite-conglomerate strata. Geochemical examinations revealed that the silica content exceeds 86 percent, while the total amount of alkali and alkali earth elements are about 1.88 percent. Loss on ignition makes up 5.77 percent of the chemical composition. The contents of undesirable alumina and iron are 3.78 percent and 1.45 percent, respectively.

Preliminary adsorption studies of copper, nickel, and cobalt ions at Istanbul Technical University laboratories using Alayunt diatomite samples show encouraging results. The experiments were conducted using 10 gm of -200-mesh natural Alayunt diatomite mixed with 200 ml of a 2 to 10 molar solution of the metal ions. Adsorption was determined after 24 hours. The Alayunt diatomite removed 84 percent of the copper, 72 percent of the nickel, but only 21 percent of the cobalt. Additionally, the cation exchange capacity of Alayunt diatomite, determined by the titrametric method, was found to be 8.92 milliequivalent grams in a dry hydrogen-form sample. In light of these data, a series of adsorption studies should be performed for other cations and anions under different conditions.

Considering the chemical data given above, the Alayunt diatomite compares favorably with well known diatomite deposits mined in Lompoc, California, USA, Soysambu, Kenya, and Niigata, Japan. Diatomite can be utilized as an excellent alternative in chemical adsorption processes, where natural zeolites, clays, and synthetic resins are currently being used.

GEOLOGY AND GEOCHEMISTRY OF BALA (ANKARA-TURKEY) GYPSUM DEPOSITS AND AN INVESTIGATION OF THE USE OF CITRIC ACID TO RETARD SET TIME OF GYPSUM PLASTERS

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In this study, Bala gypsum deposits were evaluated in terms of their geological, mineralogical, physical, chemical, and technological features. The gypsum deposits are located in the southern part of Ankara, the capital of Turkey. The stratigraphic sequence of the area, from bottom to top, consists of Upper Cretaceous ophiolitic flysch and Maestrichtian-aged sediments in seven formations. These formations are covered by Miocene gypsum deposits and Pliocene volcanic rocks. The largest exposures of rocks in the area consist of sediments varying in age from Campanian to Oligocene. Up to the middle Eocene, deposition of these sediments occurred in a deep sea, but neretic and continental facies conditions prevailed during the middle to upper Eocene and Oligocene.

All Oligocene and older rock units trend in a NNE-SSW direction, were subjected to folding and faulting, and were unconformably covered with nearly horizontal Neogene lake deposits. The area is characterized by anticlines and synclines trending N-S and NE-SW, and thrust faults which are roughly parallel to these structures. Since the folded and faulted formations are unconformably overlain by horizontal Pliocene units, the age of the main folding event can be established as Oligocene.

An average chemical analysis (in percent) of samples from the Bala gypsum deposits are as follows: $SiO_2 - 0.25$, CaO - 32.74, MgO - 0.40, $SO_3 - 45.20$, $R_2O_3 - 0.40$, C.W - 19.50, LOI - 20.71; equivalent to $CaCO_3 - 2.75$, $CaSO_4 \cdot 2H_2O - 93.30$, and natural $CaSO_4 - 3.11$.

The objective of our investigation was to understand the retardation of gypsum plasters by addition of citric acid and included studying the mechanism of set retardation, and the influence of citric acid on the microstructure and properties of gypsum plasters. Citric acid acts as a retarder by forming citrate. The citrate affects the nucleation and the crystal growth of gypsum by adsorption. It entails the retardation of the hydration period, and the habit modification. The influence on the microstructure was investigated by means of quantitative image analyses and X-ray methods. Citric acid changes the properties of hardened mortars. The volume of gypsum plaster passes through a minimum during the process of setting and hardening. Increasing amounts of added citric acid raise the volume minimum and decrease the following expansion. Strength formation was measured by compressive strength tests. A significant decrease in plaster strength was observed with increasing citric acid additions and higher humidities. In addition, the influence of citric acid on the creep behavior of hardened gypsum was examined.

THE NEW GEOLOGICAL AND MINERAL DEPOSIT MAPS OF ALBERTA

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A 1999 version of the Geological Map of Alberta was published by the Alberta Geological Survey. It replaces the 1972 version - rendered outof-date by geological mapping conducted in the province over the past 26 years. The new map, compiled on a standard 1:1,000,000 scale, is available in both hardcopy and digital formats. It features revised geological boundaries, an expanded legend that incorporates new stratigraphic definitions and lithologic descriptions, two inset tectonic maps, and a regional cross section of the Alberta sedimentary basin.

The geological map was produced using GIS technology with ArcInfo software. The geology is on an editable, vector overlay combined with a modified 1:1,000,000 provincial digital base in raster format. The digital map release is available in three formats (Eoo, PICT, and WMF), and allows for updates to be made as new geological information becomes available. GIS also allows for queries and retrievals of geological formation data.

A companion map to the new geological map, the Mineral Deposits Map of Alberta, was also published in 1999. This map presents all known deposits and significant occurrences of economic minerals (other than oil, gas, and coal) found in the province. Deposits are displayed in terms of size, geologic origin and setting, present or past production, and prospective use. Because of the largely sedimentary rock regime in Alberta, most of the deposits are of the industrial mineral variety.

GEOLOGICAL DATA MANAGEMENT FOR INDUSTRIAL MINERALS USING THE INTERDEX SOFTWARE

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Exploration and development of industrial mineral resources are expensive exercises where geologists are responsible for collecting millions of dollars worth of data each year. These data must be organized, interpreted, and visualized before determining the types and quantities of mineral products that can be produced from a deposit. Project success will ultimately depend on effective communication of these data, in a visual format, to project collaborators specializing in mining, beneficiation, marketing, and finance.

However, downsizing of geological departments by industrial mineral producers may create a critical "choke point" in the flow of digital information, due to either a lack of computer specialists in-house or alternatively, from time constraints placed on staff geologists in learning complicated geotechnical programs. One solution to this "choke point" is the INTERDEX software - a Windows-based, graphical program developed by geologists for geologists working in mineral resources. This presentation uses actual data from limestone and phosphate deposits to illustrate how the program may improve the quality, timeliness, and presentation of technical reporting in industrial mineral organizations.

GEOLOGY AND ECONOMIC DEVELOPMENT OF THE DEREBOGAZI IGNIMBRITE (TRASS) DEPOSITS, ISPARTA, SW-TURKEY

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The Derebogazi (Isparta-SW Turkey) ignimbrite occurrence formed as a result of calc-alkaline, trachyandesitic volcanism in the late Pliocene. Miocene (Burdugalien) flysch is observed below the ignimbrite strata while alluvium covers the ignimbrites. The deposit, with a thickness ranging from 15 to 130 meters, includes trachyte-trachyandesite pebbles and carbonized plant remains in macroscopic scale. On the other hand, microscopic studies revealed that the Derebogazi ignimbrite occurrence consists mainly of plagioclase (albite-oligoclase), sanidine, pyroxene, amphibole, biotite, opaque minerals, and glassy matrix.

Geochemistry was studied using wet chemical analytical methods. The average chemical composition of the deposit (in percent) is as follows: SiO₂ - 57.03, Fe₂O₃ - 2.65, Al₂O₃ - 17.75, MgO - 4.7, Na₂O - 3.91, CaO - 4.88, K₂O - 4.65, P₂O₅ - 0.41, TiO₂ - 0.55, SO₃ - 0.3, LOI - 5.5, and H₂O+ - 15. Ignimbrite has been the primary material used in historical objects and buildings in the region for thousands of years, and has remaining reserves of over 130 million metric tons. The deposit is still being mined, using open-pit methods, for the production of Portland-pozzolan cement due to its high quality and large reserves.

GRAVEL DEPOSITS OF THE SOUTH PLATTE RIVER VALLEY NORTH OF DENVER, COLORADO

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The valleys of the South Platte River and its tributaries contain large deposits of gravel used for construction in the Front Range Urban Corridor. The South Platte River valley north of Denver contains the last major commercial deposits of gravel in the Denver metropolitan area. Upstream from these deposits, most of the gravel has been mined or precluded from mining by urban development. North of Denver, gravel mining has steadily moved downstream since the early 1970s, and now may be approaching the downstream limit of commercial viability. When the deposits north of Denver are exhausted or preempted by other land use, aggregate for the Denver area will, by necessity, come from stone quarries in the mountains, or from gravel deposits in valleys to the north, such as the St. Vrain River valley.

The quantity and quality of gravel in the valley of the South Platte River is not only of interest to producers and consumers of gravel aggregate in the area, but is also relevant to urban planning. An understanding of the gravel deposits may enable better prediction of the potential downstream limit of gravel mining and of post-mining land use. To begin to assess the quality and ultimate minable extent of gravel deposits in the South Platte River valley north of Denver, the U.S. Geological Survey conducted detailed studies of the stratigraphy and composition of the gravel. Gravel underlies multiple terrace levels in the South Platte River valley. From highest (oldest) to lowest (youngest), the terrace levels are (1) remnants of high dissected terraces of Pleistocene age, (2) high continuous terraces (Louviers and Broadway terraces) of late Pleistocene age, (3) the low Piney Creek and post-Piney Creek terraces of Holocene age, and (4) the modern floodplain. The Broadway terrace makes up most of the eastern side of the South Platte River valley north of Denver; the Holocene terraces and floodplain occupy the rest of the valley. All of the Holocene levels (Piney Creek, post-Piney Creek, and floodplain) are considered together because their gravel resources are similar. Major deposits of gravel underlie the high continuous terraces, but most gravel mining is from the floodplain and low terraces.

Approximately 15 to 25 feet of gravel underlie the floodplain and low terraces. The gravel forms three distinct layers, each about 5 to 10 feet in thickness. The layers differ in coarseness and color, and can be traced throughout the South Platte valley north of Denver, as far north as Ft. Lupton. The basal gravel is composed of coarse pebble-to-cobble gravel, the middle gravel contains more sand than gravel, and the upper gravel contains variable particle sizes with concentrations of sand. Overall, the upper gravel is coarser-grained than the middle gravel. Locally, the upper layer contains abundant wood and fossil logjams. Lenses of silty clay, which impede mining, occur locally in the upper and middle layers. Downstream from Ft. Lupton, the coarse basal gravel disappears and sand dominates the valley fill. The present downstream limit of gravel mining near Ft. Lupton is probably already near the ultimate limit of commercial production.

Bedrock clay of the Late Cretaceous and Paleocene Denver Formation underlies the gravel fill of the valley north of Denver. The bedrock clay forms an impermeable seal at the bottom of the gravel aquifer, confining ground water flow to the gravel. After gravel mining, the pit walls can be lined with clay from the Denver Formation to create a watertight reservoir. The reservoir, separated from the gravel aquifer by impermeable clay walls, can be used to store water for municipal or other uses.

SURFICIAL MINERAL COMPOSITION OF SELECTED FLOOD PLAINS WITHIN THE COLORADO FRONT RANGE URBAN CORRIDOR MAPPED USING REMOTELY SENSED DATA

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Gravel deposits and soils of selected flood-plains within the Colorado Front Range region are being characterized and mapped using several sets of remotely sensed data. Aggregate mineral impurities are being identified with high and low altitude imaging spectroscopy data, while feldspar and quartz abundance will be measured using thermal data acquired during the 1999 field-season. Analysis of the reflectance data shows variability of mineral composition along stream length, but integration with the thermal data analysis is necessary to characterize change in the rock-forming minerals. Aggregate exposure is limited to sandbars and gravel mines, with vegetation and soil covering the majority of the flood-plains.

Reflectance data are collected by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) by measuring light reflected from the ground using 224 spectral channels. By analyzing the spectral features within the Front Range data, and comparing these features with library mineral spectra, the minerals kaolinite, montmorillonite, hematite, goethite, muscovite, and chlorite have been mapped.

Broad lithologic categories (for example, felsic versus mafic; presence/absence of silica) will be studied using data from the airborne simulator of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument. Spectral emissions from the surface will be mea-

sured using 10 thermal channels from 7.7 to $13.0 \,\mu$ m. The surface emissivity will be modeled and correlated with quartz and feldspar content. This technique is able to determine rock and soil characteristics through moderate vegetative growth, complementing the AVIRIS analysis.

Slight changes in mineral composition have been seen along stream length and between stream terrace versus the flood-plain using high altitude imaging spectrometry data. Analysis of low altitude AVIRIS and ASTER simulator spectral data will likely further define these mineralogic changes.

POTENTIAL LARGE CONSTRUCTION SAND RESOURCES IN SOUTHERN ILLINOIS

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Most of the construction sand needs of the seven southernmost counties in Illinois are met by material dredged from the Ohio River. This sand also supplies markets by barge as far south as Nashville, Tennessee. As these in-channel deposits become more difficult to find and permit, and as the market demand continues to increase, it may become economical to obtain sand from the glacial-age valley-fill deposits of a large, abandoned segment of the Ohio River valley in southernmost Illinois.

This ancient portion of the Ohio River valley, known as Cache Valley, is about 50 miles long and 1 to 3 miles wide. Test drilling in the valley has confirmed that fill in the main part of the valley is about 160 feet thick, and most of the valley fill is sand but, locally, gravel lenses are common, often at the same depths. Silt and clay deposits are also present, mainly at the surface, but also, locally, at depth. Two composite sand samples from a test hole near the east end of the valley were submitted to the Illinois Department of Transportation (IDOT) for preliminary testing. Both samples, one from four to 80 feet deep, and the other from 80 to 150 feet deep, passed all IDOT fine aggregate tests, except that the amount of clay lumps present in the deeper sample slightly exceeded the one percent maximum limit. Sand processing equipment should have no trouble breaking down these lumps. The particle size of the upper sample ranged from coarse to medium sand, while the lower sample was coarser, ranging from a large granule fraction to medium sand.

Land use in Cache Valley is primarily agricultural, but in selected areas, large tracts of low lands are being restored to wet lands for conservation areas and nature preserves. Two small streams, with head waters in the Shawnee Hills to the north, presently drain the valley. The lower portion of the Cache River drains westward, down the natural gradient of the valley. The lower portion of Bay Creek drains a shorter segment of the valley to the east. High water in the Ohio River backs up drainage ways in the Cache Valley, and during the record flood of 1937, flood water flowed down the length of the valley through low areas.

In the southern Illinois region, only in-channel and valley-fill sands of the Ohio, Mississippi, and Wabash Rivers can be economically processed into high-quality fine aggregate products. Locally, other smaller sand and gravel deposits can be excavated and processed into lower-quality construction aggregate products. Most coarse-aggregate needs are supplied by crushed stone because none of the sand and gravel deposits contain sufficient high-quality material to economically process into the higher grades of coarse aggregate products.

THE CUDAHY PUMICE AND PERLITE MINE, MILLARD COUNTY, UTAH

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The Cudahy open-pit mine, located approximately 30 miles southwest of Fillmore in Millard County, Utah, was developed in the early 1900s, and has been worked intermittently up to the present. From Fillmore, access to the mine is via Interstate 15 to Kanosh (15 miles) then by a well maintained and graded dirt road for 25 miles in a westerly direction. The mine can also be reached from Utah highway 257 which runs between Delta and Milford. The mine is approximately 3 miles from highway 257 via a well-graded dirt road.

The Cudahy mine, which has produced both perlite and pumice, is located at an elevation of about 4,800 feet. The mine site is on forty acres of patented land, and is surrounded by approximately 800 acres of patented land and unpatented mineral claims. The overburden is thin, with the ore being exposed on the surface or within a foot or two of the surface. A conservative estimate of available tonnage, determined by examination and drilling of the property, is 53 million short tons. The ground cover is sparse and includes sagebrush, cheat grass, a few native grasses, and a few juniper trees. The mine area is in the foothills of the valley created by the Beaver River, an intermittent desert drainage. Although the mine is situated in a dry desert area of the Great Basin, there are two springs (Black Spring and Coyote Spring) in the vicinity.

