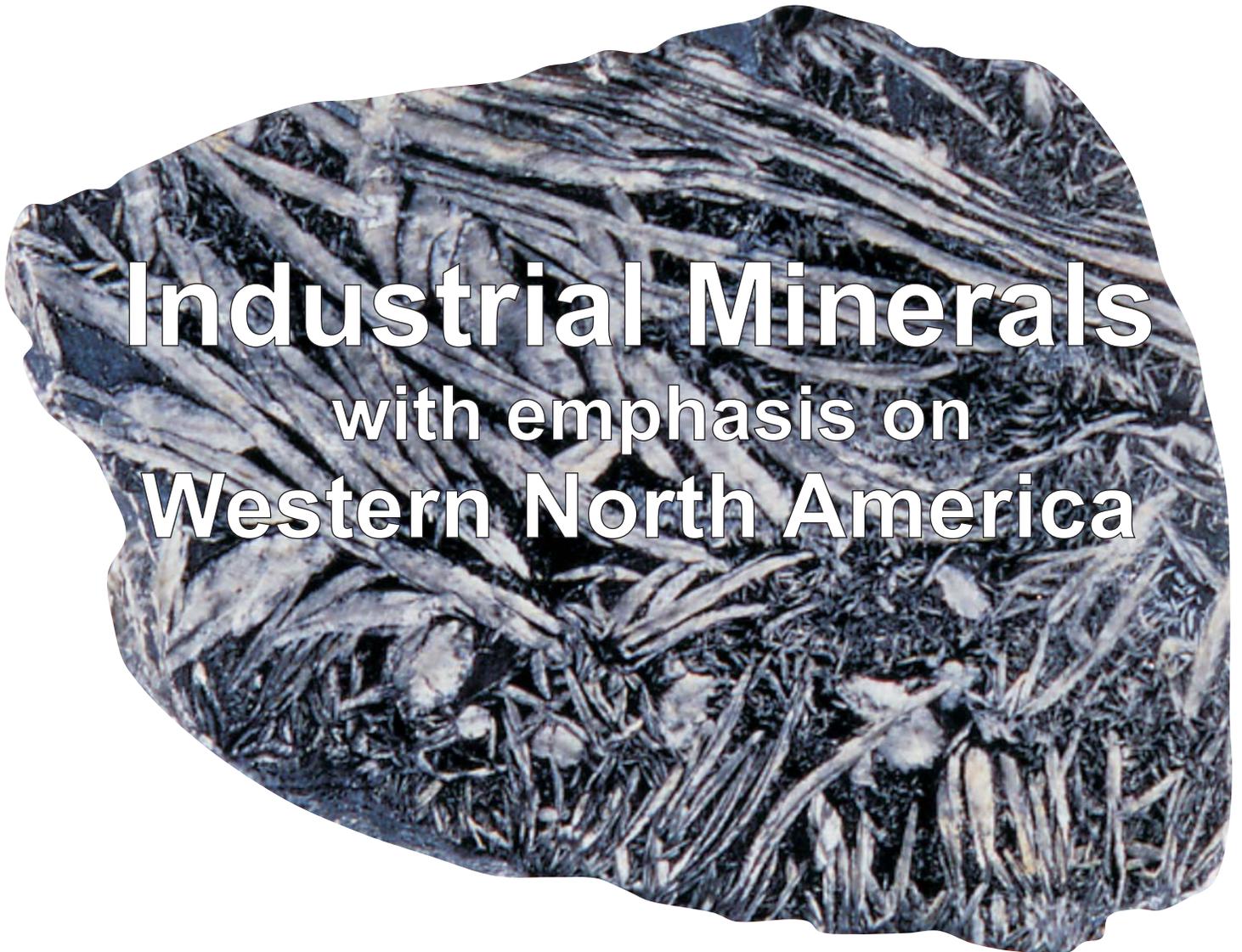




37th FORUM
on the **GEOLOGY of**
INDUSTRIAL MINERALS

MAY 23-25, 2001 • VICTORIA, BC, CANADA



Industrial Minerals
with emphasis on
Western North America



**BRITISH
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Ministry of Energy and Mines
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Cover photo: Curved, grey magnesite crystals in a black dolomite matrix. Mount Brussilof magnesite mine, British Columbia, Canada

Preface

The 37th Forum on the Geology of Industrial Minerals was held at the Victoria Conference Centre from May 23 -25, 2001.

The Forum on the Geology of Industrial Minerals has a long tradition. It was initiated by the late Professor Robert Bates of the Ohio State University and has been held on an annual basis for the last 37 years. Thirty-one meetings have been held in the USA, one in Bath, England, and five in Canada including the 37th Forum, here in Victoria.

The 37th Forum in Victoria was organized by the British Columbia Ministry of Energy and Mines (Geological Survey Branch), Canadian Institute of Mining and Metallurgy, and University of Victoria's Centre for Earth and Ocean Research. The Forum was co-sponsored by: Baymag Mines Co. Ltd, Lafarge Canada Inc., Imasco, Industrial Minerals Journal, Canmark International Resources Inc., Yorkton Securities and BHP. Westroc, Cominco, DeBeers Canada, and Diavik Mines helped keep the cost of field trips affordable.

The technical sessions focused on aggregates and transportation; value-added industrial minerals; diamonds in Canada; dimension stone; magnesite, magnesia, and magnesium metal; and exploration for and evaluation of industrial mineral deposits. There were 48 oral presentations and over 40 poster displays.

As part of the 37th Forum, eight field trips were planned. Six of these took place in southwestern BC, one trip transected the Cordillera from Calgary to Victoria, and the other visited the new diamond mines in the Northwest Territories. There were at least 50 companies that agreed to show us their operations and to share their knowledge. The field trip leaders spent a lot of time and effort to make it possible for participants to appreciate the industrial minerals wealth and potential of British Columbia. These leaders are Stan Krukowski of Graymont, Don Gunning and Dan Hora - consultants, Roger Paulen, Amy Boulton and Melissa Rotella - students of the School of Earth and Ocean Sciences, UVic, and Victor Levson of the British Columbia Ministry of Energy and Mines.

Susan Dunlop and Kathy Watson of UVic's Centre for Earth and Ocean Research efficiently handled the administrative part of the conference with assistance from UVic SEOS student Michelle Landry. Janet Holland of the BC Geological Survey formatted the extended abstract book and expertly handled the accompanying guest program. On site co-ordination of the poster session was handled by Mike Fournier of the BC Geological Survey.

Support of the Forum through corporate and commercial displays by Homegold Resources, Crystal Graphite Corporation, Electra Gold Ltd., Bondar Clegg, XRAL Laboratories, Ontario Ministry of Northern Development and Mines, Driftwood Creek Magnesite, and Blubber Bay Quarry (Ash Grove Cement Co.) is also appreciated.

*George Simandl
May 10, 2001*

FIELD TRIP SPONSORS

The following companies have helped offset the cost of the field trips:

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3. Electra Gold Ltd., Vancouver, BC
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5. British Columbia Ministry of Energy and Mines
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7. BC & Yukon Chamber of Mines/Mining Association of BC
8. Centre for Earth and Ocean Research, University of Victoria
9. Jade West Resources Ltd., South Surrey, BC and
BC Geological Survey, Victoria, BC
10. Driftwood Creek Magnesite, Kimberley, BC
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MAJOR SPONSORS



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CONFERENCES AND PUBLICATIONS

Date	Location	Publication
1st	1965 Columbus, Ohio	1966, <i>Ohio Journal of Science</i> , 66 (2), p. 97-191
2nd	1966 Bloomington, Indiana	1966, <i>Indiana Geological Survey</i> , 197p. (no publication number given)
3rd	1967 Lawrence, Kansas	1967, <i>State Geological Survey of Kansas Special Distribution Publication</i> 34 , 183p.
4th	1968 Austin, Texas	1968, <i>Texas Bureau of Economic Geology</i> , 174 p. (no publication number given)
5th	1969 Harrisburg, Pennsylvania	1970, <i>Pennsylvania Geological Survey, 4th Series, Bulletin</i> M64 , 271p.
6th	1970 Ann Arbor, Michigan	1970, <i>Michigan Geological Survey Miscellany</i> 1 , 155p.
7th	1971 Tampa, Florida	1972, <i>Florida Bureau of Geology Special Publication</i> 17 , 228p.
8th	1972 Iowa City, Iowa	1973, <i>Iowa Geological Survey Public Information Circular</i> 5 , 189p.
9th	1973 Paducah, Kentucky	1974, <i>Kentucky Geological Survey Series X, Special Publication</i> 22 , 107p.
10th	1974 Columbus, Ohio	1974, <i>Ohio Geological Survey Miscellaneous Report</i> 1 , 100p.
11th	1975 Kalispell, Montana	1976, <i>Montana Bureau of Mines and Geology Special Publication</i> 74 , 186p.
12th	1976 Atlanta, Georgia	1978, <i>Georgia Geologic Survey Information Circular</i> 49 , 78p.
13th	1977 Norman, Oklahoma	1978, <i>Oklahoma Geological Survey Circular</i> 79 , 107p.
14th	1978 Albany, New York	1980, <i>New York State Museum Bulletin</i> 436 , 120p.
15th	1979 Golden, Colorado	1980, <i>Colorado Geological Survey Resource Series</i> 8 , 126p.
16th	1980 St. Louis, Missouri	1980, <i>Missouri Division of Geology and Land Survey Special Publication</i> 7 , 78p.
17th	1981 Albuquerque, New Mexico	1982, <i>New Mexico Bureau of Mines & Mineral Resources Circular</i> 182 , 108p.
18th	1982 Bloomington, Indiana	1983, <i>Indiana Geological Survey Occasional Paper</i> 37 , 251p.
19th	1983 Toronto, Ontario, Canada	1983, <i>Ontario Geological Survey Miscellaneous Paper</i> 114 , 216p.
20th	1984 Baltimore, Maryland	1985, <i>Maryland Geological Survey Special Publication</i> 2 , 152p.
21st	1985 Tucson, Arizona	1987, <i>Arizona Geological Survey Special Paper</i> 4 , 134p.
22nd	1986 Little Rock, Arkansas	1988, <i>Arkansas Geological Commission Miscellaneous Publication</i> MP-21 , 115p.
23rd	1987 North Aurora, Illinois	1989, <i>Illinois State Geological Survey IMN</i> 102 , 105p.
24th	1988 Greenville, South Carolina	1990, <i>South Carolina Geological Survey Miscellaneous Publication</i> , 155p. (no publication number given)
25th	1989 Portland, Oregon	1990, <i>Oregon Department of Geology and Mineral Industries Special Paper</i> 23 , 100p.
26th	1990 Charlottesville, Virginia	1992, <i>Virginia Division of Mineral Resources Publication</i> 119 , 188p.
27th	1991 Banff, Alberta, Canada	1992, <i>Alberta Geological Survey, Alberta Research Council, Information Series</i> 115 , 217p.
28th	1992 Martinsburg, West Virginia	1995, <i>West Virginia Geologic and Economic Survey and U.S. Bureau of Mines Circular</i> C-46 , 227p.
29th	1993 Long Beach, California	1995, <i>California Department of Conservation, Division of Mines and Geology Special Publication</i> 110 , 355p.
30th	1994 Fredericton, New Brunswick and Halifax, Nova Scotia, Canada	1995, <i>New Brunswick Department of Natural Resources Energy, Minerals and Energy Division Miscellaneous Report</i> 16 , 261p.
31st	1995 El Paso, Texas	1996, <i>New Mexico Bureau of Mines & Mineral Resources Bulletin</i> 154 , 330p.
32nd	1996 Laramie, Wyoming	1997, <i>Wyoming State Geological Survey Public Information Circular</i> 38 , 326p.
33rd	1997 Quebec City, Quebec, Canada	1998, <i>Canadian Institute of Mining, Metallurgy and Petroleum Special Volume</i> 50 , 288p.
34th	1998 Norman, Oklahoma	1999, <i>Oklahoma Geological Survey Circular</i> 102 , 364p.
35th	1999 Salt Lake City, Utah	2001, <i>Utah Geological Survey Miscellaneous Publication</i> 01-2 , 286p.
36th	2000 Bath, England Joint with 11th Extractive Industry Geology Conference	2002, <i>Industrial Minerals and Extractive Industry Geology</i> , Geological Society Publishing House, 384p.
37th	2001 Victoria, British Columbia, Canada	2004, <i>British Columbia Ministry of Energy and Mines, Geological Survey and Development Branch</i> , Paper 2004-1, 319p.