Geologically, perlite occurs as part of an acidic volcanic flow in rhyolite, dacite, andesite, or similar glassy material. One geologist who examined the site describes it in these words: "Perlite and pumice occur at this deposit as a large 'blowout' within the dacitic flow, or similar acidic material, of wide dimensions. The perlite is light-gray to tan in color, semi-pumiceous, and fine grained. The pumice is intimately mixed with the perlite and there are large quantities of the mixed material easily available." Perlite is a volcanic glass containing water of crystallization varying from two to six percent. The volume of entrapped water is of prime importance, since it is water which causes crude perlite to expand rapidly when the water flashes to steam at high temperatures. The pumice found in conjunction with the perlite is a light-gray material which was naturally expanded at the time of formation.

In addition to the large quantities of perlite and pumice, a number of interesting historical and geological features occur on the property including walls of brecciated stone indicating faulting, evidence of a hydrothermal vent, rhyolitic outcrops, old dugout cabin ruins, and exploratory diggings from early in the century. There are also some veins of obsidian, as well as black, snowflake, and mahogany obsidian on the surface.

Perlite and pumice have many uses. They are used as abrasives, concrete aggregate, charcoal base in barbecues, filtering media insulation, packing material, paint texturizer, soil conditioner, acoustical plaster and tile, and in plaster. Perlite, mixed with concrete or cinders, tends to strengthen and enhance the insulating qualities of poured concrete and concrete building blocks. It is widely used in oil wells, as it is fireproof and mixes well with concrete. In recent years, pumice has been used in the production of stone-washed denim clothing. Lump pumice is also ideally suited for use as a decorative landscaping rock because of its light weight.

A collection of photographs, mineral samples, and other items related to this historic mine is displayed. Visitors to the mine are invited to collect samples for their personal interest or rock and mineral collections.

DIGITAL IMAGE AND DATA PROCESSING OF INDUSTRIAL MINERALS IN THE WESTERN U.S.

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Satellite imagery can be a useful tool in geologic analysis, wetlands delineation, and vegetation mapping in flood plains. Thematic Mapper data are useful in lithologic mapping for gypsum because of Band 7's short-wave infrared spectral characteristics. Wetland delineation and vegetation mapping by remote sensing can be accurate, and performed at a low per-acre cost by experienced professionals. Current advances in personal computers have made it possible to display the results of satellite mapping projects and statistical analyses in an effective manner, and at a reasonable cost.

DEVELOPMENTS IN INDUSTRIAL MINERALS IN INDIANA

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Recent developments in the industrial minerals industry in Indiana follow the fundamental features of industrial rocks and minerals first set forth in 1960 by Forum founder, Robert L. Bates: (1) diversity of occurrence, (2) interdependence in industry, (3) importance of physical properties, (4) substitution and synthesis, and (5) place value and unit value. Place value continues to be a major force in the development of new deposits, with five new crushed-stone operations opening in 1998. Eleven sand and gravel plants also came on line during the year. Most of these new plants are located near cities or major transport arteries, despite ever more stringent land-use and environmental restrictions in such areas. Special, or high-unit-value materials, such as dimension stone, have seen an increase in activity with three new limestone and one sandstone quarry opening within the past five years. Their locations are restricted to specific regions where good deposits occur.

Changing technology has improved stone production, with the introduction of belt diamond saws in the quarries, and large diamond saws in the mills. One underground dimension stone mine operating in Lawrence County uses belt saws exclusively. In addition to new construction markets, Salem Limestone enjoys a strong business in replacing damaged stone and expanding existing buildings, for example, New York City's Empire State Building renovation.

More stringent specifications, such as Superpave requirements, have necessitated new testing and preparation techniques. Sands must now meet angularity requirements, and many sand and gravel plants now crush some part of their product. Manufactured stone sand is now being produced at many limestone plants, and Indiana has established a program to train aggregate testing technicians in their Certified Aggregate Producers Program (CAPP) to help assure compliance with specifications.

Substitution by new materials, especially material formerly considered as wastes, is another factor in Indiana. Coal combustion by-products, of which several million tons are produced annually, are finding increasing use as fill, concrete aggregate, and flowable fill. By-product gypsum from flue-gas desulfurization is increasingly being used in drywall and as a fixated scrubber sludge that shows cementaceous properties. Slag from Indiana's large iron and steel industry is also used extensively as aggregate.

Other industries, especially the ceramic plants, have been consolidated as small periodic kiln plants close and production increases at new, technologically enhanced operations. Technology to reduce power plant sulfur emissions by wet limestone scrubbers has opened a specialized new market for high-calcium limestones. Efforts to improve mineral education for the public are underway, with development of a teacher's workshop, talking rock trail, Internet web sites, and other initiatives.

Recent developments in Indiana follow observations made by Bates that have proven to be just as applicable today as when he first wrote them. We anticipate that these trends will continue into the immediate future.

A 97% PURITY GYPSUM RESOURCE IN THE JURASSIC CARMEL FORMATION, EMERY COUNTY, UTAH

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A 12- to 15-foot-thick bed of high-purity gypsum crops out on approximately 800 acres north and south of the South Salt Wash drainage, along the Moore Road in Emery County, Utah. Silica, clays, carbonates, and anhydrite are essentially absent, making it the highest purity and least abrasive "soluble" gypsum currently available in the agricultural marketplace. Finely ground, it is mixed with irrigation water and applied via sprinkler systems for soil conditioning. Finely ground gypsum is also used in food and pharmaceuticals, and as a plastic filler. This two million short ton resource is being mined by Diamond K Gypsum.

Bedded gypsum occurs in the lower 450 to 600 feet of the Carmel Formation. The gypsum beds alternate with limestones, siltstone, and claystones. The gypsum resulted from evaporation in a restricted, shallow marine setting during the Jurassic Period. The gray, green, and buff siltstone and claystone represent reduced marine environments. The limestones were deposited in anoxic nearshore conditions as indicated by Chondrites trace fossils and spores. Red beds represent oxidized soil horizons.

The San Rafael Swell is an asymmetrical antiform of Sevier age with a gently dipping western flank. A structural detachment within an incompetent, red, silty claystone in the gypsum-bearing strata of the Carmel produced isoclinally folded beds named the Reed Wash Fold Train. This deformation, evident from the east edge of the Diamond K quarry for two miles northwestward along the Moore Road, is not present six miles to the west on South Sand Bench where subsurface gamma logs, which define the gypsum beds, show no signs of folding. Gamma logs from the Utah Plateau Uranium Company well no. 1-X Federal and True Oil Company well no. 14-10 True Federal show zero API gamma units for gypsum and 75 API units for silty shales.

Mineable gypsum occurs in a 75-foot sequence, both above and below the detachment, with the highest quality material in the bottom 15 feet. In the Diamond K quarry, surface radiometric units of 120 counts per second (cps) for the underlying siltstone/shale unit, and 20 cps for the gypsum are used to indicate the base of gypsum. The beds below the detachment, which are not folded, are currently being mined using a modified pavement stripper, a D-9 cat, and a loader. The upper, folded, gypsum beds to the northwest are expected to cause considerable mining difficulties.

Cryptogamic, gypsiferous soils overlie the gypsum beds. The local flora is distinctive, consisting of three types of grasses, six herbs, nine shrubs, and one type of cactus. The distributions of these plants are determined by the variable lithologies of Carmel bedrock, colluvium, and alluvium. Rehabilitation efforts must take these natural distributions into consideration.

APPENDIX 3

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FIELD TRIP NUMBER 1

IMC Kalium Ogden Corporation May 4, 1999

J. Wallace Gwynn, Utah Geological Survey, P.O. Box 146100, Salt Lake City, Utah 84114-6100 nrugs.wgwynn@state.ut.us

The field trip began at the WestCoast Salt Lake Hotel (formerly Cavanaughs Olympus Hotel), 161 West 600 South, Salt Lake City, and proceeded to IMC Kalium Ogden Corporation's operation on the Great Salt Lake by chartered bus. From the hotel, the bus headed south on West Temple to the entrance of Interstate Highway 15 (I-15) and traveled north bound approximately 39 miles. The bus exited I-15 at the 12th Street exit (346) near Ogden and headed due west on SR 39 approximately 12.5 miles. Travel distance to the site was ap-proximately 51 miles, which took about 1 hour and 15 minutes. Two short videos were viewed:"Solubility", a 20-minute educational film produced by the BBC, and a 15-minute video produced by GSL Minerals (former owners of the facility), initially shown at the opening ceremonies of the Behrens Trench. The Behrens Trench, named in honor of Peter Behrens, former president of GSL Minerals, is unique in that it transports denser brines from the west side of the lake a distance of 21 miles to a pumping station near the southern tip of Promontory Point on the east side of the lake via an open, gravity flow, underwater trench. The brines are then pumped into evaporation ponds to begin the brine concentration process. The trench was completed in 1993. An excellent history of the Great Salt Lake's brine industry is provided in J.W. Gwynn's paper this volume. A more comprehensive history of land ownership and development around the Great Salt Lake is found in Edie Trimmer and Karl Kappe's paper this volume.





Corey R. Milne, process engineer at IMC Salt and IMC Kalium Ogden Corp., was the host for the tour of IMC's facilities.

Stop 1, a one-half-hour walk-through tour of IMC's salt processing and packaging plant, located just north of the potash plant. The plant produces both block and crushed salt products. The packaging plant bags crushed salt.

The potash plant was not toured because it was not operating at the time. Instead, a bus tour was made of the company's solar evaporation ponds, starting with the salt (sodium chloride) ponds (Stop 2a) and progressing through the potash ponds (Stop 2b). The tour then proceeded west and stopped on the west side of Promontory Point (Stop 3) to view IMC's pump station No. 1, the north arm of Great Salt Lake, the Southern Pacific Railroad causeway, and discuss the Behrens Trench. Samples of oolitic sand were collected at stop 3. Following Stop 3, the bus retraced its route on SR 39 to I-15 and entered I-15 heading south. The bus exited I-15 at the Syracuse exit and headed west on SR 127 to the entrance of Antelope Island State Park. From the park entrance, the bus crossed the seven-mile-long causeway and followed the signs to Buffalo Point overlook.

Stop 4 was at Buffalo Point on Antelope Island State Park. A "buffalo burger" dinner was served to field trip participants at Buffalo Point, a high, scenic viewing area at the north end of the island. Following dinner, the bus returned to the hotel.

FIELD TRIP NUMBER 2

Historic Quarries Tour May 4, 1999

Stanley T. Krukowski Graymont Western U.S., Inc., 670 East 3900 South, Suite 205, Salt Lake City, UT 84107 geodr@graymont-ut.com

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INTRODUCTION

The Historic Quarries Tour visited three sites in the Salt Lake City area. The site at Stop 1 was the historic Church of Jesus Christ of Latter Day Saints (LDS) Temple quarry at the mouth of Little Cottonwood Canyon (south side of State Route 209). Plans originally were made to visit both the historic quarry site and the new quarry from which the LDS Church mined quartz monzonite for the new Assembly Building situated in downtown Salt Lake City. However, the visit to the latter site was canceled due to inclement weather and unsafe conditions from the previous three days of rain and snow in Little Cottonwood Canyon.

The field trip host at the LDS Temple quarry was Dallas Orchard owner/operator of Idaho Travertine, contracted by the LDS Church to quarry the "temple granite." Field Trip guide for the site visit was Laurence P. James of James GeoAssociates P.C., Lakewood, Colorado, who has been studying the geology and history of the Little Cottonwood mining district for many years.

Stop 2 was at Soldier Hollow at the mouth of Red Butte Canyon situated in the foothills of the Wasatch Range overlooking Salt Lake City from the northeast. The sandstone in the canyon had provided building stone for the settlers of the Salt Lake Valley since 1850. The field trip host at this site was Red Butte Gardens & Arboretum. W. Richard (Dick) Hildreth, former Director and presently Adult Education Director, acted as field guide of the sandstone pits and botanical gardens. (Dick Hildreth retired on June 1, 1999 and moved to Tucson, Arizona where he continues to study native flora in warmer climes). Stanley T. Krukowski of Graymont Western U.S., Inc. also served as field trip guide, describing the geology of the area.



Stop 3 on the historic quarries field trip was at Lime Kiln Gulch, located in the extreme northeast corner of Salt Lake City, overlooking the residential area known as The Avenues. The lime kilns were commissioned in 1850 by leaders of the LDS Church for the purpose of providing lime for mortar and building material. Hosting the field trip at the lime kilns was the University of Utah; field guides were Dick Hildreth and Stan Krukowski.

Mileage	Cum. Miles	Description at Mileage Points
0.0	0.0	Leave WestCoast Salt Lake Hotel (formerly Cavanaughs Olympus Hotel), 161 West 600 South, parking lot at West Temple, head south.
0.4	0.4	Enter Interstate Highway 15 (I-15) south bound.
7.8	8.2	Enter I-215 east bound.
5.5	13.7	Exit I-215 at 6200 South (exit 6).
0.3	14.0	Enter 6200 South east bound.
0.7	14.7	At Wasatch Boulevard turn right (south).
0.1	14.8	Concrete Products Company (CPC) sand and gravel pit is on east side of road.
0.9	15.7	State Route (SR) 210 begins at junction with SR 190.
2.2	17.9	Continue along SR 210 past junction with Wasatch Boulevard.
0.9	18.8	Pull off west side of SR 210 to observe outcrops along the Wasatch fault.
0.8	19.6	At junction with Little Cottonwood Road and on south side of Little Cottonwood Road is the entrance to Temple Quarry Trail, site of the Temple quarry.

STOP 1: LITTLE COTTONWOOD CANYON TEMPLE "GRANITE" QUARRIES

Geology

The first brief geologic study of Little Cottonwood granitic rocks was by a young Harvard graduate, S.F. Emmons (later the "Father of Mining Geology"), one of three geologists assisting Clarence King in his "Geological Exploration of the 40th Parallel for the U.S. Army" (Hague and Emmons, 1877). Emmons and King concluded the Little Cottonwood and other granitic bodies exposed further to the east and west along "a great flexure" were basement rock of Archean age, which graded into adjacent schists and garnetized limestones. King's seven-volume, well-illustrated report covered geology, petrology, botany, and ornithology. He and his assistants spearheaded the founding of the United States Geological Survey. Several Scottish and American geologists questioned the King-Emmons interpretation of granite in Little Cottonwood Canyon. The expedition's own petrographer, Ferdinand Zirkel, elaborated on the Little Cottonwood plutons as "eruptive granites" (Zirkel, 1876). So, after King departed the Survey for a short-lived career as a mine operator in Mexico, Emmons sent John Mason Boutwell, a young Survey geologist from a new generation of Harvard graduates, to Utah. Based on new data, Emmons (1903) published a correction to the scientific record: the Little Cottonwood pluton was intrusive into, and younger than, all of the enclosing rocks.

The porphyritic quartz monzonite, or "granite" at the mouth of Little Cottonwood Canyon is quarried at the northwest corner of a mid-Tertiary intrusive igneous rock. The rock body, the Little Cottonwood stock or pluton, extends from the Salt Lake Valley, where aeromagnetic data suggests it continues beneath deep cover, eastward to the vicinity of Snowbird ski resort. Radiometric dating by the K-Ar and fission-track (sphene and zircon) methods yield nearly concordant ages. The dates suggest this multiphase, nearly batholith-sized pluton was emplaced between 24 and 31 million years ago. This late Oligocene, or possibly early Miocene, event only shortly preceded the first uplift along the Wasatch fault, perhaps beginning as early as 17 million years ago (Parry and Bruhn, 1986, 1987). Eastward, extending from upper Little Cottonwood Canyon through Brighton to Park City, are smaller, slightly older plutons. The petrology and character of these bodies are discussed by Vogel and others (1997), and in detail by Calkins and Butler (1943). The Little Cottonwood pluton intrudes deformed, contact-metamorphosed siliceous rocks ranging from the schistose Little Willow Formation to younger, little-deformed quartzite-slate sequences (Big Cottonwood Formation) of late Proterozoic age (Crittenden, 1965).

The line of plutons lies along a northeasterly trending, anticlinal zone of igneous and hydrothermal activity extending from the edge of the Uinta Mountains near Kamas, Utah, westward to Tooele Valley, which is west of the Bingham mining district. The Bingham district contains several barren and sulfide-rich, altered quartz monzonite plutons, and hosts one of the largest known porphyry copper-gold deposits at Kennecott's Bingham Canyon mine. This major mine, whose waste dumps are visible across the Salt Lake Valley, has inspired detailed studies of the igneous history of the region. John (1991) and Wilson (1961) discuss a porphyritic phase of the Alta stock, the locus of metallic mineralization in adjacent limestone replacement and vein deposits. In contrast, the Little Cottonwood stock generally lacks disseminated sulfides and intense fracturing, which would ruin its exceptional characteristics as a building stone. The Little Cottonwood stock has minor associated sulfide and gold-quartz veins near the contacts (James, 1979). Bromfield and others (1981) describe a zone near White Pine Gulch (about 6 miles east-southeast of the "granite" quarries; figure 1) characterized by disseminated and veinlet molybdenite and tungsten. This area contains obvious multiple intrusions of varied composition within the pluton. In the canyon mouth area, "granite" outcrops also record various effects from multiple Pleistocene glaciations.



Figure 1. The "granite" or Little Cottonwood quartz monzonite pluton at the mouth of Little Cottonwood Canyon, Salt Lake County, Utah. The Wasatch fault zone (WFZ) borders the pluton on the west. Undifferentiated late Proterozoic, and possibly older, metamorphic rocks flank the pluton on the north. To the south, in the lower plate of the Charleston-Nebo thrust fault, Paleozoic sedimentary rocks flank the stock. The outline of the Wilderness Study Area (WSA), is cross-hatched. The location of the Temple quarries is shown. Other features shown include: (1) Keetley volcanic field, east of Park City; (2) abandoned Silver Lake mining district; (3) hydrothermally altered area in Little Cottonwood stock associated with the White Pine molybdenum prospect; and (4) now-dormant Alpine mining district (modified from Bromfield and others, 1981).

The rock at the granite quarries is light gray, with a white matrix of feldspar and quartz and a color index of 6 to 12. Biotite and accessory magnetite are the major dark minerals. Modal compositions from various areas of the pluton are shown in table 1. The modes, determined by point counting mineral grains with a microscope, do not take into account the scattered large potassium feldspar phenocrysts in the "granite," which locally reach 2.4 inches in maximum dimension. Dark xenoliths of more mafic, fine-grained igneous rock, possibly remnants of assimilated volcanic cover, or an earlier intrusive phase, are common. Small aplite and pegmatite dikes are abundant. The Little Cottonwood stock, the youngest of several plutons in the trend of intrusions, is the most enriched in silica and potassium,

Table 1. Modal mineralogy, in volume percent, of quartz monzonite from various areas of the Little Cottonwood Canyon stock. The quartz monzonite or "granite" contains some large, scattered potassium feldspar phenocrysts, which were not counted by this microscopic study. The RS-series modal analyses are from Bromfield and others (1981).

Samples	RS-021	RS-089	RS-177	1	2	3
Quartz Potassium	35	25	33	25	32	20
feldspar	17	18	29	19	17	20
Plagioclase	38	44	30	42	42	42
Biotite	9	6	7	12	8	7
Hornblende Opaque and	<1	4	<1	<1	<1	7
accessory	<1	3	<1	2	<1	4

(Does not include scattered potassium feldspar phenocrysts)

Sample localities:

RS-021, Dromedary Peak $7^{1}/2'$ quadrangle, about 10,000 ft. ele., above White Pine Lake. RS-089, Draper $7^{1}/2'$ quadrangle, about 9,600 ft. ele., in Bells Canyon.

RS-177, Dromedary Peak $7^{1}/2'$ quadrangle, about 10,400 ft. ele., northeast of Lake Hardy.

1, Dromedary Peak 7¹/₂' quadrangle, top of ridge between Gad Valley and White Pine Fork (Sharp, 1958).

2, Dromedary Peak $7\frac{1}{2}$ quadrangle, upper White Pine Fork (Sharp, 1958).

3, Dromedary Peak 7¹/₂' quadrangle, a third of a mile below powerhouse (now abandoned) in Little Cottonwood Canyon near Hogum Fork (Butler and Loughlin, 1916).

and probably represents the deepest-formed igneous rock along the trend. Fluid inclusion studies on the eastern lobe of the pluton (John, 1989) suggest a depth of formation of 4 to 7 miles.

As shown in figure 1, a large volume of "granite" is exposed in the vicinity of Little Cottonwood Canyon. The area is prime recreational real estate as well as a vital watershed for Salt Lake City. The canyon walls are very steep, and the quarries are close to the highway in the canyon bottom. The potential for large-scale future production of this handsome building stone is thereby limited.

History

The LDS Church commenced construction of the Salt Lake Temple, the centerpiece of its headquarters in the Salt Lake Valley, in the 1850s. Completion of this mammoth work took 40 years. Initially, sandstone from the Red Butte area east of the city was selected for the building stone (Arrington, 1958). In 1855, plans were revised to use the more durable "granite" from the mouth of Little Cottonwood Canyon, some 20 miles south of the city. Two years were dedicated to building a canal to transport the stone, but it proved impractical. The "granite" proved a readily workable and highly durable stone of excellent quality. Skilled stonemasons and quarrymen from among new European and eastern U.S. converts to the Church provided expertise needed for this work. The ornate facings of numerous buildings in Salt Lake City have not weathered significantly after standing for more than a century.

Figure 2 is a historical photograph of an outcrop of the granitic rock above the main quarry area, which is on the steep northern side of Little Cottonwood Creek a short distance west of the canyon mouth. The town of Granite was established below the quarries. The name was later adopted by a more significant settlement (farther west along Little Cottonwood Creek) which became a significant agricultural town by the late 19th century.

The original quarry town, as described by a reporter in the summer of 1873, was apparently a temporary slum that spontaneously grew to serve the nearby industrial minerals operation:

"This is the first time I ever saw Granite City, and ... a cer-



Figure 2. Photo of the Little Cottonwood "Granite" that forms the steep, glacially polished north wall of Little Cottonwood Canyon, circa 1920. Along the stream here, two miles above the canyon mouth, the village of Wasatch accomodated quarrymen and their families. The quarries and mines up-canyon at Alta were served by the Salt Lake and Alta standard gauge railroad, which ended just beyond Wasatch. Horse-drawn wagons carried ore and stone down to this transfer platform. The rails connected with the Denver and Rio Grande trackage at Midvale. Photo courtesy of the L. James collection.

tain amount of earthly happiness can be obtained on my part if I should never see it again. Granite City borrows its name from the adjoining hill sides, for nary a granite has yet found a resting place in the material forming the town. Board, slab and waney-edged shanties with here and there a half-breed dugout, appear to constitute the available...real estate of the city. It is built on the principle of a Salt Lake gull, having but one slightly-curved avenue throughout it, and that like a shepard dog's tail, very short and stumpy... In case a rival town should spring up at the proposed terminus of the Wasatch and Jordan Valley railroad, five miles up the canyon, I don't think it would set Granite City back in any respect, as they could couple the town together in an hour and move the thing up in the evening" (Salt Lake Herald, March 11 and August 5, 1873).

In April 1873, the first steam trains of the Wasatch and Jordan Valley narrow gauge railroad reached the canyon mouth. The Salt Lake Herald article was prophetic, with the arrival of the railroad, a new town, Wasatch, was established at a location farther into the canyon mouth. Wasatch served the quarries as well as the silver-lead mines in the Alta area further up Little Cottonwood Canyon. The steeper grades up canyon, ending at the mining camp of Alta, became a route for mule-drawn railcars by 1877. This rail system allowed more efficient shipment of granite until the Salt Lake Temple was complete. By the turn of the century, with the Salt Lake Temple completed and the Alta silver mines languishing, the mouth of Little Cottonwood became a placid, decaying rural setting no longer accessible by steam train. The railway owner's engineer reported that the mule tramway, once the key to successful operation at higher quarries, had degenerated to just "a right-of-way and two streaks of rust" (letter of T.E. Baxter, Denver and Rio Grande Railroad archives). Wasatch acked space to expand; it remained small and ephemeral. Today a few homes occupy its site.

Standard-gauge rails were laid to the canyon mouth in 1913 by the Salt Lake and Alta Railroad. A transfer point for ore and granite (figure 2) was erected at the end of the rails. When new ore discoveries and high prices led to a boom at the mining camp of Alta, the Little Cottonwood Transportation Company equipped the steep canyon with geared steam locomotives (figure 3). The line reached Alta in the summer of 1917. The railroad offered tiny flatcars to haul granite. An inclined cable-tram lowered granite blocks from precarious quarries on the north side of the canyon for a few years, feeding a building boom in a prospering Intermountain West. The lack of a steady market for this labor-intensive stone, the severely over-steepened rugged hillsides hosting the quarries, and improvements in reinforced concrete curtailed these 20th century quarry operations.

In the 1960s, Hansen Stone Quarries, Inc. was producing some granite (Utah Mining Association records, 1967). The LDS Church commissioned a large underground vault for storage of records, cut into the granite at its property on the north side of the canyon. This has also provided secure storage for important non-church documents.

Presently "granite" is quarried from the LDS Church property, for use in modifications and repairs of the Salt Lake Temple and other buildings, and for interior pieces in the new LDS Assembly Building adjacent to Temple Square. Slabbing and finishing work is done away from Little Cottonwood Canyon. The canyon and its roads, used intensively for skiing and other recreation, allow little space for a modern, environmentally sensitive "Granite City".



Figure 3. Photo of a Shav-type geared, steam locomotive (circa 1919) easing a string of narrow gauge cars down Little Cottonwood Canyon. Rock in foreground is "granite" and glacial talus boulders of the same rock. On this Little Cottonwood Transportation Company line, the locomotive ran forward upcanyon. There was no facility to turn the locomotive around so, as shown here, it ran backward downgrade. The photo was taken from the front seat of "the Jitney stage", a gasoline-powered rail bus operated on the same trackage that carried passengers to Alta. Photo courtesy of Robert F. Marvin (James collection).

Mileage	Cum. Miles	Description at Mileage Points
5.6	25.2	Return to 1-215 along route taken via SR 210, Wasatch Boulevard, and 6200 South; enter 1-215 northbound.
11.0	36.2	Exit I-215 at Foothill Drive (exit 1); Foothill Drive coincides with SR 186.
3.6	39.8	Continue northbound on Foothill Drive to Wakara Way, turn right (east).
0.7	40.5	Continue east on Wakara Way to the entrance of Red Butte Garden and Arboretum. Red Butte Garden and Arboretum is the site of several small pits from which building stone was produced for Salt Lake City structures and nearby Fort Douglas.

STOP 2: RED BUTTE CANYON

Location

Red Butte Canyon lies in the northeast corner of Salt Lake City. A perennial stream flows through the canyon and early settlers first utilized the canyon for its water. The field trip stopped at Red Butte Garden and Arboretum at the mouth of Red Butte Canyon, the area is known as Soldier Hollow. Red Butte Garden and Arboretum lies in the NE _ section 3, T. 1 S., R. 1 E., of the Salt Lake Base Line. Historic Fort Douglas and the University of Utah are immediately to the southwest.

Geology

Rocks in Red Butte Canyon range from Mississippian to Holocene in age (Bryant, 1990;

Davis, 1983, 1985; Ehleringer and others, 1992; and Van Horn and Crittenden, 1987). Table 2 lists and describes these units.

Table 2. Abbreviations, names, and descriptions of geologic formations in Red Butte Canyon (from Ehleringer and others, 1992).

Cenozoic era, Quaternary system, Holocene series

- *fa Flood-plain alluvium.* Sand, cobbly to silty, dark gray at top, grading downward to medium to light gray, sandy to cobbly gravel, locally bouldery.
- fe Engineered fill. Selected earth material that has been emplaced and compacted.

Cenozoic era, Quaternary and Tertiary systems, Holocene and Pleistocene series

fg Alluvial-fan deposits. Bouldery to clayey silt, dark gray to brown, rocks angular to sub rounded. *ld Landslide deposits*. Composition similar to material upslope.

Mesozoic era, Jurassic system

Jtc Twin Creek Limestone. Brownish gray and pale gray to pale yellowish gray silty limestone, intercalated with greenish gray shale.

Mesozoic era, Jurassic? and Triassic? systems

JTn Nugget Sandstone. Pale pinkish buff, fine- to medium-grained, well-sorted sandstone that weathers orange-brown. Massive outcrops for the ridge called Red Butte.

Mesozoic era, Triassic system

- *Tau Ankareh Formation, upper member.* Reddish brown, reddish purple, grayish red, or bright red shale, silt stone, and sandstone.
- *Tag Ankareh Formation, Garta Grit Member.* White to pale purple, thick-bedded, crossbedded, pebbly quartzite. Forms a prominent white ledge for long distances.
- *Tam Ankareh Formation, Mahogany Member.* Reddish brown, reddish purple, grayish red, or bright red shale, siltstone, and sandstone.
- *Tt Thaynes Formation.* Medium to light gray, fossiliferous, locally nodular limestone, limy siltstone, and sand stone.
- Tw Woodside Shale. Grayish red, grayish purple, or bright red shale and siltstone.

Paleozoic era, Permian system

Ppc Park City Formation and related strata. Fossiliferous sandy limestone, calcareous sandstone, and a medial phosphatic shale tongue.

Paleozoic era, Pennsylvanian system

- *Pw Weber Quartzite.* Pale tan to nearly white, fine- to medium-grained, crossbedded quartzite and medium gray to pale gray limestone.
- *Prv Round Valley Limestone*. Pale gray limestone with pale gray siltstone partings. Contains pale pinkish chert that forms irregular nodules.

Paleozoic era, Mississippian system

- *Mdo Doughnut Formation*. Medium gray, thin-bedded limestone with pods of dark gray to black chert and abundant brachiopods and bryozoa.
- Mgb Great Blue Formation. Thick-bedded, locally cliff-forming, pale gray, fine-grained limestone.
- Mh Humbug Formation. Alternating, tan-weathering, limy sandstone and limestone or dolomite.
- *Md Deseret Limestone*. Thick ledges of dolomite and limestone with moderately abundant lenses and pods of dark chert.

Paleozoic era

P Paleozoic rocks, undifferentiated.

Unconsolidated Lake Bonneville sediments of Pleistocene and Holocene age are found at the mouth of the canyon. Farther up the canyon, outcrops of Mississippian to Jurassic rocks are found; they decrease in age from the northwestern part of the canyon to the southeastern part (figure 4).

Beds are relatively steeply dipping to the southeast and strike northeast. Units in the northwestern part of the canyon were thrust over younger rocks. These relationships are shown in figure 4.

The principal drainage is controlled by the strike of the beds in the canyon. Limestones predominate in the upper, southeast-facing slopes of Red Butte Canyon with lesser amounts of sandstone and limy shale. Sandstones are the primary lithology in the northwest-facing slopes of the upper canyon with limestones and limy shales also occurring.