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THE GEOLOGY OF WESTERN NORTH AMERICA (ABRIDGED VERSION)

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The geological history of western North America has been, and continues to be, shaped by its position on the eastern rim of the Pacific Ocean. The modern Pacific Ocean's basin is the successor of the original ocean which split Laurentia - our continent's cratonic core - away from the rest of the Precambrian supercontinent Rodinia, an ocean that widened until in late Paleozoic time, it became Panthalassa, the World Ocean. Unlike the eastern side of the continent, where continental collision was followed by re-opening of the Atlantic Ocean - the "Wilson cycle" - western North America has always faced the same active ocean basin. Its tectonic evolution has always been that of an active margin, affected first by multi-episodic rifting, and then by plate-margin subduction and transcurrent faulting, over a 700 million year period of time. Throughout this long interval, fluctuating regimes determined by relative plate vectors have created the complex and varied geology and topography of the region; its thrust belts, volcanoes, and granite canyons; its scarps, plateaus, and cordilleras.

The geological history of this area can be viewed as four distinct plate-tectonic phases. The Rifting/Open Margin phase lasted from initial breakup at about 700 Ma (late Proterozoic) until 400 Ma (Middle Devonian), when widespread subduction began along the margin. The Oceans and Islands phase commenced as subduction built arcs and the continent retreated away from them, creating a scenario like the modern southeastern Pacific ocean. This phase lasted until about 180 Ma (Early Jurassic), when opening of the Atlantic ocean reversed the motion of North America such that it drove strongly westward relative to the long-standing subduction zones off its west coast, creating a broad zone of compression in the offshore arcs and ocean basins as well as its own miogeocline (Collisional/Orogenic phase). The final, Post-Collisional phase commenced during the Early Tertiary when parts of the East Pacific Rise subducted under the continent and turned the plate margin from pure subduction to a regime with both transcurrent faulting and continued subduction of short, remnant segments. Industrial mineral deposits formed during each of these tectonic phases. Combined effects of two or more phases were required to form some of these deposits.

The Cordilleran miogeocline developed during the Rifting/Open Margin phase, from its inception with deposition of the late Proterozoic, syn-rifting Windermere Supergroup, through the deposition of the thick sequences of Paleozoic-early Mesozoic carbonate and terrigenous

siliciclastic strata that are now beautifully exposed in the Canadian Rocky Mountains. The Mt. Brussilof magnesite deposit is hosted by Middle Cambrian carbonate within this continental shelf sequence. Equivalent platformal strata are best exposed in the southwestern United States, the Grand Canyon being a world-renowned example. The opening of Panthalassa was not a single event in western North America: convincing Cambrian as well as late Proterozoic rift-related sequences occur, and alkalic to ocean-floor basalts in the miogeocline range through Ordovician into Devonian age. The implied protracted nature of this rift event, in contrast to the short-lived and efficient opening of the Atlantic Ocean, continues to puzzle. The exact identity of the missing twin continent or continents, also provides grounds for lively debate, with Australia, Australia/Antarctica, and Siberia attracting the most adherents.

The Oceans and Islands phase began in Devonian-Mississippian time with the first widespread arc volcanism and plutonism along the continent margin: these rocks are recognized from southern California to Alaska. West of the North American miogeocline, a large portion of California, Oregon, Washington, British Columbia, and most of Alaska are made up of rocks of intra-oceanic island arc to oceanic affinity that occur in relatively coherent packages separated from each other by faults. These assemblages, famously termed a collage of "suspect terranes" by Peter Coney and Jim Monger, had uncertain relationships to the North American continent during at least part of their history. Most of them have now been shown either to contain faunas of eastern Pacific affinity (an excellent example can be viewed at the Lafarge limestone quarry near Kamloops, B.C.), or to exhibit sedimentological, geochemical and/or historical aspects that link them, however distally, to the continent. Some, however, are more convincingly exotic imports: the Cache Creek Terrane of central British Columbia with its Tethyan, Japanese-Chinese, late Permian fusulinid fauna; Wrangellia and Alexander, a linear belt on the coasts of B.C. and southeastern Alaska, with its late Paleozoic cold-water, Baltic-affinity fauna; and fragments of continental crust in Alaska with Precambrian ages that are unknown in North America.

At present, the Pacific Ocean is highly asymmetric, its west side festooned with island arcs, its east side bare, bordering a continental margin made up of fragments of just such arcs and marginal oceans. It is reasonable to suppose that both sides of the Pacific were once mirror

images. However, opening of the northern Atlantic Ocean at about 180 Ma destroyed that symmetry. Although earlier compressional events affected the suspect terranes, their thrusting on top of the North American miogeocline dates from the latest Early Jurassic, roughly 183 Ma - the same age as early rift basalts on the eastern seaboard. From that time until the end of the Mesozoic, both suspect terranes and sedimentary strata of the miogeocline were stacked into a complex but overall easterly-tapering thrust wedge. Oceanic terranes incorporated into the wedge have provided both asbestos (Cassiar Mine) and jade deposits. During this Collisional/Orogenic phase, successive Jurassic and Cretaceous magmatic arcs draped across the growing accretionary collage. Numerous dimension stone quarries exploit granites from this phase. The notably voluminous mid-Cretaceous arc was probably linked to an episode of rapid subduction around the entire northern Pacific Rim. Broad plutonic provinces of this age occur from China, through Russia, into Alaska and British Columbia and south into California and Mexico - a spectacular example of the global geological consequences of relative plate motion.

Towards the end the Collisional/Orogenic phase, dextral (Pacific-northward) transcurrent motion became an increasingly important part of tectonic development, with at least hundreds of kilometres of displacement along faults such as the Denali, Tintina, Pinchi and Fraser. By early Tertiary time, thrusting in the Canadian Rockies and Foreland Belt had ceased, and crustal extension was accompanied by volcanism and graben development in southern British Columbia and northern Washington-Idaho. At about 38 Ma ago, the edge of North America began to impinge on the East Pacific Rise, shutting off subduction along increasingly long sections of the margin. Major dextral faults - the San Andreas, Queen Charlotte, and Denali faults - began to express the strong component of lateral motion between the American and Pacific plates.

Some 300 kilometres of crustal extension related to this lateral motion generated the Basin and Range Province in

the western United States. Limited subduction continues today off the coast of Washington, giving rise to the Cascade volcanoes; and the westward turn of the continent margin in Alaska creates a continuing collision zone in the Wrangell and Alaska Ranges, resulting in North America's highest summits. Late Cenozoic uplift, perhaps due to mantle heating events, has rejuvenated the Canadian Rockies and the Coast Mountains. In terms of industrial mineral deposits, late Cretaceous and Cenozoic volcanic and terrestrial deposits of bentonite, diatomaceous earth, pumice, zeolites, and opals have attracted exploration and mining interest.

The saga continues, with the recent February 28, 2001 earthquake in Washington State rattling our knick-knack shelves and causing short term cell-phone and 911 overloads. This west coast is by nature Pacific Rim, not just in cultural orientation, but in terms of day-to-day tectonic reality as well.

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AN OVERVIEW OF ALASKA'S INDUSTRIAL MINERALS

By Thomas K. Bundtzen, Pacific Rim Geological Consulting, Inc., Fairbanks, Alaska, USA

In 1948, Alaska's Territorial assayer Arthur Glover wrote "non-metallic minerals can ill afford to be overlooked if there is to be an orderly development of Alaska—the very existence of new industry in the territory may well depend on local development of minerals previously deemed valueless".