Figure 4. Geologic map and cross section of the Red Butte Canyon Research Natural Area. Formation abbreviations are explained in table 2. Solid lines represent contacts between formations, dashed lines represent normal faults, and T-dashed lines represent the Black Mountain thrust fault. The transect A-Al is shown in cross section (Ehleringer and others, 1992).

The rocks in Red Butte Canyon form the northern flank of a large syncline whose axis trends northeast. The southern limb is in Mill Creek Canyon about 3.5 miles to the southeast. Rocks have been cut by numerous normal faults which have displaced the rocks horizontally. These faults are part of the larger Wasatch fault zone that runs from north to south along the western edge of the Wasatch Mountains. The Black Mountain thrust fault has placed older sedimentary rocks on top of younger rocks in the extreme northwestern part of the canyon (see figure 4).

History

Beginning in 1848, early settlers in the Salt Lake City area mined red sandstone from the Triassic-Jurassic Nugget Sandstone and the Triassic Ankareh Formation found in Red Butte Canyon. Many Salt Lake City buildings of red sandstone can still be seen today (Wilker-

son, 1999). There are at least 33 open-pits throughout the canyon where sandstone was mined (W. Richard Hildreth, personal communication, 1999). The red sandstone from the Nugget was the preferred building stone because of its uniform color, durability, and workability. The Nugget also weathered more evenly. The sandstones in the canyon were also mined for aggregate.

Mormon settlers believed that all the natural resources in the area were jointly owned by, and for, society at large (Arrington, 1958; Arrington and others, 1992). As early as 1848, the Salt Lake Rock Company quarried stone from Red Butte Canyon. Brigham Young (LDS President) licensed them to mine stone from the canyon for public works projects. The red sandstone was hauled down to Temple Square by a narrow-gauge railroad built in 1850 (Arrington, 1958; Gunnison, 1856). The tracks and ties were made of oak, and teams of oxen hauled the stone over this railroad in wooden rail cars. The three-mile trip to Temple Square was made twice daily.

Mine operators, at one point, attempted to build a canal system to transport the stone to Temple Square. However, this proved futile, and the railroad remained the reliable means of hauling the red stone to the downtown distribution center.

Several buildings in Salt Lake City used large blocks of stone from the Nugget Sandstone for foundation stone. These buildings include the LDS Temple and Tabernacle. Original plans called for using sandstone in building the Temple, but deterioration due to weathering during the 1860s compelled the builders to use more durable quartz monzonite ("granite") (Arrington, 1958). Many homes in The Avenues were built using this red stone, as well as homes east of downtown Salt Lake City (Hylland, 1996). Aggregate from Red Butte Canyon quarries was used for railroad ballast in building the Central Pacific Railroad.

Between 1848 and the turn of the century, several private companies mined the red sandstone. In 1862, the U.S. Army moved its garrison at Camp Floyd, near the present town of Fairfield in Cedar Valley, to Camp Douglas (later Fort Douglas), at the mouth of Red Butte Canyon. The Army established Camp Douglas at the mouth of the canyon for its strategic location and because it provided a source for water. The Army gained title to most of the canyon by 1909. The water resource of Red Butte Canyon was a point of conflict between the Army and the occupants of the valley throughout the Army's tenure at Fort Douglas. Fort Douglas was built with stone quarried from the Nugget Sandstone; the Army utilized the resource intermittently until 1940 (Hance and Warr, 1962; Hibbard, 1999). Figure 5 is a photo of Soldier Hollow where stone was removed for use at Fort Douglas. John W. Young built a railroad in the canyon in the late 1880s to transport dimension stone

from land he had purchased in the canyon. The enterprise went into receivership in 1894, partly because of mismanagement, and the depression of 1893 (Arrington, 1958).



Figure 5. Looking east at Soldier Hollow from the Fort Douglas area. Tailings immediately below quarry faces are observed particularly on north-facing slopes. Most of the quarry operation occurred about two miles farther up the canyon, however, outcrops near the point of use were often quarried even under difficult quarrying conditions.

Red Butte Canyon quarries still produced stone during the Depression in the 1930s when U.S. Works Progress Administration stone masons were trained in their craft there. The Rock House (figure 6), located near the boundary of Red Butte Garden and the Wasatch National Forest, probably served this purpose. Chisel marks can still be seen on the stone in the Rock House and in stone debris which litters the area.

The Rock House existed in the 1920s, but it is not known when it was built. The area in front of the Rock House probably was the site for a corral complex for oxen and horses. Several walled embankments found at the bases of rock pits and rock dumps were probable load out sites for the railroad line along the bottom of the canyon. Stonemasons who



Figure 6. Rock house at the boundary between Red Butte Garden and the Wasatch National Forest in Soldier Hollow. Nugget Sandstone immediately above Rock House provided stone for masons learning their craft at the site during the time of the Great Depression.

worked in the quarries are known from their signed work on tombstones in the Fort Douglas cemetery (W. Richard Hildreth, personal communication, 1999).

In 1970, the U.S. Army declared Fort Douglas surplus property and administration was transferred to the U.S. Forest Service, which designated the canyon a Research Natural Area. The Army protected the watershed for the Fort Douglas water supply for the entire time it occupied the canyon. Today, the U.S. Forest Service protects the canyon as a declared Research Natural Area with the purpose of maintaining the riparian and shrub ecosystems for future reference. Red Butte Garden and Arboretum of the University of Utah is located at the mouth of the canyon providing "…the Intermountain West a world-class botanical garden, arboretum, and pristine natural area…" (Ehleringer and others, 1992).

Mileage	Cum. Miles	Description at Mileage Points
0.7	41.2	Return to Foothill Drive (SR 186) via Wakara Way, turn right (north).
1.1	42.3	Turn right (north) at the intersection of 1300 East.
0.7	43.0	Turn right (east) at the intersection of South Temple.
0.1	43.1	Turn left (north) at Virginia.
1.0	44.1	Turn right (east) at Chandler Drive.
0.3	44.4	Turn right at Tomahawk Drive.
0.1	44.5	Stop at lime kiln ruin at the bottom of Lime Kiln Gulch. The restored lime kilns are about a 15 minute walk up the gulch.

STOP 3: LIME KILN GULCH

Location

Lime Kiln Gulch is located in the extreme northeast corner of Salt Lake City. The gulch is

located mostly in section 33, T. 1 N., R.1 W., of the Salt Lake Base Line. The gulch is recognized by the presence of a dilapidated stone structure on the north side of the road. The dilapidated structure is one of the old lime kilns which has fallen into disrepair over time. A footpath along the floor of the gulch leads to the restored lime kiln.

Geology

The Pennsylvanian Weber Quartzite (referred to as Weber Sandstone by Bryant, 1990) forms the western slopes of Lime Kiln Gulch and is in fault contact with the upper member of the Permian Park City Formation (Bryant, 1990; Davis, 1983, 1985; Van Horn and Crittenden, 1987). The Weber Quartzite is a tan to gray quartzite with thinner beds of conglomerate and quartzitic sandstone (see table 2 and figure 4); it is 1,000 to 1,150 feet thick. The upper member of the Park City Formation, the Franson Member, is a dark gray, cherty, fossiliferous limestone with interbedded sandy and silty limestones. A geochemical assay of a grab sample of limestone from the mine tailings yielded the following analysis by the Graymont Western U.S., Inc.'s Central Laboratory: 94.62 percent CaCO3, 1.31 percent MgCO3, 0.09 percent Fe2O3, 0.20 percent Al2O3, 3.10 percent SiO2, and 0.68 percent other elements.

Mining

The Franson Member limestone was mined from the canyon walls directly above the lime kilns. Miners took advantage of gravity feed whenever possible, however, haulage roads between the limestone pits and the kilns was developed for the benefit of all operations. It is apparent from the limestone tailings that the kiln feed was of grapefruit or softball size (figure 7).



Figure 7. View of restored lime kiln from the east side of Lime Kiln Gulch showing the limestone quarry benches immediately above the kilns. Gravity feed was utilized whenever possible, however, haulage roads linked the kilns and other quarry operations in the vicinity.

The original plans called for the manufacture of lime utilizing the small chips remaining from cutting dimension stone. Various drilling and blasting techniques were used in the quarrying of limestone during this time period. Separating the stone by size and for impurities was done by hand because it was a job that one or two men could handle. Horse and wagon performed the majority of haulage (Utah State Historical Society, n.d.).

History

Lime kilns were built in Lime Kiln Gulch in 1850 and 1853. Brigham Young, LDS President, commissioned A. Knowlton and Stephen Winchester to burn lime there. A. Knowl-

ton & Company controlled the lime business for many years and the commission was later passed on to the Crystal Lime and Cement Company who maintained the business through the turn of the century. Lime was sold by the bushel, but no production records were kept during much of the 1800s. In 1900 it was recorded that 10,000 bushels of lime were manufactured annually. The early Salt Lake Valley settlers utilized the limestone for the manufacture of lime that was used for masonry mortar, plaster, and whitewash, and as a whitening agent in sugar (Utah State Historical Society, n.d.).

Originally, there were three lime kilns in Lime Kiln Gulch. One kiln no longer exists. Another kiln at the mouth of the gulch has been silted in from sediments transported down the canyon and has suffered through many years of neglect. The University of Utah restored one lime kiln located farther up the gulch, as required by the former landowner when the land was donated to the university (University of Utah Archives, n.d.).

The early settlers built homes of adobe, however, they did not hold up to seasonal climate extremes. Brick manufacture, therefore, was one of the earliest industries in the valley. The refractory bricks lining the kilns were manufactured locally. The heat of calcination glazed the bricks lining the kilns during the manufacture of lime. During restoration of the lime kilns, this glaze could not be duplicated; therefore, original glazed brick was used in the restoration (Utah State Historical Society, n.d.).

Calcination took place in the shaft of the kiln by stacking alternate layers of wood fuel and limestone (Rockwood, 1949). Fuel to fire the kilns came from timber in the surrounding hills and canyons. Coal and charcoal were not economical for calcining because they did not burn with an even flame or with a constant temperature. The process was conducted over a two-week period before the fires were allowed to burn out and the lime to cool (Utah State Historical Society, n.d.).

Quarried limestone blocks were used to build the lime kilns. Charred wood fragments can be observed in the mortar between limestone blocks in the kiln. The aggregate used in the mortar (hydrated lime) was derived locally from Quaternary sand and gravel. Some of the original lime found under the kilns was used to match the appearance of the original mortar. Cement was added to the mortar during the restoration for strength and durability. The original lime kilns did not have a parapet wall at the top. This was added to the kiln in the restoration for safety reasons. The gratings over the tops of the hoppers were also added safety features (Utah State Historical Society, n.d.).

Mileage	Cum. Miles	Description at Mileage Points
1.4	45.9	Return to South Temple via Tomahawk Drive, Chandler Drive, and Virginia. Continue west along South Temple.
2.1	48.0	Turn left (south) at State Street.
1.1	49.1	Turn right (west) at 600 South.
0.1	49.2	Turn left (south) into the WestCoast Salt Lake Hotel parking lot.

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FIELD TRIP NUMBER 3

South Salt Lake Valley and South Shore Great Salt Lake May 6, 1999

Stanley T. Krukowski, Graymont Western U.S., Inc., 670 E. 3900 S., Ste. 205, Salt Lake City, Utah 84107 geodr@graymont-ut.com



Miles	Cum. miles	Description of Mileage Points
0.0	0.0	The field trip begins at the east parking lot of WestCoast Salt Lake Hotel (formerly Cava naughs Olympus Hotel), 161 West 600 South, and travels south on Interstate Highway 15 (I-15). Turn south out of parking lot onto West Temple.
0.3	0.3	Junction 900 South and I-15. Enter I-15 heading south.
2.3	2.6	I-15 intersects Interstate Highway 80 (I-80). To the east (left) along the Wasatch Front is the mouth of Parleys Canyon. The canyon nearly coincides with the axis of the Parleys Canyon syncline (Bryant,1990).
1.4	4.0	Looking east (left) along the Wasatch Front at mile post 306 (3300 South) one may observe the mouth of Mill Creek Canyon. The canyon coincides with the axis of the Mill Creek syncline (Bryant, 1990). The tall peak to the south of Mill Creek Canyon is Mount Olym- pus.

Miles	Cum. miles	STOP 1: INTERSTATE BRICK COMPANY, POWELL PIT
		Utah Lake, seen to the southeast, occupies the drainage basin for the Lake Mountains on the west shore of the lake and the Wasatch and Traverse Mountains on the east and north shores, respectively. The outlet of this fresh water lake, the Jordan River, flows north to Great Salt Lake.
3.4	33.2	Turn right (west) off paved road; dirt road leads to Interstate Brick Company's Powell pit.
3.0	29.8	Turn left (south) at junction SR 68.
1.1	26.8	Turn right (west) at junction SR 73. The Jordan river is crossed before junction of SR 68.
1.4	25.7	Turn right (southwest) at junction SR 197.
		ing and knitting factories. Stone cutting was also an important early industry (Arrington, 1958). More recently Micron Electronics, Inc. has begun building a microchip factory in Lehi.
5.6	24.3	Exit I-15 at Lehi exit 285, junction State Road (SR) 89 at the town of Lehi. Lehi is an agri- cultural community and a bedroom community for the cities of Provo and Salt Lake City. Early Lehi industries were associated with agriculture, for example grist mills, and weav-
6.9	18.7	Approaching mile post 291, notice the large excavation at Point of the Mountain, the extreme western end of the Traverse Mountains. Several sand and gravel operators mine the Lake Bonneville longshore bar complex deposits here. The demand for sand and gravel along the Wasatch Front has grown astronomically in the past few years (Isaacson, 1999). Sand and gravel is used in the manufacture of concrete for Wasatch Front development and, most recently, for road base and fill in the I-15 and I-80 construction project.
		The ancient shoreline of Lake Bonneville is easy to recognize beginning at the mouth of Little Cottonwood Canyon and continuing to the south.
2.3	11.8	Milepost 298 is at 9000 South. The mouth of Little Cottonwood Canyonis seen to the east (left). The U-shaped profile is the result of Pleistocene glaciation. Several hanging valleys and landslide tracks can be observed on either side of the canyon. The Little Cottonwood (Alta) mining district (James, 1979) farther up the canyon supplied some lead-silver ore for processing at the Murray smelter. U-shaped glacial valleys are seen along the Wasatch Front. The LDS Temple quarry in Little Cottonwood Canyon is a planned stop in Field Trip 2 this volume.
		Notice the east-west spurs originating in the Wasatch Mountains which terminate as west- facing triangular slopes. This is the scarp of the Wasatch Fault from which the Wasatch Front is defined.
2.4	9.5	The Midvale slag heaps can be seen to the west (right) at mile post 301 (7200 South). From the late 1880s to 1958 a variety of firms operated copper smelters in the vicinity (Keahey, 2000). They were eventually shut down when it was determined that the operations had harmful effects on agriculture in the Salt Lake Valley (Christenson, 1990). Reclamation of this Superfund site is now complete. To the east (left) of mile post 301 is the mouth of Big Cottonwood Canyon. The Big Cottonwood mining district was a source for some of the lead-silver ores processed at the Murray smelter (Laurence P. James, personal communication, 1999).
		because the cost of stabilization for earthquake preparedness was too costly.
3.1	7.1	Looking west (right) at mile post 303 (5300 South) is the site of the American Smelting and Refining Company's (ASARCO) smelting operation which processed up to 1,200 short tons (st) of ore per day. Most of the ore came from the lead-silver mining districts of Utah, but additional custom ores were also processed from California, Oregon, Idaho, Washington, Wyoming, and Colorado (Smouse, 1991). The historic smokestacks which marked the site were demolished in August 2000, to make way for commercial development and
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0.9 34.1 (Due to heavy rains several days immediately prior to our visit, it was necessary to cancel this stop.) The gate to the Powell pit is at the bend in the road. Interstate Brick mines the

- 0.9 35.0 Return to SR 68 and head north.
- 3.4 38.4 Junction, SR 73. Continue north on SR 68.
- 3.1 41.5 Utah National Guard's Fort Williams Post is on the east (right) side of the road.
- 4.8 46.3 Turn left (west) at junction SR 194 (Bangerter Highway). Observe the Bingham Canyon mine to west.
- 7.954.2Bangerter Highway bends north. At 9000 South turn left (west).
- 0.754.99000 South terminates just over the railroad tracks. Turn left
(southwest) at the stop sign at Old Bingham Highway.
- 1.5 56.4 Turn left off Old Bingham Highway to Interstate Brick Company road.