In many ways, the far-sighted statement above has come true, while in many other ways, the prophecy remains unfulfilled. Most Alaskans understand the importance of the State's energy and metallic mineral industries. Among the 50 American States, Alaska is currently the largest producer of zinc, the second largest producer of petroleum, the third largest producer of silver, and the sixth largest producer of gold. Most Alaskans are also familiar with the robust copper industry that was active during the earlier part of the 20th Century in the Price William Sound and Wrangell Mountains regions. But these same citizens remains largely ignorant of the importance of Alaskan suppliers of building stone, sand and gravel, and limestone. Additionally chemical and structural grade limestone, gypsum, garnets, asbestos, barite, pumice, and clay have all been mined in the 49th State. Nationally significant reserves of barite, asbestos, zeolites, fluorite, and phosphate minerals were discovered and explored during the 1970s and 1980s. A summary of industrial mineral resources judged to be important to Alaska's future follows.

Sand and gravel and building stone

From 1948-1999, an estimated 1.02 billion tonnes of sand and gravel and 50 million tonnes of building stone worth US\$2.7 billion have been quarried at more than 200 locations throughout Alaska. The sand and gravel industry is an important factor in the development of the North Slope oil and gas fields, the growth of larger urban areas like Fairbanks and Anchorage, providing harbor infrastructure in coastal communities, and for the construction and maintenance of the State's highway system. Modern fluvial deposits supply most of the gravel needs of the North Slope and Anchorage areas, whereas past placer gold mining tailings are the source of a significant portion of the gravel used in the Fairbanks, Nome and selected Interior highway areas. The building stone industry focuses largely on satisfying the needs of the domestic transportation industries. Although some quarry stone from Nome has been shipped offshore to selected markets, most is used in bridge, causeway, and river abutment applications throughout Alaska.

Marble and Limestone

Before the Russian period, Tlingit Indians used Alaskan marble in southeast Alaska for carved objects such as utensils, art forms and religious symbols. Potentially valuable marble resources on Prince of Wales Island were some of the first mineral localities mentioned in late 19th Century United States Geological Survey reports. During the early 20th century, high quality ornamental marbles were quarried from more than 20 deposits near Tokeen and Calder. More than 72 buildings in nine western and eastern states used Calder marble for columns, wainscoting and trim designs. Examples include the Isaacs Building in Los Angeles, the State Capital in Juneau, Alaska, and the admissions building of the University of Utah. Prior to Statehood, more than two million tonnes of limestone and marble from the same area were shipped to chemical grade market vendors. In 1998, Sealaska Native Corporation re-opened the high grade calcite limestone quarry on Calder Bay and began production at the rate of 150 000 tonnes per year. The company created the mining subsidiary Sea-Cal LLC to manage the quarry, which produced a very bright calcium carbonate for paper coating, paint, and other applications.

Barite

From 1963 to 1980, mine operator Chromalloy Inc. produced about 856 000 tonnes of barite from Castle Island near Petersburg, also in Southeast Alaska. Most of the ore body was drilled, blasted, and retrieved underwater by using a barge-mounted clamshell. The entire production was used for drilling mud applications. Millions of tonnes of barite mineralization have been delineated in the Noatak SEDEX district in northwest Alaska, and in the Atigun Canyon district near the Alyeska Pipeline in the Central Brooks Range. The main reserve was defined at the Red Dog Mine, where a 100 meter thick massive barite cap covers the zinc-lead-silver deposits currently being mined. Other base metal VMS and SEDEX districts throughout Alaska contain significant barium resources

Gypsum and Clay

Pacific Coast Gypsum Company mined high quality 'blue' gypsum from folded and tilted beds of Permian age at Iyoukeen Cove on Chichagof Island in southeast

Alaska. Although production was modest (500 000 tonnes from 1902 until 1926), Kaiser Industries acquired the property during World War II for Portland Cement and wallboard applications. Prior to Statehood, structural grade clay deposits, located north of Anchorage in the south-central Alaska 'rail belt', were systematically investigated by the U.S. Bureau of Mines. Small clay manufacturers have used kaolinite-based deposits at Sheep Mountain and in the Bootlegger Cove Clay near Anchorage to manufacture bricks and flue tile. During the 1970s, ceramic tiles, bricks, and sewer pipes have been manufactured during evaluation of large clay deposits in the Nenana Coal Bearing Group near Healy, but no firm markets have been secured.

Asbestos

During World War II, asbestos was declared a strategic mineral by the US government, and small scale production occurred from deposits in the Kobuk River valley of northwest Alaska. In 1980, Doyon Limited announced the discovery of a major chrysotile asbestos deposit on Slate Creek in the historic 40-Mile mining district of Interior Alaska. Drilling indicated reserves of 55 million tonnes grading 6.5 percent asbestos fiber that could be exploited by surface mining technologies. Unfortunately, highly restrictive environmental policies caused the Slate Creek project to be put on hold.

Other Industrial Minerals

In past years, gem quality almandine garnets have

been selectively mined from schist and migmatite near Wrangell, in southeast Alaska. More recently, placer mining firms in the Circle and Rampart districts of Interior Alaska have submitted test shipments of almandine garnets for abrasive testing and marketing ventures. Zeolite, sulphur, and perlite deposits have all been studied in Jurassic to Tertiary volcanic terranes throughout the 49th State, but no serious exploration has ever been attempted. Similarly, high quality diatomaceous earth deposits documented on the Kenai Peninsula lack follow-up exploration work.

SUMMARY

Most Alaskan industrial mineral resources are low unit value products that face obstacles such as lack of local markets, poorly developed transportation infrastructure, and inadequate energy availability. In addition, the commercialization of these products has been held back by a fundamental lack of technical data and market information. Nevertheless, Alaska is a peninsular region, positioned to furnish industrial minerals to markets throughout the Pacific Rim. For example, representatives from California, Hawaii, and Japan have approached Alaskan producers about supplying them with aggregate. Coastal dimension stone could be an attractive product for the same markets. There is virtually no ornamental stone industry in Alaska, but Asian ornamental stone (granite) buyers have tested several deposits located near the existing infrastructure.

INDUSTRIAL MINERALS IN BRITISH COLUMBIA REVIEW AND OPPORTUNITIES

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INTRODUCTION

Industrial minerals are an increasingly significant component of international trade and British Columbia is strategically located on the west coast of North America (Figure 1).



Figure 1. Strategic geographic location of British Columbia in western North America with access to Pacific Rim countries.

British Columbia has a well-developed infrastructure in the southern, highly populated third of the province, several deep-water ports, and a well-maintained highway system that permits efficient long distance trucking. Rail links British Columbia industrial centres to terminal points across the continent. The province has attractive energy costs and untapped mineral resources.

The value of solid mineral production for 2003 is estimated at \$2.9 billion (Figure 2). Officially, industrial minerals and construction materials account for \$578 million of this total; however, this value would be substantially higher if the value-added aspect of the industry was fully taken into account.

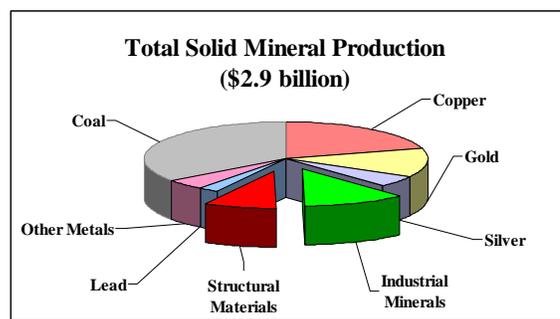


Figure 2. Estimated solid mineral production in British Columbia for the year 2003.

The forecast value of structural materials (including construction aggregates) is approximately \$238 million, while the value for traditional industrial minerals estimated by Natural Resources of Canada reached \$340 million. Our own preliminary estimates suggest that the value of industrial mineral production could be substantially higher than this figure.

Sales of sulphur declined to an estimated 770 000 tonnes; however, this decline may have been offset by higher sulphur prices. Most of the sulphur in British Columbia is derived as a byproduct of oil and gas processing. Further reductions in sulphur sales are anticipated in the coming years, if the trend of disposing of sour gas into depleted oil and gas reservoirs continues.

Overall exploration expenditures in British Columbia reached \$55 million in 2003, up 25% to 38% from 2002. Overall exploration drilling in 2003 was estimated at 300 000 metres, whereas drilling for industrial minerals was estimated at 10 800 metres, about the same as for 2002.

MAJOR TRENDS AND POTENTIAL

Aggregate

In recent years, the most significant industrial minerals trend in British Columbia has been an increasing

export of crushed stone and natural aggregate to urban centres along the west coast of the United States and higher sales within British Columbia's Lower Mainland. These markets are becoming very competitive as industry identifies new potential for development. A good example of this is the \$100-million construction aggregate complex and ship-loading facility planned for development near Port Alberni. The project has been granted an Environmental Assessment Certificate. This project, a joint venture between Eagle Rock Materials Ltd., the Hupacasath First Nation, the Ucluelet First Nation, and Polaris Minerals Corporation, will have a capacity of 6 million tonnes per year. In 2001, a basalt quarry and related roofing-granule plant was built in the Ashcroft area. In 2003, the plant operated at 50% of its designed capacity of 500 000 tonnes but production will increase proportionally as the market grows.

Cement Industry

An increase in the use of natural pozzolans and lightweight aggregates in the cement industry is expected. The use of natural pozzolans and fly ash reduces energy consumption and greenhouse gas emissions. Most of the major cement-producing companies are conducting research to find out how highly reactive pozzolan may, in some cases, replace as much as 60% of Portland cement and result in concrete with good set times and early strength. Pozzolan deposits, which are located in southern and central British Columbia (near major population centres), may benefit from increased interest from cement companies. Deposits of specialty, natural and lightweight aggregates, such as pumice, may also benefit.

Niche Markets

Niche markets, such as medical clay, jade, flagstone, tufa and other landscaping materials, have been expanding. They continue to provide opportunities for smaller-scale operators.

Green Minerals

Over the next few years, new opportunities will arise in the field of "green" minerals. Green minerals are those that can be used in environmental clean-up, agriculture, waste disposal, and for other environmental applications. Agricultural markets for zeolites appear to be improving. Absorbent minerals may be in higher demand because the moratorium on new salmon-farm developments in the province has been lifted. British Columbia has a number of well-documented bentonite deposits. Depending on test

results, some of these deposits could supply material for linings and barriers in waste disposal applications, clay tile manufacturing, and possibly drill-mud applications. For example, depending on the design specifications, some of British Columbia's bentonite could be used at the future Ashcroft Ranch Landfill solid waste project that is currently in the planning stage. This landfill will serve the Greater Vancouver Regional District.