Miles Cum. miles STOP 2: INTERSTATE BRICK COMPANY, OLD WELBY PIT AND BRICK PLANT

0.2 56.6 Our hosts at Interstate Brick, Jerry North, Geologist/Materials Manager, and John Hewitt, Process Engineer, conducted the tour of the stockpiles and plant.

The Interstate Brick organization has been manufacturing brick since 1870. The name Interstate Brick has been in use since 1890. The company has been in West Jordan, Utah since 1971. In 1991 it became a division of Pacific Coast Building Products. Two plants are currently in operation at the West Jordan site. A residential products plant manufactures 30 million bricks annually for the Utah/Mountain West market. A commercial/architectural materials plant annually manufactures 75 million brick equivalents for national distribution with half the supply shipped east of the Mississippi River. The commercial/architectural plant is the only plant in the United States that regularly produces large quantities of structural units such as 8 in. x 4 in. x 6 in. AtlasTM brick. The large-sized units, unique pink/rose color, and high quality account for Interstate's unique nationwide market presence.

Eleven clay pits lie within a 200-mile radius of the plant. Seven of the pits are on the west side of Utah Lake, about 20 miles from the plant. Approximately 240,000 st of clay are hauled to the plant annually. The mining season is generally from May through October, then ceases due to winter conditions. Stockpiles stand at the mines for one year under weathering conditions before hauling to the plant. Most mining is done by ripping with a bulldozer, then stockpiling using trackhoe and dump truck. Overburden depths average 5 ft at these mines.

The clays from the 11 pits are blended to make various mixes, then ground to 10 to12 mesh (1.5-2 mm) before being extruded into brick. Various kiln temperatures, kiln flashing (exposing brick to a reducing atmosphere), and the addition of processed manganese and chromite, result in 35 non-coated brick colors. Recycled, ground, fired brick (also called grog), is added to the clay mix (approximately 5 percent by volume) to minimize shrinkage during drying and firing.

The average moisture content of materials at the plant is 5 to 7 percent. During extrusion 9 to 11 percent water is added to the mix. Total extruded brick moisture content is approximately 16 percent. Total shrinkage of the extruded brick after drying and firing is 5 to 7 percent. Typical firing temperature is 2,1000 F.

Most of Interstate's raw materials contain trace amounts of sulfur and fluorine. Both tunnel kilns at Interstate have wet, acid-gas scrubbers that capture sulfur dioxide and fluorides released during firing. A mass balance test program (part of an air pollution operating permit) quantifies the amount of sulfur and fluorine released by each materials mixture. (Interstate Brick Company, 1999).

0.2 56.8 Return to Old Bingham Highway and turn left (southwest) at the stop sign. Straight ahead is Kennecott's Bingham Canyon mine. U.S. Army soldiers from Fort Douglas discovered lead in Bingham Canyon in 1863. Later, gold and silver, then copper were discovered. The Bingham Canyon mine has produced more copper than any other mine in history (15 million st of copper). The Bingham pit is the largest man-made excavation in the world. 460,000 st of rock are removed from the mine 365 days per year; consisting of 160,000 st of copper ore and 300,000 st of waste rock. The mine, smelter, and refining complex occupy the foothills and pediment slopes along the eastern edge of the Oquirrh Mountains (Kennecott Utah Copper, 1999). Old Bingham Highway intersects with 10200 South; continue heading west on 10200 South.

- 2.7 59.5 Junction, SR 111. Turn right (north) and continue north along SR 111.
- 0.7 60.2 Junction, New Bingham Highway. Continue straight (north) along SR 111 after stop sign.

7.9 68.1 Along the eastern edge of the Oquirrh Mountains, and out onto the valley floor, are a series of mines that produce sand, gravel, and boulders from unconsolidated pediment and valley-fill deposits. Boulders are sold for landscape rock, or crushed and screened for aggregate. The rapid urban development in Salt Lake Valley has increased the demand for sand and gravel and aggregate. The I-15 construction project also has increased demand for locally produced construction materials. As development has spread to the west side of the valley, local sources of sand and gravel have become more important (Isaacson, 1999). Most of these west side sand and gravel pits began operating in the last five or six years. The aggregate operations are all on privately owned land. The town of Magna is ahead. Magna developed around the Magna mill, which was a facility for crushing, concentrating, and dewatering copper ore from Bingham Canyon, circa 1906. By 1916, the town was composed of a business community, residential sections, and had an ethnically diverse population. Many southern and eastern European immigrants settled here seeking employment in the mining industry.

- 2.4 70.5 Junction, SR 201. Turn left (west) and continue traveling west.
- 7.1 77.6 Junction I-80. Enter I-80 heading west. Great Salt Lake is to the right (north). I-80 follows the southern shoreline of the lake. The Tooele Valley is seen to the left (south). A branch of Lake Bonneville once filled the valley. The profile of the valley is broad and flat, which is characteristic of basins filled with fine lake sediments. The valley is structurally a graben formed in the Basin and Range physiographic province. The shoreline of Lake Bonneville can be seen along the valley walls, in some places draped with porous calcium carbonate deposits called tufa.
- 17.2 94.8 Leave I-80 at mile exit 84. To the right (north) is the Morton International, Inc. salt plant and salt stockpiles. Farther north in the Great Salt Lake is Stansbury Island. The island is a long narrow fault block of Paleozoic sedimentary rocks that have been folded into an anticline which extends south into the Stansbury Mountains. Extractive industries along the shore of the Great Salt Lake use the mudflat area between the southern lake shoreline and Stansbury Island for evaporation ponds. They utilize the dissolved minerals in the Great Salt Lake to produce salt and magnesium.
- 0.3 95.1 Turn left at junction with frontage road.
- 0.3 95.4 Turn left (south) at junction with SR 138.
- 2.7 98.1 At junction with Ellerbeck Road turn right (northwest).

Miles

100.3

2.2



Figure 1. Chemical Lime Company's dolomitic lime plant is located just north of Grantsville, Utah. The mine is located immediately above and adjacent to the plant.

Russell Curtis, Plant Manager, and Ken Ginnard, Geologist, hosted the visit to the quarry and lime plant. Chemical Lime Company is a subsidiary of Lhoist Group of Liege, Belgium. Products currently produced at the plant include bagged and bulk, Type-S hydrated lime, dolomitic quicklime, and uncalcined dolomite. The dolomite for calcination has an average chemical value of 55.30 percent CaCO3, 43.73 percent MgCO3, 0.25 percent SiO2, 0.25 percent AL2O3, and 0.38 percent Fe2O3 (Smouse, 1991).

CHEMICAL LIME COMPANY GRANTSVILLE, UTAH QUARRY

Ken Ginnard, Chemical Lime Company, 3700 Hulen Street, Fort Worth, TX 76107-6916

The Chemical Lime Company's Grantsville quarry and plant are located at the northern end of the Stansbury Mountains in Tooele County, about 35 miles west of Salt Lake City. Salt water marshes and the Great Salt Lake lie to the north of the property.

The immediate mine property is dominated by two north-south trending hills, East Hill and West Hill. The crushing plant abuts East Hill, which contains two small quarries. West Hill currently is being mined. It is on federal land managed by the U.S. Bureau of Land Management. The land immediately to the south is a State lease and forms the southern boundary of the quarry. The quarry has six benches, each 25 feet high, that span an elevation of 4,600 to 4,750 feet.

There are three geologic formations in the West Hill area. In ascending stratigraphic order they are:

Formation	Age
Stansbury Formation	Devonian
Fish Haven Dolomite	Ordovician
Swan Peak Formation	Ordovician

These beds dip steeply to the east at 450 to 700. The Swan Peak Formation consists of alternating beds of cherty limestone and siliceous dolomite that have a brown color when weathered. This formation forms the ridge of West Hill. The ore-bearing Fish Haven Dolomite is a gray to black dolomite and is more than 550 feet thick stratigraphically. This unit forms the outcrops on West Hill. The Stansbury Formation lies unconformably above the Fish Haven and consists of sandstones and conglomerates. West Hill is part of the eastern limb of a large regional fold that formed the Stansbury Mountains. Movement along bedding planes occurred during folding; evidence consists of the following:

- contacts between beds are marked by slickensides and local breccia zones;
- numerous parallel, white dolomitic veinlets lie at an angle to individual beds with slickensides reflecting "shattering" of these beds and subsequent "healing" of the openings by precipitated dolomite; and,
- very small, cave-like features occur parallel to bedding.

The large arroyo that separates East Hill and West Hill may be due to a series of small faults at or near the contact of the Fish Haven and the Stansbury Formation. Exploratory drilling will establish the relationship between the dolomite deposits on East Hill and West Hill.

The unconformity between the Fish Haven and the Stansbury Formation is marked by the occurrence of conglomerates at the base of the Stansbury. The contact between the Swan Peak and overlying Fish Haven is easy to distinguish. The Swan Peak limestone and dolomite are brown in color. The Fish Haven, where exposed on West Hill, weathers dark gray to black, with alternating beds of light gray. Occasionally, silicified fossils can also be found in the Fish Haven. The Fish Haven is composed of a series of very thin beds and very massive beds. The Fish Haven is subdivided into six zones based upon silica content (zone 1 is the basal unit). There is no well-exposed occurrence of the unconformable contact between the Fish Haven and the overlying siliciclastic Stansbury.

- 2.1 102.4 Leave the Grantsville lime plant and return to the junction of Ellerbeck Road and SR 138. Turn left (northeast).
- 2.8 105.2 At the junction with frontage road, turn right to access I-80 west bound.
- 0.2 105.4 Continue west on I-80.
- 7.0 112.4 Leave I-80 at Rowley/Dugway exit 77.
- 0.3 112.7 Junction, SR 2652, turn right (north) at the stop sign, then make an immediate left (west) turn; proceed west and then north on Route 2652. The Lakeside Mountains to the left (west) contain rocks of Cambrian to Mississippian age. The north-south trending fault block mountains are typical of the Basin and Range. These rocks are folded into a syncline. The ancient horizontal shoreline of Lake Bonneville is obvious along the flanks of the Lakeside Range. Continue north on SR 2562 to Rowley.

Miles	Cum. miles	STOP 4: MAGNESIUM CORPORATION OF AMERICA (MAGCORP),
		MAGNESIUM PLANT

14.7127.4G. Thomas Tripp, Production Manager, and Chris Menefee, Environmental Engineer, were
host and tour guide, respectively.

MagCorp extracts magnesium metals from the waters of the Great Salt Lake. The Rowley magnesium plant has a current production capacity of more than 44,000 st annually. This includes pure magnesium metal and various alloys.

The first step in extracting magnesium from the waters of the Great Salt Lake is brine concentration. Lake water is pumped into solar evaporation ponds to increase its density. The ponds at the Rowley facility cover more than 120,000 acres. Brines reach densities over 20 times the original concentration before being pumped into holding ponds where they are further prepared for processing (Magnesium Corporation of America, n.d.).

During brine preparation, impurities are removed from the magnesium chloride. Initially, a mixture of calcium carbonate (CaCO3) from local sources (limestones from Graymont Western U.S. Inc.'s Pilot Peak plant west of Wendover, Nevada) and MagCorp's by-product hydrochloric acid (HCl) are mixed to form a calcium chloride (CaCl2) solution. CaCl2 is mixed with the brines and reacts with sulfate in the brine to form gypsum, which is then removed in a thickener circuit. The final step is the removal of boron from the brine by solvent extraction.

The magnesium chloride solution is pumped through high-volume spray dryers and flash dried into magnesium chloride powder. This powder is melted and purified. The molten magnesium chloride is then transferred to electrolytic cells where it is separated into liquid

magnesium metal and chlorine gas. By-product chlorine is recycled and used in the production process or sold on the open market for use as swimming pool water purification and in plastic production. In the foundry, liquid magnesium is cast into ingots ranging in size from 15 to 750 pounds (Toomey, 1980).

- 14.8142.2Return to the junction with frontage road. Turn right (south) to I-80 access; enter I-80 head-
ing east.
- 7.1 149.3 Leave I-80 at Grantsville exit 84.
- 0.5 149.8 At junction SR 138 turn left (north) onto Solar Road.
- 0.5 150.3 At Solar Road junction, turn right (east).

Miles Cum. miles STOP 5: MORTON INTERNATIONAL, INC., SALT PLANT AND SOLAR PONDS

1.0 151.3 Field trip host and tour guide was James H. (Jim) Huizingh, Facility Manager. Morton Salt manufactures solar salt for water softening systems (pelletized and crystal salt), salt blocks for livestock, and various other products at their Great Salt Lake plant site (figure 2).



Figure 2. Morton salt plant and stockpiles are located on the north side of I-80 near exit 87. The salt is stockpiled during the fall and winter months just after harvesting takes place.

Salt has been extracted from Great Salt Lake for human consumption since prehistoric times (Madsen, 1980). Early Utah pioneers also utilized the minerals from Great Salt Lake (Miller, 1980). In recent times, Great Salt Lake salt and brine-derived products are the largest contributors to the value of industrial minerals in Utah (Bon and others, 1996, 1997).

Morton Salt Company and its predecessor has produced salt from Great Salt Lake since 1918. In 1923, Morton Salt purchased controlling interest in the Inland Crystal Salt Company and re-incorporated under the name Royal Crystal Salt Company, after acquiring the remaining stock in the former company. In 1958, the Royal Crystal Salt Company was dissolved and Morton has produced salt under the name Morton Salt Company ever since (Clark and Helgren, 1980).

Great Salt Lake provides excellent natural conditions for evaporative salt production: low rainfall, high rates of evaporation, large flat areas of land (mudflats), and brines highly concentrated in dissolved solids (originally three times that of sea water). During salt production, brines are pumped into large concentrating ponds. Insoluble materials are allowed to settle out of suspension and the brines are further concentrated by solar evaporation to the point of sodium chloride saturation. The brines are then transferred to crystallizer ponds where the salt is precipitated.

The floors of the crystallizer ponds are composed of a permanent layer of halite. This allows the salt to precipitate more rapidly because the salt on the floor acts as seed crystals. Secondly, the salt can be harvested without contamination from the underlying soils. Today, special harvesting machines gather up the top 4 to 6 inches of salt crop, loading it directly into dump trucks for hauling.

Production usually begins in March, when ponds are initially filled. Salt concentration takes place primarily during the summer months (May through August). Harvesting begins in September and continues through November. Another harvest may be possible if weather conditions are favorable.

- 1.0 152.3 Return to junction SR 138. Turn left (south) to access I-80 east.
- 0.5 152.8 Junction I-80 east access ramp.
- 20.0 172.8 At mile post 104, take the Saltair exit (104) for a refreshment stop. Saltair is a reincarnation of a historic dance hall and amusement park originally built in 1893 (figure 3).



Figure 3. Saltair building: originally a dance hall and amusement park.

Miles	Cum. miles	STOP 6: SALTAIR CONCERT AND DANCE HALL
		Today, Saltair is a concert and dance hall, and a tourist attraction with access to the Great Salt Lake shoreline. Take a closer look at the beach sands along the shore of Great Salt Lake. Formed in the lake, the grains are mostly ooids. The sphericity of the grains make walking through the beach sand relatively difficult. Conditions necessary for the formation of ooids are: water saturated with calcium carbonate (CaCO3), warm temperatures, a continuous source of agitation (Great Salt Lake is only a few meters deep at the most, so wave base is relatively shallow), and grains to act as nucleation centers (here silt grains eroded from the surrounding mountains and brine shrimp fecal pellets provide the latter).
		Antelope Island is in the Great Salt Lake to the left (north). The southern part of the island contains some of the oldest rocks in Utah; Precambrian gneisses and schists.
5.9	178.7	Eastern end of the Kennecott mill tailings complex to the right (south).
		Follow access road back to I-80 and head east to Salt Lake City (approximately 14 miles). Merge with I-15 south bound and take City Center exit (600 South). Continue east bound on 600 South about 5 blocks to hotel.

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FIELD TRIP NUMBER 4

Industrial Minerals In West-Central Utah May 6-7, 1999

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Miles	Cum Miles	Description at Mileage Points
0.0	0.0	Exit WestCoast Salt Lake Hotel (formerly Cavanaughs Olympus Hotel), 161 West 600 South. Proceed south on West Temple to Interstate Highway 15 (I-15). Enter I-15 south bound.
20.0	20.0	I-15 milepost 290 - Point of the Mountain gravel pits. Massive deposits of interbedded sand and gravel deposited in Lake Bonneville. The stratigraphy of the deposit shows the layered accumulation by longshore currents. The geomorphic feature is a large spit which divides Utah Valley to the south and Salt Lake Valley to the north. West of highway is the

		Jordan Narrows which is a gorge incised in Great Salt Lake deep-water sediments by the Jordan River.
1.5	21.5	I-15 mile post 288 - Historic sand and gravel pits. Most of the commercial gravel deposits in Utah Valley are along Lake Bonneville shorelines.
11.6	33.1	I-15 milepost 276 - Geneva Steel plant. Geneva is both a consumer and producer of indus- trial minerals. The steel plant uses large quantities of limestone for flux. Geneva produces nitrogen and about 5 short tons (st) of byproduct elemental sulfur per day from their coke batteries. The plant has been in production since WWII and produces steel slab, coils, and tubes. The company's web site is http://www.geneva.com.
18.1	51.2	I-15 milepost 256 - The highway rises to the Provo shoreline of Lake Bonneville.
7.6	58.8	I-15 milepost 249 - Keigley quarry. The Keigley quarry primarily supplies limestone and dolomite from Cambrian Formations for steel smelting, flux, coal mine rock dust, and aggregate. The quarry produced 126,400 st in 1996 (Utah Division of Oil, Gas and Mining files). In 1999, Geneva sold the quarry to Staker Paving and Construction Company (a division of Oldcastle, Inc.). Reserves in 1999 were estimated to be 133 million st (Tripp, B.T., this publication).
16.1	74.9	I-15 milepost 229 - Earth flow and quarry. The earth flow is the result of unusually heavy rains during the Pleistocene. Lake Bonneville sediments lap onto the toe of the earthflow; therefore, the flow occurred before or during the time that the lake existed. Between mileposts 229 and 228 recent movements of the Wasatch Fault offset alluvium deposits by as much as 80 feet (Chronic, 1990).
1.0	75.9	Exit I-15 at milepost 228, note sand and gravel pit, turn right and proceed into the town of Nephi.
12	77.1	View of T.J. Peck and Son's gypsum quarry to the south and the Wasatch Fault Zone.
1.4	78.5	Junction with State Route (SR) 132, proceed west.
Miles	Cum. miles	STOP 1: ASH GROVE CEMENT COMPANY, LEAMINGTON PLANT
22.1	100.6	The Learnington Plant was constructed in 1980 by Martin Marietta, and the first clinker was produced on November 15, 1981. In 1984, the plant was leased by Southwestern Portland Cement Company. Ash Grove Cement West, Inc. acquired the mine and plant in 1989. The plant was expanded in 1995-1996 to a capacity of 850,000 st per year. The product is sold throughout the Intermountain West. Limestone is mined from near-vertical beds of the Cambrian Dome Limestone. The Nielson quarry, developed in the friable Permian Diamond Creek Sandstone, is seven miles east of the plant and provides silica. Alumina comes from the County Canyon quarry, also east of the plant. The alumina quarry is in the Mississippian Long Trail Shale Member of the Great Blue Limestone.
3.0	103.6	Historic charcoal kilns (beehive coke oven). The Learnington fault separates the Gilson Mountains to the north, composed of Upper Paleozoic rocks, from the Canyon Range to the south. Present on the Canyon Range side is the Mutual Quartzite (purplish) overlain by the Tintic Quartzite (tan) and Pioche Shale (predominantly greenish gray).
6.5	110.1	Junction with U.S. Highway 6, proceed west. The Intermountain Power Project power plant is visible to the northwest. The plant uses 18,500 acre feet of water per year, and burns approximately 5 million st of coal per year. Almost all of the coal is produced from coal mines located along the Wasatch Plateau. The plant also consumes limestone from Utah quarries.
Miles	Cum. miles	STOP 2: BRUSH WELLMAN, INC., PLANT (2A) AND MINES (2B)
3.9	114.0	Brush Wellman mines beryllium ore (bertrandite) from open-pit mines located in the Topaz- Spor Mountain region of Juab County. The mines produce the only bertrandite ore in North America. Additionally, some beryl ore is imported and processed at the mill. At present production rates, Brush Wellman maintains 60 years of reserves. The bertrandite is hosted
in volcanic tuff and is overlain by rhyolite. The mill processes 450 st of ore each day. Brush Wellman recovers approximately 4 pounds of beryllium per ton of ore, or approximately 1,800 pounds per day. The process employs the Kiellgren-Sawyer hydro-metallurgical method. For a more complete description of the geology of Spor Mountain beryllium deposits see D. Lindsey paper this volume. For more information on Brush Wellman, visit the company's Internet web site (http://www.brushwellmanutah.com).

- 10.1 124.1 Enter the town of Delta. Remain overnight at the Best Western Motor Inn.
- 1.1125.2Start day two. Travel southwest from Best Western Motor Inn to junction with U.S. Highway 6/50, proceed west through Delta.
- 5.2 130.4 Junction with SR 257, proceed south.
- 4.3 134.7 Optional Stop, Fort Deseret. Constructed in 1865 (Delta Area Chamber of Commerce, no publication year), Fort Deseret was laid out in a 550 foot square. The fort was constructed in response to the Black Hawk War of 1865. Ninety-eight men constructed the fort in 18 days. The foundations for the walls were made with three-foot-wide lava rock footings. The walls of the fort are composed of adobe and were manufactured by running water into a trench, then adding clay and straw which was then mixed by the hooves of oxen and the feet of humans. The mud was stacked on the footings to form walls 10 feet high; four feet wide at the base and 1.5 feet wide at the top. Taller bastions were constructed in the northeast and southwest corners extending beyond the walls. Rough-hewn lumber was used to make the gun portals. Fort Deseret was acquired by the State and is managed by the Division of State Parks and Recreation.
- 1.5 136.2 Great Stone Face turnoff. The Great Stone Face was known as the "Guardian of Deseret" by the Mormon settlers. Some Mormons claim that the "face" resembles the Mormon prophet Joseph Smith. Conversely, many people simply see just a "face". Nonetheless, the Great Stone Face makes for an interesting diversion while driving in the desert.
- 6.9 143.1 Sunstone Knoll. Sunstone Knoll is formed of volcanic vents that erupted during the early Pleistocene. These eruptions left deposits of basaltic lava and volcanic breccia. Sunstone is the common name for transparent, yellowish labradorite (a plagioclase feldspar mineral) found in the volcanic rocks and on the flats surrounding the knoll (Wilkerson, 1994).
- Miles Cum Miles

STOP 3: GRAYMONT WESTERN U.S., INC. (CONTINENTAL LIME COMPANY), CRICKET MOUNTAIN PLANT

14.6 157.7 The first 500-ton-per-day kiln was brought on line in July, 1980. A second kiln was added in 1987, a third in 1992, and a fourth kiln was added in 1998. The Cricket Mountain plant is one of largest, most modern, and efficient lime plants in the Western U.S. Cricket Mountain has a total annual capacity of 900,000 st of quicklime. High-calcium limestone (Cambrian-age Dome Limestone) is mined from the Cricket Mountain Formation in the Poison Mountain and Flat Iron quarries. Graymont also produces dolomitic lime from the BB Dolomite quarry. The limestone and dolomite is crushed and screened at the quarry and hauled to the plant where it is processed in one of the four kilns. The plant manufactures a full line of bulk high-calcium quicklime, dolomitic quicklime, and crushed limestone products.

Exit Cricket Mountain plant and continue south on SR 257.

- 7.9 165.6 Historic lime kilns are located on canyon slope west (right) of highway. Kilns were constructed by blasting two vertical shafts into the bedrock. Limestone and coal and/or coke were charged into the top of the kilns. After calcining, quicklime was removed from adits at the bottom of the kilns. These kilns probably operated in the early through mid-1900s.
- 10.6 176.2 Black Rock. Railroad station and ponds. Established to service steam powered railroad engines.
- 11.5 187.7 Roosevelt Hot Springs. Site of the Blundell Geothermal plant. The plant is located on the flank of Mineral Mountains east of the highway. Roosevelt Hot Springs is the most explored geothermal system in Utah. The steam field is operated by Intermountain Geo-

thermal Company. The 26 megawatt plant is owned and operated by Pacificorp, parent of Utah Power Company. Electricity is produced from steam at the site and is fed into Pacificorp's power grid. Wells up to 7,500-feet deep have been measured at temperatures up to 2650 C. (Mabey and Budding, 1994). Opal (geyserite) deposits are found at the springs.

- 4.1 191.8 Cross railroad spur to Twin Mountain Rock Company ballast mine.
- 3.7 195.5 Intersection with road to ballast mine (turn west).
- 0.6 196.1 Intersection with gravel road (turn north).
- 2.0 198.1 Power line intersection, proceed north. Note old copper mine on saddle west of road.

Miles Cum Miles STOP 4: TWIN MOUNTAIN ROCK COMPANY, MILFORD QUARRY

2.0 200.1 Twin Mountain Rock Company is a subsidiary of Peter Keiwit and Sons, Omaha, Nebraska. The Milford quarry is located in the Rocky Range, approximately five miles northwest of the town of Milford in Beaver County. The quarry produces crushed rock primarily for railroad ballast. The geology of the region has been described in some detail in several publications, one of which is Whelan (1982). The project site is located on the flank of a large volcanic flow, which ranges in composition from andesite to quartz latite. A petrographic analysis of a sample taken from the quarry site described the sample as being mediumgrained grey/white, and containing massive crystalline quartz, hornblende, and orthoclase. Abundant, anhedral, chalky white plagioclase phenocrysts make up 30 to 50 percent of the rock.

Mining and processing at the Milford quarry is typical of most quarries and consists of four steps: drill and shoot, load and haul to the crusher, crush and screen, and load into a railcar. Major equipment at the quarry consists of Caterpillar Equipment Company (Cat) 988 and Cat 980 front end loaders, Cat 769 35-ton haul trucks, Telsmith 36 x 46 jaw crusher, Nordberg 1560 Omnicone crusher, 6 x 20 3-deck screen, 6 x 16 wet screen and numerous conveyors and stackers. The ballast size produced is 2-1/4 in. x 3/4 in. A five-mile-long rail spur connects the railroad mainline to the quarry (Craig Pfingston, Twin Mountain Rock Company, personal communication).

- 0.6 200.7 Junction with SR 257, continue north.
- 27.9 228.6 Turn right (east) to pumice pit; sign in southbound lane as you approach the turnoff is labeled "Kanosh 26". Travel east on gravel road.
- 5.4 234.0 Pumice deposits of Tertiary (Pliocene) age silicic volcanic rocks. Road follows the trace of the Lake Bonneville shoreline.

Miles Cum Miles STOP 5: UTAH PUMICE AND PERLITE, INC. AND RAY MINING LC, CUDAHY PERLITE MINE

0.5 234.5 The Cudahy perlite mine, located approximately 30 miles southwest of Fillmore in Millard County, was developed in the early 1900s, and has been worked intermittently up to the present. The mine, which has produced both perlite and pumice, is located at an elevation of about 4,800 feet. The mine area is in the foothills of the valley created by the Beaver River, an intermittent desert drainage. Although the property is situated in a dry desert area of the Great Basin, there are two springs (Black Spring and Coyote Spring) in the vicinity. The mine site is on 40 acres of patented land, and is surrounded by approximately 800 acres of patented land and unpatented mineral claims.

The overburden is thin, with the ore being exposed on the surface or within a foot or two of the surface. Perlite is a volcanic glass containing water of crystallization varying from two to six percent. The volume of entrapped water is of prime importance, since it is water which causes crude perlite to expand rapidly when the water flashes to steam at high temperatures. Geologically, perlite occurs as part of an acidic volcanic flow in rhyolite, dacite, andesite, or similar glassy material. The perlite at the Cudahy mine is light gray to tan in color, semi-pumaceous, and fine grained. The pumice found in conjunction with the per-

		lite is light gray and was expanded naturally at the time of formation. Pumice is intimate- ly mixed with the perlite and large tonnages of each material are available. A conservative reserve estimate of 53 million st has been made.
		In addition to the large quantities of perlite and pumice, a number of interesting historical and geological features occur on the property, such as: walls of brecciated stone indicating faulting, evidence of a hydrothermal vent, rhyolitic outcrops, old dugout cabin ruins, and exploratory diggings from early in the century. There are also some veins of obsidian, as well as black, snowflake, and mahogany obsidian on the surface.
0.6	235.1	Obsidian area. An obsidian-rich area is located within the main open-pit and is a good source for black, snow flake, and mahogany colored obsidian.
0.3	235.4	Black Spring. The spring has been developed for stock watering; note obsidian in soils surrounding the spring.
0.3	235.7	Fork in road, turn west-northwest.
4.3	240.0	Turn north to gravel road to Kanosh, turn west to SR 257.
1.6	241.6	Junction SR 257, turn right (north); return to Salt Lake City (approximately 190 miles).

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FIELD TRIP NUMBER 5

Southeastern Idaho and Southwestern Wyoming May 6 and 7, 1999

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Detailed Road Log		Description of Points
Miles	Cum. Miles	Exit WestCoast Salt Lake Hotel (formerly Cavanaughs Olympus Hotel), 161 West, 600 South, parking lot on Main Street (east side of hotel) and go one block north, turn left (west) on 500 South and go 3 blocks, turn right (north) at 300 West and continue north until road merges with Beck Street.
0	0	The field trip begins at 300 West and Beck Street in Salt Lake City. Settled in 1847, Salt Lake has become one of the largest cities in the Intermountain West. The Salt Lake Valley lies within the old depositional basin of Pleistocene Lake Bonneville. The Wasatch Mountains on the east and the Oquirrh Mountains on the west surround Salt Lake City.
		Proceed north on Beck Street and enter Interstate Highway 15 (I-15) north bound.
		Lake Bonneville – Remnant shorelines and terraces of ancient Lake Bonneville are evident to the east of I-15 in the foothills of the Wasatch Mountains. Alluvial fans extend out into the valley. Flat-topped deltas have become prime locations for residential areas, allowing homeowners great views of the valley and evening sunsets.

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3 Oil refineries – just north of Salt Lake City are a number of oil refineries owned by Chevron, Amoco, Phillips, and Flying J.