Offshore

Should an offshore oil and gas industry become a reality, opportunities may expand for minerals used in drilling fluids and other related products. New markets may also develop for heavy aggregate along the coast. Magnetite and olivine are commonly used as ballast materials on ocean drilling platforms.

Coal-Related Opportunities

Over the long term, the market for magnetite used in coal washing may also indirectly benefit from the Kyoto agreement; it is environmentally friendly and reusable. We expect that a future trend may develop where coal is processed near mine sites (ground, cleaned and slurried), then piped to a power station where it could be de-watered and used. Increased processing of Canada's coal will make the process more efficient and reduce CO₂ emissions.

Gemstones

Highly publicized announcements of emerald and blue gem-quality beryl discoveries in the Yukon resulted in a Canada-wide coloured gemstone fever. British Columbia has good exploration potential for beryl gemstones, and more specifically, for emerald and aquamarine deposits.

Diamond exploration in British Columbia is in its infancy. Recent geological research suggests that northeastern and southeastern British Columbia is underlain by old crystalline basement similar to diamond-bearing regions in the Northwest Territories and Alberta. Unlike the Northwest Territories, most of eastern British Columbia was not staked or explored for diamonds. Recent findings of diamonds in ultra-high pressure metamorphic rocks also suggest that diamonds may be found west of the Rocky Mountain Trench. For more information on the subject, please consult: <http://www.em.gov.bc.ca/DL/GSBPubs/GeoFile/GF2004-3/DiamondsinBC.pdf>.

At - Aggregate
Ba - Barite
Bn - Bentonite
Cc - Ca-carbonate
Ch - Chrysotile
Cr - Crushed stone
Do - Dolomite

Ds - Dimension stone
Fc - Fireclay
Fr - Fuller's earth
Fs - Flagstone
Gy - Gypsum

Jd - Jade
Ls - Limestone
Ma - Magnetite
Mt - Magnesite
Pu - Pumice
Rg - Roofing Granules
S - Sulphur

Sa - Sulphuric Acid
Sg - Slag
Sh - Shale
Si - Silica
Sl - Slate
Tu - Tufa
Ze - Zeolite



Figure 3. Selected Industrial Mineral Mines and Quarries in British Columbia.

PRODUCTION AND EXPLORATION REVIEW

The most economically significant industrial minerals produced in British Columbia are magnesite, white calcium carbonate, limestone, silica, dimension stone, gypsum, sulphur, construction aggregate, and crushed rock. Commodities produced in lesser quantities include

jade (nephrite), magnetite, dolomite, barite, volcanic cinder, pumice, flagstone, clay, tufa, fuller's earth, and zeolites. There are more than 40 mines or quarries (Figure 3) and at least 20 major sites where upgrading of industrial minerals into value-added products takes place; this excludes aggregate operations listed by the British Columbia Aggregate Producers Association. Most of these operations are concentrated close to existing infrastructure and markets (Figure 4).

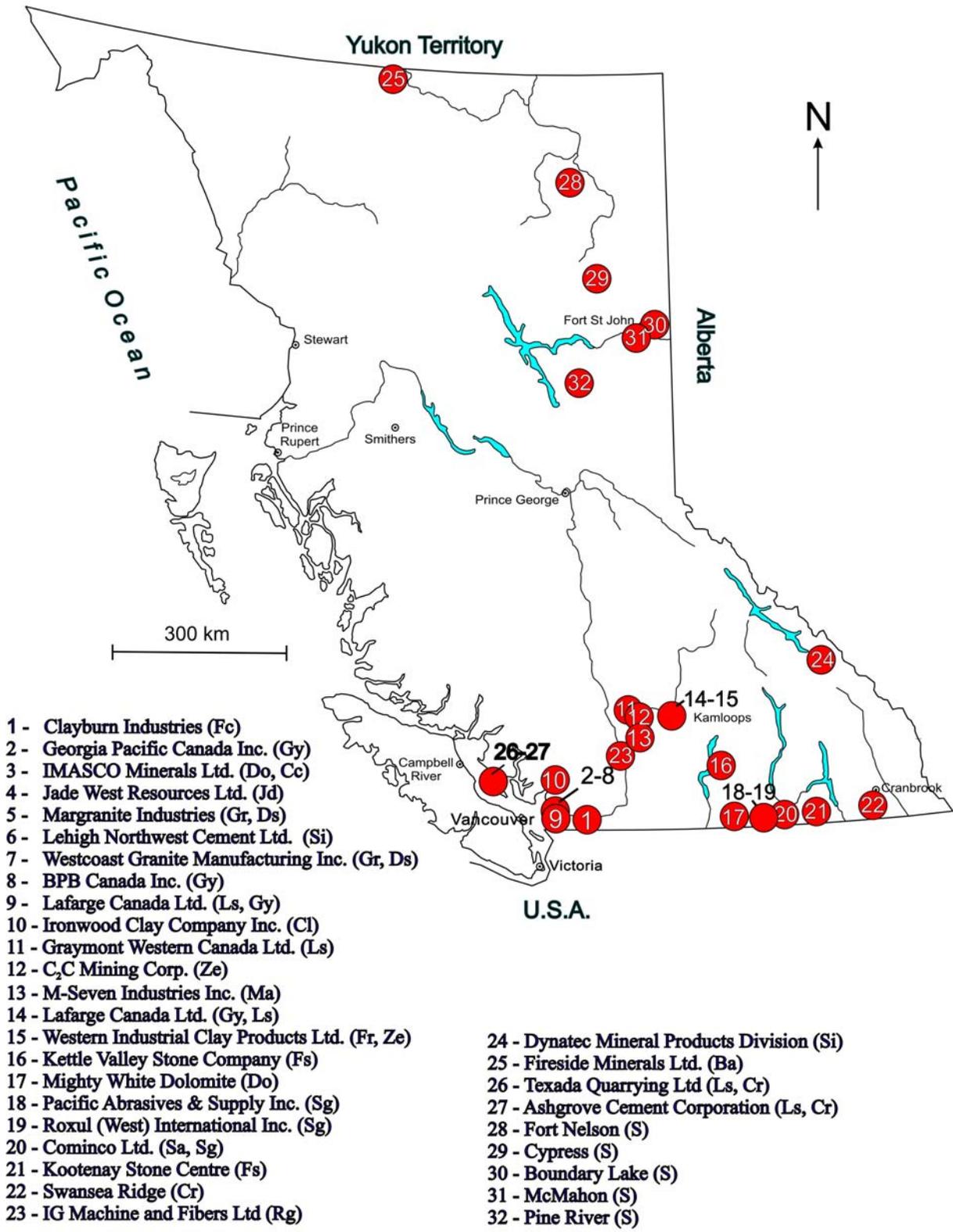


Figure 4. Industrial Mineral Processing Plants in British Columbia (same abbreviations as Figure 3).

GYPSUM

BPB Canada Inc. (formerly BPBP Westroc Inc.) production for 2003 is estimated at 500 000 tonnes of gypsum from its Elkhorn quarries near Windermere.

During the last several years, the company drilled 98 holes, which outlined a resource of 16.7 million tonnes of gypsum on its Koot property, northeast of Canal Flats. However, new reserves found at Elkhorn West will delay the need to develop the Koot deposit. In 2003, Georgia Pacific Canada Inc. produced approximately 175 000 tonnes of gypsum from its Four J quarry near Canal Flats, and about 100 000 tonnes were shipped to its wallboard plant near Edmonton, Alberta. Both BPB Inc. and Georgia Pacific operate wallboard plants in the Vancouver area. Lafarge Canada Inc. mines a small quantity of gypsum from its Falkland pit (approximately 6000 tonnes) for its Kamloops cement plant; if needed, it supplements it with gypsum supplied by BPB Canada Inc..

MAGNESITE

Baymag Inc. produces magnesite at Mount Brussilof at a rate of about 200 000 tonnes/year. The company has two plants in Exshaw, Alberta. The first is a converted limekiln producing sintered magnesia; the second houses a 50 000-tonne capacity, multiple hearth furnace, a vertical-kiln dedicated to producing specialty calcined MgO, and an electrofusing installation. Although calcined magnesia is the main product, a portion of production is further processed to high-quality fused magnesia for export. The company also sells crushed white magnesite for landscaping.

SILICA

In 2003, the Dynatec Mineral Products Division (Mountain Minerals) of Dynatec Corporation extracted approximately 85 000 tonnes of silica from its Moberly mine, and shipped it mainly to Lavington, British Columbia. In the past, it also shipped lump silica to Springfield, Oregon and other destinations; however, these shipments have stopped since American silicon and ferrosilicon production collapsed.

During 2003, Lehigh Northwest Cement Limited (formerly Tilbury Cement Ltd.) mined 49 000 tonnes of geyserite from its quarry at Monteith Bay on western Vancouver Island to supply its cement plant in Delta. Electra Gold Ltd. and Homegold Resources Ltd. mined 30 000 tonnes of geyserite (silica material and minor clay) from their Apple Bay deposit on Vancouver Island;

this material was successfully tested at the Ashgrove Cement plant in Washington State.

LIMESTONE

The largest limestone production centre in the province is Texada Island with two quarries, Gillies Bay (Texada Quarrying Ltd) and Blubber Bay (Ashgrove Cement Corporation). They traditionally ship 5 to 6 million tonnes annually to customers in British Columbia, Washington, Oregon and California, for cement, chemical and more recently, agricultural use. In 2003, 3.25 million tonnes of limestone and 750 000 tonnes of aggregate were shipped from Gillies Bay, where limestone production capacity is over 5 million tonnes a year and aggregate (crushed rock) capacity is approximately 1.5 million tonnes. Depending on customer demand, aggregate may be sourced from newly quarried granitic rock, stockpiled granite, limestone or a combination of these products.

Ashgrove upgraded its crushing plant in 2002. In 2003, approximately 4 million tonnes of rock were mined and more than 2 million tonnes of limestone were shipped from Blubber Bay. Aggregate production was about 400 000 tonnes. Depending on its ability to win future contracts in California, the company is considering building a \$10-million ship-loading facility on Texada Island. A joint venture of Lehigh Northwest Cement Limited and Chemical Company of Canada Limited conducted exploration drilling and trenching on the Lehigh Central Texada project.

In addition to pulp mills, which normally produce lime internally, three cement plants and two lime plants in British Columbia process limestone. Graymont Western Canada Inc.'s Pavilion Lake limestone quarry and lime plant near Cache Creek has a production capacity of about 190 000 tonnes of lime annually. In 2003, Lafarge Canada Inc.'s Kamloops cement plant operated at less than 50% of rated capacity and in 2004, they expect to operate at full capacity. Lafarge's plant in Richmond, and Lehigh Northwest Cement Limited's plants in Delta, are state-of-the-art operations. The Richmond plant has the capacity to produce one million tonnes of cement annually. Pacific Lime Products Ltd. at Giscome, near Prince George, sells small quantities of limestone to pulp mills in the region. Three thousand tonnes of limestone for environmental and agricultural applications was quarried near Kelowna by Western Canada Limestone Ltd.

White Calcium Carbonate

White, high-calcium carbonate was produced by Texada Quarrying Ltd. from its Gillies Bay quarry on Texada Island, by IMASCO Minerals Ltd. from its Benson Lake quarry on Vancouver Island and, if needed, its Lost Creek quarry near Salmo. This carbonate has a

variety of uses, including paper, paint and plastic filler. Imperial Limestone quarried a small quantity (less than 10 000 tonnes) of white calcium carbonate from its deposit on Texada Island. There were no sales.

Dolomite

Dolomite is quarried by IMASCO Minerals Ltd. at its Crawford Bay mine on Kootenay Lake (Figure 5) and by Mighty White Dolomite Ltd. near Rock Creek.

Dolomite is used for soil conditioning; to produce white ornamental aggregate, stucco and roofing; as fine aggregate; and in synthetic marble products. In 2003 Ashgrove Cement started mining dolomite from Pit 7 adjacent to Pit 6, their limestone quarry on Texada Island.

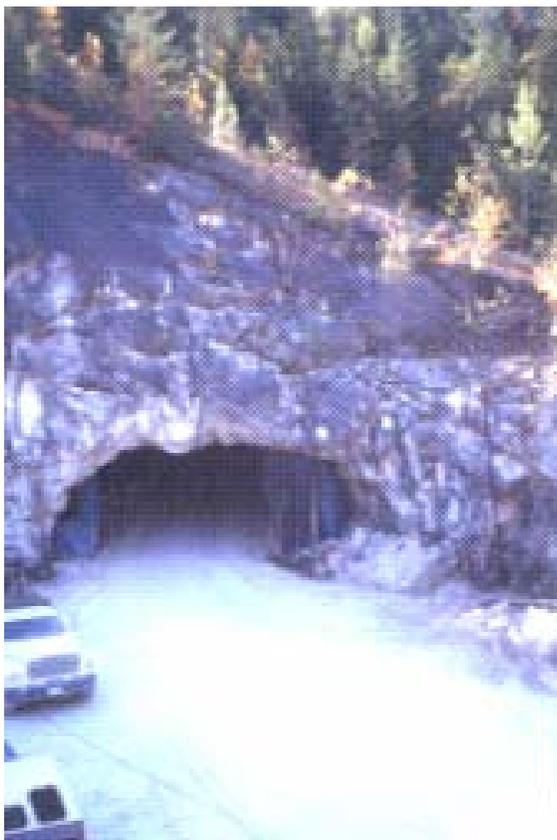


Figure 5. IMASCO Minerals Ltd. Crawford Bay dolomite mine.

AGGREGATE AND CRUSHED STONE

Grassroots exploration for traditional construction materials continues to expand along the British Columbia coast. Shipments of crushed stone from Texada Island and other coastal sources are making significant inroads into the Vancouver, Seattle, San Diego, San Francisco and Los Angeles markets. Texada Island limestone producers have already started to exploit this opportunity (see under limestone). Texada Island producers are well established, and crushed rock is a natural byproduct of

their limestone operations. Natural aggregate is the focus of similar market demands. Lehigh Northwest Materials Limited shipped approximately 1 million tonnes of aggregate from its facility at Sechelt to the San Francisco Bay area in 2003.

Polaris Minerals Corporation, one of the key partners in Eagle Rock Materials Ltd., is participating in the development of an aggregate operation near Port Alberni. Qualark Resources Inc. The Yale First Nation has proposed a 12 million tonne-per-year aggregate operation, in conjunction with placer gold washing, at its Hillsbar quarry near Yale. Polaris Minerals Corp. and the Kwakateil First Nation propose to quarry material from its Orca Sand and Gravel operation near Port McNeil. Other companies are working on similar ventures, including Southern Pacific Development Corp.'s project near Port Renfrew on southwestern Vancouver Island.

Approximately 210 000 tonnes of railroad ballast was produced in 2003 from British Columbia Railway's Ahbau basalt quarry, northeast of Quesnel. Canadian Pacific Railway's Giscome basalt quarry, northeast of Prince George, was inactive. The existing inventory of crushed ballast material at the site was sufficient to address the company's maintenance requirements in the region.

Canadian National Railways, however, also operated at least six other railroad ballast operations in British Columbia: McAbee (near Ashcroft), Boulder (near Clearwater), Taverne (near Tete-Jaune), Pacific (east of Terrace) and Kwinitsa (Mile 40 on the Skeena River). Canadian Pacific Railway mined, crushed and shipped railroad ballast from its Swansea Ridge gabbro quarry south of Cranbrook. No information is available about Canadian Pacific's Wallachin quarry.

Exploration for aggregate to support the expanding infrastructure of the oil and gas sector in northeast British Columbia is ongoing. One major producer, Teko pit, southwest of Taylor near Fort St. John, was a major aggregate-crushing operation in 2003.

ROOFING GRANULES

IG Machine and Fibers Ltd., a subsidiary of IKO Industries Ltd., and operates an Ashcroft basalt quarry and roofing-granule plant. In 2003, the plant was producing six distinct colours, and operated at about 50% of its rated capacity of 500 000 tonnes of granules per year. Basalt is quarried, crushed, sized and coloured on site, prior to shipping to IKO Industries shingle plants in Sumas, Washington, Calgary, Winnipeg and Chicago.

INDUSTRIAL CLAY AND SHALE/SANDSTONE

Clayburn Industries Ltd. of Abbotsford processes fireclay from Sumas Mountain into a variety of refractory bricks and castable products that are exported worldwide. Sumas Clay Products Ltd. also manufactures small quantities of flue-line pipe and ornamental and facing bricks from its plant near Abbotsford. Clayburn, Lafarge Canada Inc. and Lehigh Northwest Cement Ltd. can produce around 500 000 tonnes of shale and sandstone from their Sumas shale quarry. Clayburn is developing new lightweight aggregate with good insulation properties based on this material. Exploration for alumina-rich materials increased due to difficulties that were encountered to access resources from the Sumas quarry in early 2003. As a result, the Lang Bay deposit, Klinker from the Hat Creek area, and a new occurrence discovered by Quinsam Coal are receiving attention. Pacific Bentonite Ltd. mined and shipped about 3000 tonnes of Hat Creek burnt shale. Lafarge is testing the Hat Creek shale as a potential source of alumina for cement manufacturing.

MEDICAL CLAYS

Ironwood Clay Company Inc. is the largest producer of cosmetic/medical clay in British Columbia. It mines seasonally from the De Cosmos Lagoon on Hunter Island, west of Bella Coola.

Similar material from at least one other British Columbia locality, Carrie Cove in the Comox Valley, also reached market. It is currently sold by Carrie Cove Cosmetics for medicinal and cosmetic applications. It is also expected that Glacial Marine Clay Inc. will be producing clay for specialized hydroponics applications. Mr. Robert Davie has an undeveloped clay deposit on King Island. The market for cosmetic/medical clay is limited; however, the processed product may retail at about \$100/kilogram. The market for specialized hydroponics clays is larger and product specifications are less stringent. Such material may retail at about \$20/kilogram.

DIATOMITE, ZEOLITE AND BENTONITE

Western Industrial Clay Products Ltd. produces domestic and industrial absorbents (Figure 6), principally from its Red Lake fuller's earth deposit near Kamloops. In the Princeton area, the company also is mining bentonite from the Bud property. The company secured a contract to sell humic acid (a leonardite derivative) to a major retail chain and is looking for an optimum humic acid extraction method. The leonardite is found between

the diatomite horizons at Red Lake. There are a number of known bentonite deposits in British Columbia.

Dynatec Corporation continues to report increasing annual sales of zeolite from the Ranchlands Z-1 quarry near Cache Creek. The company drew from existing stockpiles during 2003, so mining was very limited. Near Princeton, progress was made to bring the Zeo (Bromley Vale) zeolite project into production. Zeo-Tech Enviro Corp. obtained a contract to supply 30 000 tonnes in late 2003, and has formed a partnership with C2C Zeolite Corp. to build a micronizing plant. The new company, United Zeolite Products Ltd., will be a jointly owned operating company. A 5-year supply agreement has been signed with Haliburton Energy Services Inc. to deliver a specialty zeolite for use in a new lightweight oil and gas well cementing system.

Although Canmark International Resources Inc. is attempting to develop a market in the Lower Mainland for zeolite from its Sunday Creek deposit near Princeton; the mine remained inactive during 2003.

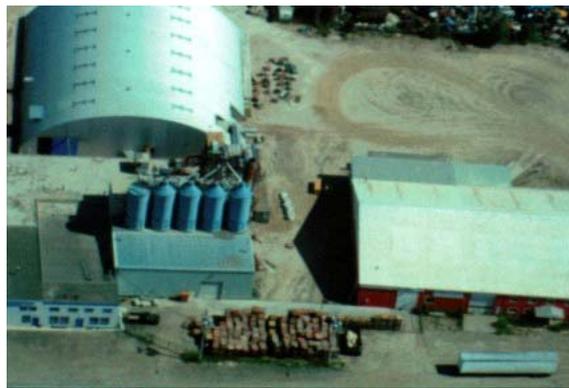


Figure 6. Western Industrial Clay Products Ltd. Processing Plant in Kamloops (aerial view).