- 3 6 Bountiful Paleozoic sedimentary rocks make up the part of the Wasatch Range just north of Salt Lake City and south of Bountiful. Streams flowed through this area depositing their sediments and merging their deltas that were modified by longshore currents and wave action in Lake Bonneville. These sand and gravel deposits are rapidly being exploited for use in highway, residential, and commercial construction projects.
- 1016Farmington Precambrian rocks make up this part of the Wasatch Range. Historically, this
area has been prone to massive mudslides that extended out into the Great Salt Lake. The
easternmost tip of the Great Salt Lake reaches almost to the mountains indicating minimal
erosion of harder Precambrian rocks.
- 20 36 Ogden Just south of Ogden, the Weber River flows into the Great Salt Lake. Originating in the Uinta Mountains farther east, the Weber River carries its sediments and deposits them in a large delta, providing ideal locations for gravel quarries. Mountains east of Ogden developed during Miocene as a result of Basin and Range faulting. Recent fault scarps form triangular faces just above the Lake Bonneville shoreline. The valley to the west is just above lake level. Marsh areas form where the Bear River delta empties into the Great Salt Lake. The Bear River Bay and its marshes are the site of the Bear River National Wildlife Refuge. Much of this area was flooded during the very high Great Salt Lake water levels in the mid-1980s.
- 17 53 Willard/Brigham City The Willard thrust fault cuts the slope of Willard Peak just north of Ogden. This is a major fault plane within the Sevier thrust belt, a major east-west compressional zone, formed in Cretaceous time. The fault plane tilts to the east. Along the foothills, sand and gravel quarries are located in the ancient beaches and terraces of Lake Bonneville.

Wellsville Mountain – Wellsville Mountain is an upward faulted ridge of Precambrian metamorphic rocks east of Honeyville. These rocks are covered with layers of Paleozoic sedimentary rocks. The Precambrian rocks are about 1.2-billion-years old and appear at the bottom of the slope. Higher up the slope is the Geertzen Canyon Quartzite. The Geertzen is a well-cemented Cambrian rock formed from beach sand deposits. Above the Geertzen are units of Cambrian shales, shaley limestones, and limestones/dolomites.

Bear River – The Bear River exits Bear Lake in extreme southeastern Idaho heading north, then curving around to the southwest to enter the Malad Valley just southeast of Plymouth, Utah. The Bear River parallels the Malad River through the flat valley floor finally dumping into Bear River Bay, an arm of the Great Salt Lake. The flat valley floor is made up of Lake Bonneville sediments.

Malad River – I-15 follows the Malad River across sediments deposited in Lake Bonneville. The hills to the west consist of Pennsylvanian and Permian limestone and quartzite. These hills are part of the Sevier thrust belt which has displaced strata eastward by more than 40 miles. Further to the west is the Raft River Range, a metamorphic-cored complex. These mountains are of Precambrian and Paleozoic metamorphic rocks. The range rose in Miocene time.

The mountains to the east are the result of the Wasatch fault, which parallels I-15 from southern Idaho to southern Utah, a distance of more than 200 miles. The Wasatch fault is the easternmost edge of the large Basin and Range extensional fault system. Frequent earthquakes show that movement along the fault continues today.

Tremonton to Pocatello, ID – The route from the Utah State line north to Pocatello follows broad structural valleys down dropped by Basin and Range faults. Recent sediments and basalt cover the older bedrock. Mountains to the east and west are generally of Paleozoic sedimentary formations raised by Basin and Range faults.

From the Utah line north to Malad Summit, the route crosses over lake bottom sediments deposited when Lake Bonneville existed. Red Rock Pass is about nine miles east of Malad Summit. This is where Lake Bonneville drained catastrophically into the Columbia River

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		drainage approximately 14,500 years ago, discharging 4,750 km3 (1,100 mi3) of water (O'Connor, 1993) in a relatively short period of time. Water flowed at approximately 15 million cubic feet per second, scouring the valley north of Malad Summit. This scouring effect is very evident between Downey and McCammon because the basalt appears to have been scrubbed. In this same area, large sand and gravel mounds are evident like giant waves ten feet high and tens of feet across.
		Precambrian metamorphic rocks are seen to the extreme north of our route near Pocatello. The absence of Mesozoic strata is attributed to their movement eastward by the Overthrust belt. At the junction of U.S. Highway 30 and I-15, we encounter the Portneuf lava flow. One can see the distinct vertical columns within the flow. The Portneuf lava flow is dated at about 600,000 years. This flow extends about 30 miles from Pocatello to Lava Hot Springs.
36	108	Exit I-15 at Malad City (exit 13); the Hess Pumice plant is located on the south edge of town. The pumice mine is located approximately 25 miles northwest of the plant in Reed Canyon.
Miles	Cum Miles	STOP 1: HESS PUMICE, MALAD, IDAHO
		Hess Pumice has been in continual operation since 1958 and is a world class producer of a variety of processed pumice products due to a high purity product and precision-controlled grinding. The present plant was constructed in 1986, produces over 30 standard grades of pumice, and can custom grind special orders. Finely ground pumice is widely used for polishing TV screens, but also has many other applications such as in hand soaps and exfoliates, dental supplies and tooth paste, and plastic filler. Hess Pumice products are exported world wide.
		Pumice is derived from Tertiary volcanics and is surface mined with a combination of bull- dozers with rippers, and scrappers. The present pit occupies approximately 10 acres and produces on average 110,000 st of raw material annually. The ratio of overburden to ore is 1:4. The mine plant has a capacity of 250,000 st per year and the Malad finishing plant has a capacity of 50,000 st per year.
		Retrace route to I-15 and continue heading north.
45	153	Exit 1-15 at exit 57 near the town of Inkom. The mine and plant are on the west side of the Portneuf River.
Miles	Cum Miles	STOP 2: ASHGROVE CEMENT COMPANY, INKOM PLANT, INKOM, IDAHO
		The quarry produces about 450,000 st of limestone annually from the Early to Middle Cambrian Gibson Jack Formation. Shale is extracted from the Permian-Triassic Elkhorn Ridge Formation. The Inkom cement plant has a capacity of 350,000 st annually and is currently producing about 280,000 st of cement per year.
		Retrace route back to I-15 and head south approximately 12 miles to the Lava Hot Springs (exit 47). Enter U.S. Highway 30 and head east toward Lava Hot Springs and then on to Soda Springs.
		I-15 – U.S. Highway 30 – to the Wyoming Line – The road from I-15 to the bottom of Fish Creek Pass, just east of Lava Hot Springs, passes through Paleozoic sedimentary rock formations deposited 600 million to 200 million years ago.
21	174	Lava Hot Springs – Several hot springs emerge from the base of a normal fault near the town of Lava Hot Springs. A year-round resort town has provided access to the hot springs since the early 1900s.
		Lava Hot Springs to Soda Springs – The highway heads east from Lava Hot Springs across Fish Creek summit to Soda Springs. The road crosses the Gem Valley, consisting of a Basin-and-Range-fault-bounded graben. Basalt lava flows make up much of the bedrock. Weathering of these lava flows provided fertile soil for barley, wheat, and Idaho's famous potatoes.

The hills surrounding the Gem Valley are made up of limestone, dolomite, and quartzite. These deposits are Cambrian and Ordovician aged rocks, 500 million to 600 million years old.

23 197 Soda Springs was a famous landmark on the historic Oregon Trail. The emigrants found Soda Springs an enjoyable stop with its many carbonated springs. Covered wagon ruts can still be seen at the nearby Oregon Trail Golf Course. Many of the springs have formed extensive mounds of travertine. In an effort to tap subsurface geothermal waters, a well was drilled in Soda Springs. While drilling, carbon dioxide-rich water was encountered under significant pressure. The well was capped and a valve and timer installed. Every half hour the geyser erupts. The geyser is every bit as impressive as Old Faithful Geyser in Yellowstone National Park. Stay overnight at Soda Springs.

The next morning continue on U.S. Highway 30 through Soda Springs until the junction with State Route (SR) 34, turn left (north) and proceed approximately 11 miles. Turn right (east) at China Hat and proceed approximately five miles. Turn left (north) at the Monsanto private haulroad and follow the road about nine miles to the Enoch Valley mine offices.

Miles Cum Miles STOP 3: MONSANTO, INC., SOLUTIA PHOSPHATE OPERATION

Since the early 1900s, some of the highest quality phosphate in the U.S. has been mined in the Soda Springs area from the Permian Phosphoria Formation. The Phosphoria Formation was deposited approximately 200 million years ago in an area running northwest to southeast, from southwestern Montana through Soda Springs to western Wyoming and northeastern Utah.

Editors note: The following report summarizes the presentation made at the Enoch Valley mine.

PHOSPHATE ORE PRODUCTION AT MONSANTO'S ENOCH VALLEY MINE, SODA SPRINGS, IDAHO

INTRODUCTION

In September 1997, Monsanto spun off their chemical businesses and formed a new company called Solutia. Unique to the creation of Solutia, was the Soda Springs plant. With both Monsanto and Solutia needing phosphorus for their downstream operations, the Soda Springs plant was owned by Solutia and Monsanto under a joint-venture agreement. In mid-2000, Monsanto merged with Pharmacia-Upjohn to form a new company called Pharmacia. At the same time, Solutia merged their phosphorus and derivatives businesses with FMC and formed a new company called Astaris.

In October 2000, Pharmacia executed a partial Initial Public Offering and re-created the company called Monsanto, consolidating all of Pharmacia's agricultural and biotechnology business under the Monsanto umbrella. At the same time, Monsanto elected to exercise its option under the joint-venture agreement with Solutia and bought back the Soda Springs plant. As a result, the Soda Springs elemental phosphorus plant and mining operations are now fully owned and operated by Monsanto.

The Soda Springs operation consists of an elemental phosphorus manufacturing plant located 2.5 miles north of the southeastern Idaho city of Soda Springs. Monsanto has been associated with Soda Springs since 1951, and has remained dedicated to the people, the community, and the environment. The plant encompasses approximately 530 acres, and is about 6,000 feet above sea level in a mountain valley surrounded by high ridges. The general topography of the valley floor is level to gently sloping, occasionally broken by cinder cones and lava flows.

The Enoch Valley mine, Monsanto's third and current mine site, is located approximately 19 miles northeast of the plant. The mine began operating in 1989 and will continue to about 2001. The mine property is situated along a long, low ridge that runs northwest to

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southeast. The Enoch Valley mine produces approximately 1 to 1.5 million short tons (st) of ore and removes from 3.5 to 5 million bank cubic yards of waste each year. The mine operates on two 10-hour shifts, four days a week, for 10 to 12 months of the year with a combined workforce of 75 to 90 people. The 1,475-acre site includes 55 acres owned by Solutia at the north boundary, 838 acres owned by the Idaho Department of Lands, and 582 acres of U.S. Forest Service (USFS) land to the south. The areas immediately northwest of the mine are dryland farms. Other adjacent areas are mostly public lands which are used for grazing and outdoor recreation. Grays Lake National Wildlife Refuge is located about 12 miles north of the mine site and contributes significantly to the wildlife diversity of the area, particularly its bird and aquatic plant species. The office and shop facilities for Solutia and the mining contractor, Dravo-Soda Springs, are located on the west side of the property.

Mining and reclamation are concurrent, with active mining taking place in two pits, one near the north end of the property on state land, and the other near the southern end of the property on state and USFS land. The two mine pits are about one-half mile apart and are converging. The final pit will be near the middle of the leases by 2001.

Elevations within the mine property range from about 6,600 feet to over 7,100 feet. The diverse topography includes grassy meadows, steep drainages, and exposed rock outcrops along the ridges. Vegetation consist of bitterbrush and sagebrush communities on south and west facing slopes, while the north and east facing slopes, and drainages, consist of aspen and douglas fir communities.

GEOLOGY

Phosphorite Deposition

During the late Permian (245-285 Ma), southeast Idaho lay on the outer shelf edge and the open marine basin of the Phosphoria sea. A shallower, embayment extended eastward into western Wyoming. Upwelling currents from the deep basin to the west supplied nutrients for plant and animal growth, and organic matter that resulted in the deposition of dark mudstone, phosphorites, dolomites, and limestones that make up the Meade Peak Member of the Phosphoria Formation. The combination of wave action, high water temperatures, topography, and chemical deposition of phosphate-rich sediments formed the extensive deposit that is referred to as the western phosphate field. Of economic interest is the phosphorite; which occurs as: fine grained, pelletal phosphorite; phosphatic mudstone; dense, structureless phosphorite; fine-grained pelletal phosphorite; oolitic phosphorite; pisolitic phosphorite; nodular phosphorite; and bioclastic phosphorite (McKelvey and others, 1967).

Folding and Faulting

The two events that most affected the structural attributes of southeast Idaho are the Cretaceous-early Tertiary (63-135 Ma) thrusting and folding of the Laramide orogeny, and late Cenozoic (25-63 Ma) Basin and Range normal faulting.

Weathering - Outcrop Appearance and Enrichment

Post-deformational weathering and the erosion of folds on the flanks of ridges exposed the Phosphoria Formation. Erosion had a two-fold benefit in the economic development of the deposits. First, it exposed the limbs of folds on the flanks of ridges so that the deposit was relatively easy to locate and develop. The Meade Peak is overlain by chert (Rex Chert Member), and underlain by dolomite (Grandeur Tongue of the Park City Formation), which are both resistant to erosion. The intervening Meade Peak forms a characteristic "swale" between the two resistant rock types. In addition to this difference in relief between the strata, the Meade Peak also develops a rich soil that is conducive to thick vegetation, further highlighting the Meade Peak outcrop. The "swale" is readily identifiable when examining aerial photos, as well as on the ground when conducting field studies. Secondly, weathering leaches magnesium, carbon, and carbonate content from the formation leaving a phosphate-enriched deposit. This weathering along the outcrop can occur to a depth of several hundred feet.

Phosphate Resources

The western phosphate field stretches from southwestern Montana to northeastern Utah and contains billions of tons of phosphate rock. The richest deposits, containing 40 percent of the nation's phosphate reserves, are found within a hundred-mile radius of the highlands of southeastern Idaho. It is within this area that the current producers of elemental phosphorus and phosphate fertilizers have concentrated their mining activity.

EXPLORATION METHODS

Reverse Circulation Drilling

Reverse circulation drilling is preferred over regular rotary drilling to explore for, and develop, phosphate deposits. Because of the dual-walled construction of the reverse circulation pipe, samples have less chance of contamination from rock fragments higher in the drill hole. Reverse circulation drilling is a cost effective method of conducting exploration, where the emphasis is on determining pit boundaries and the tonnage and grade of the deposit.

Wire Line Core Drilling

Wire-line core drilling is another method used for exploration of phosphate deposits. Although core drilling is more expensive than reverse circulation drilling, it provides more accurate sampling and details of the deposit that can not be collected by other drilling methods. Core drilling is also used to drill into the underlying Grandeur Tongue Member of the Phosphoria Formation and the Wells Formation to collect samples for slope stability analysis. Core drilling is the only means of collecting a sample that can be used for compressive strength, Brazilian Disk Tension, and direct shear tests. Solutia has had a core-drilling program for more than 30 years.

MINE DESIGN AND DEVELOPMENT

With the information obtained from exploration drilling, mining engineers and geologists are able to develop a mine plan. The depth of an average pit ranges from 350 to 450 feet; the average width is about 1,000 feet. The ore zone, from bottom to top, includes the lower ore seam that is approximately 40 to 50 feet thick, a middle waste zone containing shale that is about 75 to 90 feet thick, and the upper ore seam that is approximately 15 to 20 feet thick.

Prior to mining, sediment retention basins are constructed to trap any sediments that might be present in runoff water. These retention basins are ultimately converted to wetlands as part of the reclamation process.