DIMENSION STONE



Figure 7. Nipple Mountain Flagstone Quarry, Kettle Valley Stone Company.

Westcoast Granite Manufacturing Inc. in Delta, Margranite Industries in Surrey, and Matrix Marble

Corporation in Duncan operate stone-processing plants. Garibaldi Granite Group Inc., which was located in Squamish, declared bankruptcy. Margranite processes imported stone, and nine local granite varieties from at least three quarries located in the East Anderson River, Beaverdell and Skagit Valley areas. Huckleberry Stone Supply Ltd. of Burnaby and Mountain High Properties Ltd. of Pemberton produced basalt from small quarries in the Whistler area. In 2003, Matrix Marble Ltd. concentrated on processing imported and domestic materials at its plant near Duncan, but also extracted marble from its quarry near Cowichan Lake.

Hardy Island Granite Quarries Ltd. extracted about 3500 tonnes of stone this year, and the product was sold through Bedrock Granite Sales in Coquitlam, British Columbia. In 2003, Quadra Stone Ltd. produced a small tonnage of "Cascade Coral" blocks from its new Fox Island quarry. Near Kelowna, the Kettle Valley Stone Company produced flagstone, ashlar, thin veneer and landscape rock products from several quarries. The most popular product was dacite ash (Mountain Ash) from its Nipple Mountain quarry (Figure 7). Kettle Valley purchased a new automated saw that should help increase production.

Revelstoke Flagstone Quarries, Kootenay Stone Centre, and other small operators in the West Kootenays quarried flagstone. Small flagstone quarries were also opened in the North Thompson and Golden areas. Rocky Mountain Tufa produced about 2500 tonnes of material, mainly for landscaping applications. In 2003, Golden Rock Products Inc. secured a number of tufa, travertine, and limestone occurrences along the Rocky Mountain Trench in southeast British Columbia. The company plans to market products from these occurrences to Alberta.

CHRYSOTILE

Cassiar Resources Inc. (CRI) sold its mining property located in Cassiar, British Columbia, to Cassiar Jade Contracting Inc. (CJC) of Watson Lake, Yukon. The assets transferred include all mining titles, the remaining infrastructure and chattels on the property, and an environmental reclamation bond posted with the regulators. CJC agreed to perform the remaining reclamation work and assumed all liabilities related to the property. CRI has an option to reacquire the Cassiar property if a major commercial opportunity should arise. CRI changed its name to Troutline Investments Inc..

JADE

Jade West Resources Ltd. and its affiliated company, Polar Gemstones Ltd., are the province's main nephrite producers. In 2003, they produced about 200 tonnes of nephrite from the Kutcho Creek, Cassiar and Serpentine Lake areas in northwestern British Columbia. Jade West

also operates a jade processing facility in south Surrey. Jedway Enterprises Limited extracted small quantities of nephrite from its Kutcho Creek and Polar sites. Cassiar Mountain Jade, with outlets in Jade City and Quesnel, produced approximately 20 tonnes of raw material from its Princess property. Cassiar Jade Contracting Inc., who bought chrysotile-related assets from Cassiar Resources Inc., continues to recover nephrite from mine dumps near Cassiar.

PUMICE, TEPHRA AND LAVA ROCK

Canada Pumice Corporation produced about 20 000 cubic metres of tephra from its Nazko quarry, west of Quesnel. The material is used for landscaping, sporting facilities, growing and filtration media, and lightweight aggregate applications. In March 2004, Crystal Graphite Corporation signed an agreement in principle to acquire 100% of shares of Canada Pumice Corporation. Great Pacific Pumice Ltd. (Figure 8) is shipping a variety of pumice-based products from its Pum property on Mount Meager, north of Pemberton. Production in 2003 was estimated at 7000 cubic metres, and material from this deposit was successfully tested by two major cement-producing companies as a pozzolanic additive. Garibaldi Aggregates Ltd. also initiated production of pumice from the Mount Meager area.

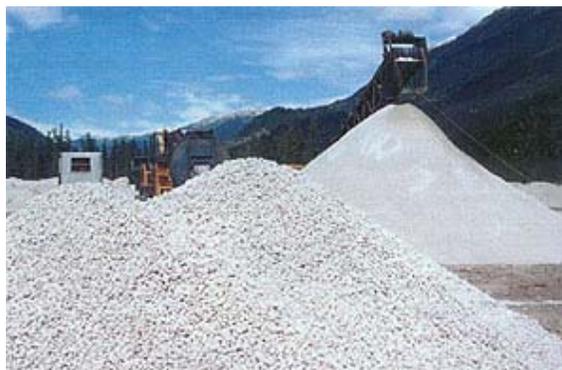


Figure 8. Processing Pumice, Great Pacific Pumice Ltd., near Mt. Meager.

MINERAL WOOL

Roxul (West) International Inc. made new investments in plant improvements at their insulation/mineral wool manufacturing plant in Grand Forks. From 1999 to 2001 Roxul invested \$25 million in the project and a further \$4 million in 2002. The company continues to improve its competitive position. The plant's main source of raw material was the Winner diorite quarry in the Greenwood mining camp, 4 kilometres south of the former Phoenix mine. In 2003, approximately 50 000 tonnes of diorite were mined and crushed. Material from Winner quarry is supplemented by

talus material from Cannon Creek. During the last few years, slag was recovered from Roxul's operation in Greenwood; however, this year the company reverted to Pacific Abrasives & Supply Inc., its original supplier in Grand Forks.

SLAG

Pacific Abrasives & Supply Inc. is producing and processing slag from Grand Forks dumps, mainly for sandblasting at major shipyards, and for roofing granules. Some slag was also shipped from Anyox by Tru-Grit as abrasive for cement industry applications, mainly in the Vancouver area, as roofing granules, and for other abrasive applications. Teck Cominco Ltd. is also a major slag producer at its Trail smelter. It markets slag mainly for cement production and abrasive applications. For the last few years, slag has also been recovered in the Greenwood area, mainly as one of the raw materials for the production of mineral wool by Roxul (West) International Inc. in Grand Forks. In 2003, MRI Americas purchased slag from Greenwood and trucked it to Mission, where it was put on barges and transported to Texada Island. From there it was shipped to Poland. An initial shipment of 25 000 tonnes was extracted in October 2003, however, conflicting information exists as to the intended use of shipped material.

MAGNETITE

Craigmont Mines Ltd. typically produces between 60 000 and 70 000 tonnes of magnetite annually for industrial applications by processing the Craigmont mine tailings; however, in 2003 the production was reduced to 45 000 tonnes. The company is supplying most coal mines in western Canada with heavy media material for their wash plants. Quinsam Coal optioned the Iron Mike and Iron Ross magnetite occurrences, which are approximately 6 kilometres south of Sayward. Benson Magnetics Ltd. continues to investigate the feasibility of installing a 25 000 tonne-per-year plant near Benson Lake, on Northern Vancouver Island. Current trends in clean coal processing may lead to development of additional magnetite resources in British Columbia.

GRAPHITE

In 2002, Crystal Graphite Corp. released new resource calculations for its Black Crystal graphite deposit in the Slocan Valley. The weathered zone has 648 000 tonnes containing 1.82% "fixed carbon" in measured and indicated resources, and 516 000 tonnes of inferred resources containing 1.69% fixed carbon. The underlying unweathered zone has indicated resources of 4 763 000 tonnes containing 1.21% fixed carbon, and 4 591 000 tonnes of inferred resources containing 1.24% fixed carbon. In 2002, the company also received a

mining permit to process flake graphite to a maximum feed rate of 250 000 tonnes per year. In February 2003, the company announced that its processing plant was ready for continuous operation, and is now planning upgrades to enhance productivity. The company planned to mine an additional 2500 tonnes of graphitic material plant feed during October 2003.

SULPHUR

Duke Energy Corporation, Petro-Canada Inc. and Anadarko Canada are major sulphur producers. Sulphur is a byproduct of natural gas processing at a number of plants in the northeastern region of the province. A rough estimate of production for 2003 is 770 000 tonnes. Liquefied SO₂ and sulphuric acid are also produced at Cominco's smelter in Trail mostly for internal use. Sulphur prices are increasing due to greater Chinese demand. All of British Columbia's sulphur production in 2003 was sold on contracts, so none was available for sale on the spot market.

HIGH TECH MINERALS

Commerce Resources Corporation continued to evaluate its Fir carbonatite deposit near Blue River in 2003. Newly released resource estimates for the Fir are 5.6 million tonnes of indicated and 6.7 million tonnes of inferred resources, both grading 203.1 g/t of tantalum pentoxide and 1047 g/t of niobium pentoxide. The Fir ferrocolumbite- and pyrochlore-bearing carbonatite is apparently nearly flat lying, and has been outlined over an area of 425 by 325 metres.

The company also announced completion of two preliminary cost assessments for processing and beneficiation of these tantalum and niobium enriched carbonatites. A bulk sample of approximately 800 kilograms, comprised of core from a number of diamond-drill intercepts, was used in a small-scale metal recovery test. It indicated recoveries for tantalum and niobium in the range of 83 to 91%. Gravity testwork was also carried out. Other metallurgical testing is ongoing. The focus of the 2003 exploration program was to define the extent of mineralization in the Upper Fir carbonatite zone that may be an offset of the Fir deposit. According to the company, average concentrations for all the 2003 samples from the Upper Fir carbonatite are 267 g/t Ta₂O₅ and 3746 g/t Nb₂O₅.

GEMSTONES

Okanagan Opal Inc. mined a small quantity of precious opal in 2003 from its Klinker deposit near Vernon. Follow-up prospecting and excavating also were conducted on the Northern Lights precious opal occurrence in the Whitesail Range, south of Houston.

During 2003, the Schaefer family continued to extract precious opal by hand from its Firestorm property, west of Burns Lake. Cream Minerals Ltd. discovered ice blue to deep greenish-blue beryl crystals (aquamarine) on its Kootenay Gemstone property (formerly Bayonne Aquamarine), located near Salmo. The beryl occurs in pegmatites and quartz veins. Most of the mineralization appears along a favourable contact between pegmatitic dikes and sedimentary rocks. Eagle Plains Resources Ltd. discovered gem-quality aquamarine associated with pegmatites on its Blue Hammer property in the Doctor Creek area, 45 kilometres northwest of Cranbrook.

BARITE

Tiger Ridge Resources Ltd. continued underground development and bulk sampling of two adits on its barite project at Jubilee Mountain, west of Spillimacheen.

In 2003, barite production by Fireside Minerals Ltd. from its Fireside quarry east of Watson Lake amounted to 10 000 tonnes, and some 12 000 to 15 000 tonnes of rock was mined from the Bear Pit. In northern British Columbia, the high-grade Nonda and lower grade BV barite deposits are being investigated by Mr. Horst Klassen.

WOLLASTONITE/GARNET

In 2003, RossWoll Industries Inc., a private company formed by Grid Capital Corporation, purchased a wollastonite deposit located near Rossland from Mr. Klassen. This material could be potentially used as flux at Teck Cominco's smelter in Trail.

PERLITE

In September 2003, BBF Resources Inc. took a 180-tonne bulk sample of perlite from the Frenier deposit, which is located west of Clinton. The material was trucked to Abbotsford for processing and test marketing for horticultural use. At this time, a number of prospectors are exploring for perlite deposits closer to Vancouver, where there is a good potential for a perlite expander installation.

INDUSTRIAL MINERAL ENDOWMENT AND DEVELOPMENT OPPORTUNITIES, NORTHEAST-CENTRAL BRITISH COLUMBIA

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INTRODUCTION

The industrial mineral endowment of northeast-central British Columbia is rich and varied. There are 390 industrial mineral occurrences in MINFILE, the Ministry of Energy and Mines electronic database (www.em.gov.bc.ca/Mining/Geosurv/Minfile/default.htm) that are located within the administrative boundary of the region (Figure 1). These occurrences are reviewed with respect to physiography, tectonic terrane, deposit type, character and resource potential (Table 1).

Commodities of interest include sand and gravel, diatomite, limestone, clay and shale, rare earth elements, volcanic material, silica, barite, dimension stone, and jade. Glaciated areas of central British Columbia make sand and gravel (aggregate), the most abundant and economically important commodity in the region. Primary aggregate sources include terraces along the Nechako and Fraser Rivers, major meltwater channels, raised shorelines of former glacial lakes and, to a lesser extent, esker systems. Sand and gravel generally have a structural end use and are not discussed further here.

The region is serviced by a well-developed road and rail network. The city of Prince George (Figure 1) is central to the region, and is the transportation hub for the northern two-thirds of the province. Major transport routes radiate east to markets in Alberta, south through the province to markets in the Lower Mainland and the United States, and west to the port of Prince Rupert. Other routes extend northward and provide access to resource-rich areas. Most industrial mineral development is close to transportation corridors, such as highways 16 and 97, and a large number of logging arteries that span the region. Summaries of selected mineral commodities highlight the economic significance of past producers and introduce the importance of potential deposits. MINFILE reference numbers follow deposit names where applicable.

REGIONAL GEOLOGIC SETTING

The Canadian Cordillera can be divided into five,

orogen-parallel belts of either continental or oceanic affinity (Monger and Nokleberg, 1996). Three of the belts – the Foreland, Omineca and Intermontane - trend north-westerly across northeast-central British Columbia (Figure 1). The Foreland Belt is comprised of folded and thrust sedimentary rocks derived from the North American craton. The Omineca Belt is made up of complexly deformed and metamorphosed sedimentary, volcanic and granitic rocks of the pericratonic Kootenay (Barkerville and Cariboo subterranea) and Cassiar terranes, and the oceanic Slide Mountain terrane. The Intermontane Belt is an amalgamation of two major island arc assemblages, the Quesnel and Stikine terranes, that sandwich the Cache Creek terrane accretionary (or subduction) complex. The Overlap Assemblage, a package of younger sedimentary and volcanic rocks, covered all the major terranes. The wide range in depositional environments resulted in potential for diverse industrial mineral commodities, many of which are underexplored. Some industrial mineral commodities are restricted to, or concentrated in, particular terranes (Table 1). Selected industrial mineral occurrences and deposits are shown in Figure 2.

DIATOMITE

There are a number of recorded diatomite occurrences in the region (Hora and Hancock, 1995), including four past producers: Crownite (093B 023), Buck Ridge (093B 042), Quesnel (093B 059) and Big Bend (093G 039). Most are concentrated in the Quesnel area. The occurrences are mainly stratiform lacustrine deposits that formed within Tertiary volcanic and sedimentary sequences that crop out along a 40 kilometre belt that parallels the Fraser River from Big Bend (12 kilometres north of Quesnel) to Alexandria. The diatomite ranges in colour from white to grey to buff and consists mainly of *Melosira granulata* diatoms; most are very small, with variable amounts of clay, silt and volcanic ash.

Diatomite at the Crownite deposit (Hora and Hancock, 1995) 3 kilometres southwest of Quesnel occurs in beds up to 31 metres thick with interbeds of

TABLE 1. DISTRIBUTION OR SELECT INDUSTRIAL MINERAL OCCURRENCES IN NORTHEAST-CENTRAL BRITISH COLUMBIA

COMMODITY	STATUS & NUMBER OF OCCURRENCES		COMMODITY/DEPOSIT TYPE	DEPOSIT CHARACTER	TECTONIC BELT		TERRANE
Asbestos	Showing	10	Ultramafic-hosted	Vein	Intermontane	Cache Creek	8
			Sediment-hosted	Stockwork	Omineca	Barkerville Slide Mfn.	1 1
Barite	Developed Prospect Prospect Showing	3	Carbonate-hosted	Stratiform	Foreland	Ancestral NA	43
		5	Other/Unknown	Vein	43	Barkerville	2
		40	Vein	Massive	5	Cariboo	1
			Sedex Zn-Pb-Ag	Other	2	Cassiar	1
Bentonite	Showing	4	Unknown	Stratiform	Intermontane	Slide Mfn.	1
			Sandstone		Foreland	Ancestral NA	2
Building Stone	Developed Prospect	2	Marble		Foreland	Overlap Assemblage	1
		1	Granite		Omineca	Slide Mfn.	1
Dimension Stone	Prospect	2	Flagstone	Massive	Foreland	Ancestral NA	2
		2	Unknown	Stratiform	Intermontane	Cache Creek	1
Granite/Marble	Past Producer	2	Unknown	Stratiform	Intermontane	Cassiar	1
		2	Unknown	Stratiform	Unknown	Cariboo	1
Slate	Showing	2	Unknown	Stratiform	Unknown	Other	2
		1	Fireclay			Overlap Assemblage	8
Clay	Prospect	1	Fireclay			Quesnel	7
		4	Expanding Clay	Stratiform	Intermontane	Ancestral NA	4
		17	Unknown	Unknown	Foreland	Other	3
Shale	Showing	17	Unknown	Unknown	Foreland	Other	3
		4	Lacustrine			Overlap Assemblage	5
Diatomite	Past Producer	4	Volcanic Ash	Stratiform		Cache Creek	4
		6	Unknown	Stratabound	Intermontane	Stikine	1
Dolomite	Showing	1	Dolomite		Foreland		
		3	Limestone	Stratiform	Omineca	Ancestral NA	4
Fluorite	Developed Prospect	1	Carbonate-hosted	Stratabound			
		6	Barite-fluorite vein	Vein	4		
		12	Unknown	Stratiform	3		
			Unknown	Other	2	Foreland	Ancestral NA
Graphite	Showing	4	Crystalline flake	Disseminated	Omineca	Cassiar	2
			Unknown	Other	2	Intermontane	Other
Gypsum	Developed Prospect	1	Unknown	Layered	Foreland	Ancestral NA	1
		1	Bedded	Unknown	Intermontane	Quesnel	1

TABLE 1 (CONTINUED)

COMMODITY	STATUS & NUMBER OF OCCURRENCES		COMMODITY/DEPOSIT TYPE	DEPOSIT CHARACTER		TECTONIC BELT		TERRANE	
Jade/Nephrite	Past Producer	6		Podiform	3			Cache Creek	4
	Showing	1	Jade	Massive	2	Intermontane	7	Plutonic Rocks	3
Kyanite	Showing	3	Kyanite-sillimanite schists	Layered	3	Omineca	2	Ancestral NA	3
	Producer	2				Foreland	1	Ancestral NA	17
Limestone	Developed Prospect	5						Cache Creek	13
	Prospect	6		Stratiform	47	Omineca	25	Cariboo	10
	Past Producer	10		Stratabound	4	Intermontane	17	Slide Mtn.	6
	Showing	29	Limestone	Massive	1	Foreland	10	Cassiar	3
Magnetite	Showing	3	Umic-host Talc-Magnesite	Stratiform	1			Quesnel	3
	Prospect	1	Unknown	Stratabound	2	Intermontane	2	Cache Creek	2
Manganese	Showing	7	Mgmatic Oxide	Vein	1	Foreland	1	Ancestral NA	1
	Showing	1	Unknown	Massive	2	Foreland	1	Ancestral NA	1
Perlite	Showing	1	Mn/Vein Replacements	Vein	2	Intermontane	1	Quesnel	1
	Showing	1	Unknown	Layered	2	Intermontane	6	Cache Creek	5
Phosphate	Past Producer	3	Pegmatite	Concordant	3	Omineca	14	Cassiar	9
	Showing	13	Kyanite/Sillimanite schists	Massive	3	Foreland	1	Kootenay	5
Silica	Showing	6	Unknown/Other	Unknown	4	Intermontane	1	Other	2
	Showing	1	Volcanic Glass	Stratabound	1	Intermontane		Overlap Assemblage	
Sulphur	Showing	4	Gypsum-hosted	Massive	2	Foreland	4	Ancestral NA	4
	Showing	17	Upwelling-type	Stratabound	18	Foreland	18	Ancestral NA	18
Talc	Developed Prospect	2	Silica Sandstone	Stratiform	5	Foreland	4	Ancestral NA	4
	Past Producer	1	Silica Veins	Vein	4	Intermontane	4	Barkerville	3
Travertine	Showing	1	Other	Other	3	Omineca	2	Other	3
	Showing	1	Unknown	Stratiform	2	Foreland	4	Ancestral NA	4
Vermiculite	Showing	1	Umic-host Talc-Magnesite	Massive	2	Foreland	2	Other	3
	Prospect	2	Other	Vein	1	Intermontane	3	Other	3
Vermiculite	Showing	1	Unknown	Massive	2	Foreland	2	Ancestral NA	2
	Prospect	2	Vermiculite	Disseminated	2	Intermontane	2	Stikine	2