Before mining begins on a new site, any marketable timber is harvested. Non-marketable timber is pushed into slash piles or is placed in reclamation areas to be used as habitat for small mammals. Topsoil is then removed and stockpiled for reclamation. As soon as areas are ready for reclamation, topsoil is replaced on these new areas prior to planting.

Harder rock layers such as limestone, shale, and chert are blasted and removed as waste. The phosphate ore is usually soft enough that it does not need to be blasted. Shovels and trucks are used to extract ore and waste rock. At the Enoch Valley mine, the contractor uses three Hitachi shovels and nine Caterpillar 777B, 85-ton capacity trucks. Two of the three shovels have traditional front shovel attachments, while the third shovel has a backhoe attachment for digging the ore out of the last cut in the pit, or for excavating rock from restricted mining areas. During winter, mining efforts concentrate on waste removal. Extraction of ore occurs in winter as well, but not to the same extent as in summer months.

As mining progresses, waste rock and ore are removed in 20-foot lifts. Typically, 80-foot benches are left in the overlying limestone to maintain slope stability; haulage ramps are mainly built in the chert zone. The shale between the two ore seams is evaluated for its color and texture to determine if it can be used as a planting medium. Softer, brown shales in the upper leached zones can be used as a planting medium if soil is in low supply, where-

as the harder, black shales in the lower, unaltered (or unleached) zones do not make a good planting medium.

Quality Control

To assure quality control at the mine, trenches are dug in the mining zone and sampled at each break in lithology within the ore seams. The samples are analyzed at the company lab, and results are used for grade control; then added to the chemical database that is used to track and predict grades in the mine. Trenches are dug on 300-foot intervals along the strike of the deposit and are offset 100 feet for each 20-foot lift.

A slope-board attached to a Caterpillar D10 bulldozer is another useful tool that is used to assure quality control at the mine. The bulldozer operator can peel away any remaining ore from a waste seam, or peel mud seams as thin as 6-8 inches from the adjacent ore with this device.

Ore Transport

Ore is conveyed onto screens at the tipple near the mine and crushed to a minus 2-inch diameter material. The larger, 2- to 6-inch diameter material is recrushed, and the plus 6-inch diameter material is stored in a separate pile at the mine. Ore is stockpiled at the tipple load-out facility in two separate piles; a blend 1 pile for higher-grade ore, and a blend 2 pile for lower-grade ore. Ore from each pile is hauled separately to the plant site, 19 miles, and blended at the plant in appropriate ratios for feed stock. Triple-trailer trucks (ore trains) transport approximately 13,000 to 15,000 st of phosphate ore to the plant each day. Each hopper, or trailer, hauls approximately 70 st of material; each truck has a 210 st payload and a gross vehicle weight of approximately 315 st.

Reclamation

Concurrent land reclamation is an integral part of the mining process at the Enoch Valley mine. During the initial excavation of the first pit, waste rock is placed outside the pit boundary in external overburden dumps. Typical pit lengths are between one quarter to one half mile, so the overburden dumps are minimal. After the initial pit is mined out and a new section of pit is started, the backfilling of the initial pit usually takes place. Monsanto takes pride in keeping reclamation as close to the active mining as possible. Most companies build external dumps by end-dumping from a final maximum elevation; Monsanto and Dravo-Soda Springs construct external dumps from the toe upward in lifts. This method allows minimal acreage to be disturbed throughout the process.

In the past, when new areas of the pit were being opened, much of the native vegetation was cleared from the site by bulldozing. Now, during reclamation at the Enoch Valley mine, large clumps of native trees and shrubs are carefully salvaged. This is referred to as bucket-loader transplants. These clumps are then placed into the newly graded land being reclaimed. The transplants help to break-up the landscape of the typical low-growing grasses and forbs, and provides an island of native vegetation. The cooperative relationship between Monsanto and its contract miner, Dravo-Soda Springs, has allowed this work to become second nature to the operators preparing new areas for mining.

In addition to bucket-loader transplanting, lodge pole pine and quaking aspen seedlings are planted each fall on north- and east-facing slopes to re-establish native vegetation. Monsanto collects aspen seeds from trees on site each spring, and sends them to a native plant nursery, Bitterroot Restoration, in Hamilton, Montana for propagation. Seedlings are returned to the mine each fall for planting. This method ensures the genetic make-up of a known seed stock, and trees in the area. It is also critical for plant species to be planted at or near the same elevation from which they come to ensure survival.

Reclamation planning incorporates multiple uses for post mined land. These include livestock grazing, wildlife habitat, and recreation. Monsanto has taken great efforts in creating and enhancing wetlands where few previously existed. Many features were initially built to serve as sediment retention basins. By aggressively controlling upstream erosion, keeping sedimentation to a minimum, and planting native aquatic vegetation, areas that were once sediment retention basins are transformed into healthy and productive wetlands. These wetlands benefit large game and other mammals, and also serve as important rest stops and nesting areas for migrating waterfowl and other migratory species including Sandhill cranes. Each year since 1994, there has been at least one pair of cranes successfully nesting in one of the wetlands, fledging one to two chicks each summer. In a cooperative effort with the U.S. Fish and Wildlife Service, Monsanto and Dravo-Soda Springs are allowed to harvest several 5-gallon buckets of aquatic plant species from nearby Grays Lake National Wildlife Refuge each year to be used in wetland construction.

An additional habitat improvement project, done in partnership with the Idaho Falconers Association, was the construction of raptor nesting platforms on the limestone highwalls. Two platforms were installed at the Henry mine. The construction of brush and rock piles on newly reclaimed areas provides habitat for small mammals and birds. Monsanto's most recent habitat project was the construction of an artificial bat cave. This first-of-its-kind project was a cooperative effort among Monsanto, the Caribou National Forest, and Bat Conservation International. The project was initiated to provide habitat in an area that historically had very little or no habitat for bats.

COMMUNITY EDUCATION AND AWARDS FOR EXCELLENCE

Each year, the company provides tours for as many as 500 people in an effort to educate the public. Young people, in particular, are given the opportunity to learn and understand the importance of mining, and to see first hand how mining and the environment coexist. Monsanto, other phosphate producers, and land management agencies, have worked together to develop a series of video tapes and booklets that have been disseminated in schools and libraries throughout Idaho and the northwest.

The goal of Monsanto is to remain the leader in elemental phosphorus production and to be a responsible steward of the land. The company is fortunate because the agencies it works with recognize its efforts. In 1992, Monsanto was awarded the Partners in the Public Spirit award from the U.S. Bureau of Land Management for its operations at the Enoch Valley mine. This award was one of six presented nationwide. In the summer of 1994, Monsanto received two awards for accomplishments in 1993. One award was for Excellence in Annual Operations, and the other was awarded to the Reclamation Specialist for Outstanding Company Environmental Coordinator. Both were multi-agency Outstanding Achievement awards from the Idaho Mined Lands Committee representing the U.S. Forest Service, the Idaho Department of Lands, the U.S. Bureau of Land Management, the Idaho Fish & Game Department, the Department of Health and Welfare, and the Idaho Department of Water Resources. Since 1993, Monsanto has been repeatedly nominated for either Excellence in Reclamation or Excellence in Annual Operations awards. The efforts of the Soda Springs operation contributed significantly to Monsanto being awarded the Presidential Award for Sustainable Development by Vice President Al Gore on March 7, 1996. At Monsanto, our philosophy has always been, and will remain, "to return the land to a better condition than we found it."

Retrace route back to Soda Springs. From town, take the Government Dam Road heading north for approximately 3.5 miles. Turn left (west) at the entrance to the quarry and follow the road about 0.5 miles to the quarry office and shop.

Miles	Cum	Miles

STOP 4: MONSANTO INC., QUARTZITE QUARRY

Monsanto's Quartzite quarry is located about 3 miles northeast of Soda Springs (2 miles west of the Monsanto Soda Springs Plant). The quarry has been in operation since the mid-1950s and is located on privately owned lands. Over the next few years the mine will extend onto state leased lands to the south. The deposit is in the Middle Ordovician (Champlainian Series) Upper Eureka Member of the Swans Peak Formation. The mine produces more than 400,000 st of high quality quartzite (+98 percent SiO2) per year. Approximately 275,000 st of -1 in. x + 1/4 in. sized rock is shipped and stockpiled at the Monsanto Soda Springs Plant and then eventually used a metallurgical flux in the manufacture of elemental phosphorus. The remaining undersized material (-1/4 in.) is either sold or backfilled in the mined-out portions of the pit.

20 242 Retrace route back to Soda Springs. At the junction with U.S. Highway 30 turn left (east) and continue to Montpelier.

31	273	Soda Springs to Montpelier – The highway heads south/southeast from Soda Springs to Montpelier generally following the Bear River. Most of the exposed rock outcrops are basalt lava flows. East of Soda Springs, the road crosses a field of rhyolite less than one million years old, and Recent sedimentary alluvial fan deposits.
		The mountains between Soda Springs and Montpelier are part of the Overthrust belt. The Overthrust belt is a fold or thrust belt, or a series of over thrust sheets of rock that overlap one another. The Overthrust belt was formed 55 to 150 million years ago as a result of compression and contraction of the earth's crust. The belt dips to the west and hosts extensive oil and gas resources. Most of the rock formations present are Paleozoic and early Mesozoic age, deposited between 280 and 120 million years ago. Older limestone formations are also locally present. Some Paleozoic sedimentary formations, which are 450 to 600 million years old, have been thrust over younger formations.
		The area between Montpelier and the Wyoming border crosses the Overthrust belt where Mesozoic sedimentary formations have been tightly folded as they have moved east along large thrust faults.
		At Montpelier, turn right (west) onto U.S. Highway 89 and continue to Garden City, Utah. At Garden City, take SR 30 which continues along the west and south side of Bear Lake and then heads east to the Wyoming border. As you cross the border into Wyoming, the road becomes Wyoming SR 89. Follow SR 89 to Sage. At junction with U.S. Highway 30 (Sage Junction) turn right (west) and continue approximately 24 miles to the entrance of Fossil Butte National Monument.
26	299	Bear Lake – The Bear Lake Valley lies at about 6,000 foot elevation. The valley is a graben bounded by normal faults on the east and west. The valley has been slowly dropping for over 10 million years, with a total displacement of about 10,000 feet. Rocks of Early Paleozoic and Late Proterozoic age crop out in the valley.
		From Bear Lake we travel east to Sage Junction and then to Fossil Butte National Monu- ment. The formations encountered in this part of Wyoming consist of varying colors of
		sandstone, siltstone, and claystone.
Miles	Cum Miles	sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT
Miles 59	Cum Miles 358	sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT Just west of Kemmerer is Fossil Basin where Fossil Butte National Monument is located. The Green River Formation outcrops in this area and is the source of world-famous fos- silized fish. Approximately 50 million years ago, a large, warm, shallow lake was home to many animals including herring, perch, bass, gar, paddle fish, lizards, insects, birds, and turtles. The marl deposited in the open lacustrine facies preserved large numbers of fossil remains of these animals.
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Miles 59 6 50	Cum Miles 358 364 414	 sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT Just west of Kemmerer is Fossil Basin where Fossil Butte National Monument is located. The Green River Formation outcrops in this area and is the source of world-famous fossilized fish. Approximately 50 million years ago, a large, warm, shallow lake was home to many animals including herring, perch, bass, gar, paddle fish, lizards, insects, birds, and turtles. The marl deposited in the open lacustrine facies preserved large numbers of fossil remains of these animals. Continue east to Kemmerer. At junction U.S. Highway 189, turn right (south) and proceed to Evanston. Kemmerer to Evanston – This stretch of highway winds through Cretaceous formations of tufaceous sandstone, siltstone, shales, and marlstone. Kemmerer is home of the original J.C. Penney Company store which was built in 1902.
Miles 59 6 50	Cum Miles 358 364 414	 sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT Just west of Kemmerer is Fossil Basin where Fossil Butte National Monument is located. The Green River Formation outcrops in this area and is the source of world-famous fossilized fish. Approximately 50 million years ago, a large, warm, shallow lake was home to many animals including herring, perch, bass, gar, paddle fish, lizards, insects, birds, and turtles. The marl deposited in the open lacustrine facies preserved large numbers of fossil remains of these animals. Continue east to Kemmerer. At junction U.S. Highway 189, turn right (south) and proceed to Evanston. Kemmerer to Evanston – This stretch of highway winds through Cretaceous formations of tufaceous sandstone, siltstone, shales, and marlstone. Kemmerer is home of the original J.C. Penney Company store which was built in 1902. Evanston to Salt Lake City – I-80 from Evanston to Salt Lake City crosses through Cretaceous deposits, and Mesozoic rocks near the Salt Lake Valley. At higher elevations – Triassic, Permian, and Pennsylvanian rocks are visible.
Miles 59 6 50	Cum Miles 358 364 414	 sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT Just west of Kemmerer is Fossil Basin where Fossil Butte National Monument is located. The Green River Formation outcrops in this area and is the source of world-famous fossilized fish. Approximately 50 million years ago, a large, warm, shallow lake was home to many animals including herring, perch, bass, gar, paddle fish, lizards, insects, birds, and turtles. The marl deposited in the open lacustrine facies preserved large numbers of fossil remains of these animals. Continue east to Kemmerer. At junction U.S. Highway 189, turn right (south) and proceed to Evanston. Kemmerer to Evanston – This stretch of highway winds through Cretaceous formations of tufaceous sandstone, siltstone, shales, and marlstone. Kemmerer is home of the original J.C. Penney Company store which was built in 1902. Evanston to Salt Lake City – I-80 from Evanston to Salt Lake City crosses through Cretaceous deposits, and Mesozoic rocks near the Salt Lake Valley. At higher elevations – Triassic, Permian, and Pennsylvanian rocks are visible. At Evanston, enter I-15 heading west and continue approximately 31 miles to junction I-84. Enter I-84 and proceed west approximately 8 miles to the Devil's Slide view area.
 Miles 59 6 50 50 Miles 	Cum Miles 358 364 414 Cum Miles	 sandstone, siltstone, and claystone. STOP 5: FOSSIL BUTTE NATIONAL MONUMENT Just west of Kemmerer is Fossil Basin where Fossil Butte National Monument is located. The Green River Formation outcrops in this area and is the source of world-famous fossilized fish. Approximately 50 million years ago, a large, warm, shallow lake was home to many animals including herring, perch, bass, gar, paddle fish, lizards, insects, birds, and turtles. The marl deposited in the open lacustrine facies preserved large numbers of fossil remains of these animals. Continue east to Kemmerer. At junction U.S. Highway 189, turn right (south) and proceed to Evanston. Kemmerer to Evanston – This stretch of highway winds through Cretaceous formations of tufaceous sandstone, siltstone, shales, and marlstone. Kemmerer is home of the original J.C. Penney Company store which was built in 1902. Evanston to Salt Lake City – I-80 from Evanston to Salt Lake City crosses through Cretaceous sedimentary rocks, Paleozoic rocks overlying Jurassic and Cretaceous deposits, and Mesozoic rocks are the Salt Lake Valley. At higher elevations – Triassic, Permian, and Pennsylvanian rocks are visible. At Evanston, enter I-15 heading west and continue approximately 31 miles to junction I-84. Enter I-84 and proceed west approximately 8 miles to the Devil's Slide view area.

stone, and appears much like a vertical chute on the flank of the mountain. The Twin Creek is not fully exposed at this site, but is over 3,140 feet thick (Stokes, 1959). On the opposite side of the river, the Twin Creek has been mined extensively for the manufacture of cement by Holnam, Inc.

54 57 Re-enter I-84 and retrace route to I-80. Enter I-80 heading west and continue to Salt Lake City. Exit I-80 at junction I-15 and proceed north to City Center exit (600 South). Proceed on 600 South approximately four blocks to hotel.

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