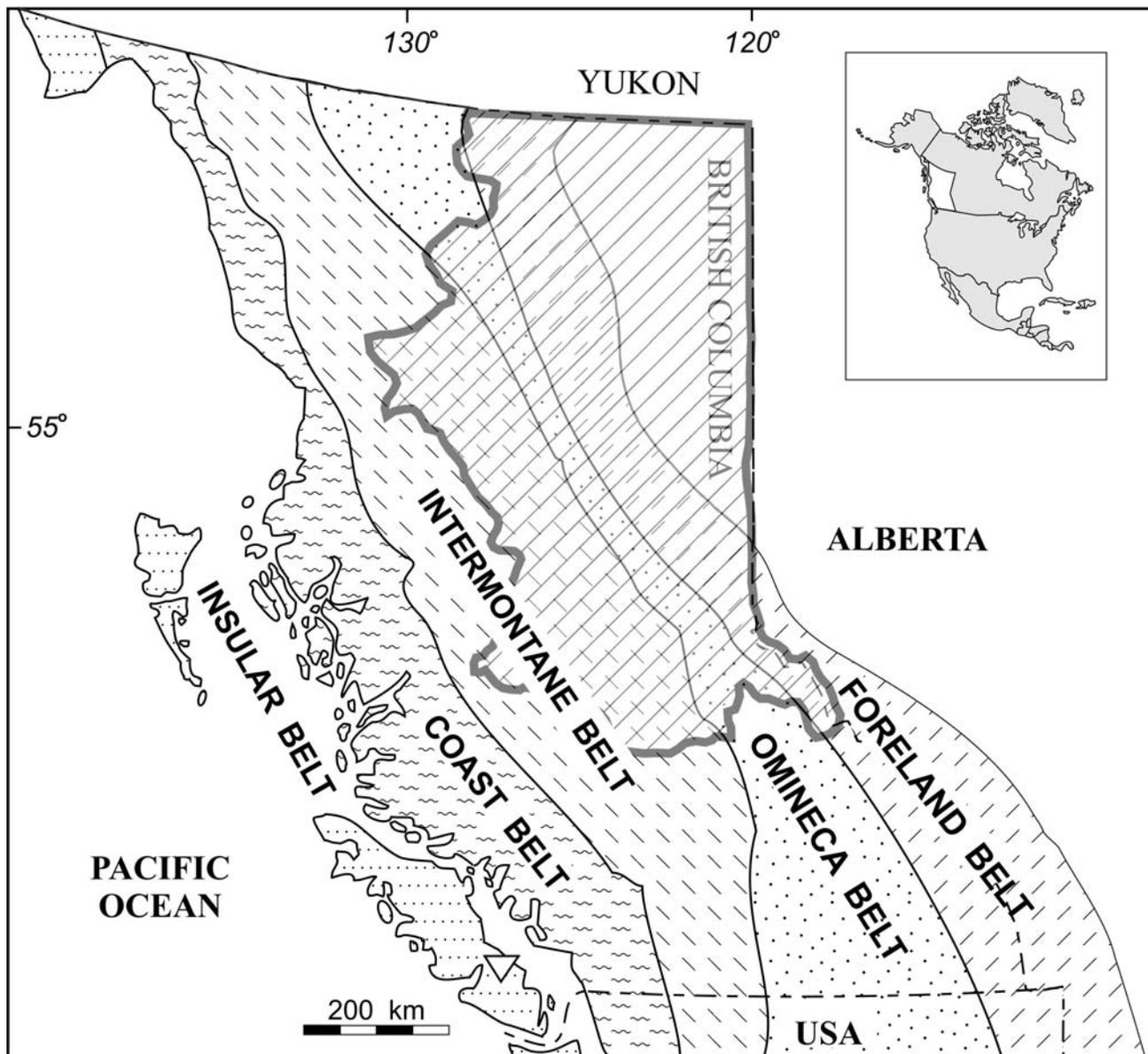


Figure 1. The tectonic belts of British Columbia. The cross-hatched area indicates the administrative region of Northeast-Central British Columbia.

clay, silt and ash. Recorded production has been 22 074 tonnes, and proven and probable reserves were estimated at a conservative 750 000 tonnes. The Buck Ridge deposit is located on the west side of the Fraser River, 27 kilometres south of Quesnel. It encompasses a number of separate diatomite showings that crop out over a distance of about 6 kilometres along the west bank of the Fraser River. At the Quesnel occurrence (Hora and Hancock, 1995), 2 kilometres north of Buck Ridge, recorded diatomite production for 1987 to 1993 totaled 15.2 tonnes. The Big Bend deposit is located along the east side of the Fraser River, 13 kilometres north of Quesnel. Three major exposures of diatomite occur close to water level at the downstream end of the big bend. Diatomite was mined in limited batches and periodically shipments made to Vancouver. A 3 to 6 metre bed of white stoneware clay underlies the

diatomite. The Upper Blackwater area of the southern Nechako Plateau is also prospective for diatomite, but few occurrences are reported. The Tsacha showing (093F 041) occurs within volcanic and intercalated sedimentary rocks of the Eocene Ootsa Lake Group. Diatomite and pumice may have accumulated and been preserved in a fault depression. Another diatomite locality of note is reported near Chilako (MINFILE 093G 034) on the Canadian National Railway.

LIMESTONE

The MINFILE database records 52 limestone occurrences, including 2 producers and 5 developed prospects, for the region. The occurrences are mainly stratiform deposits in Ancestral North American rocks,

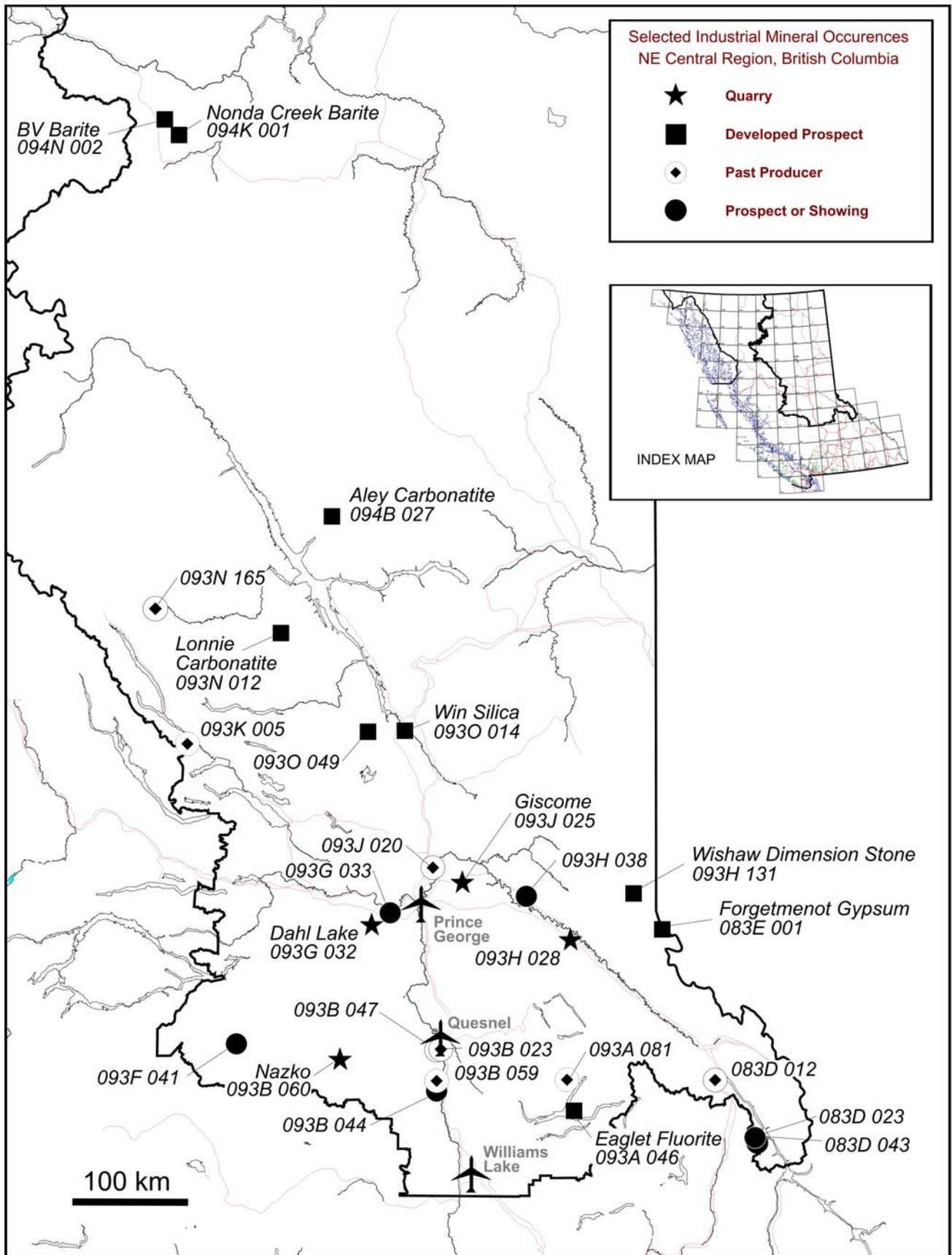


Figure 2. Selected industrial mineral occurrences in northeast-central British Columbia. Producers and developed prospects are identified by name; all others are identified by Minfile number.

and in rocks of the Cariboo and Cache Creek terranes of the Foreland, Omineca, and Intermontane Belts, respectively. The large number of deposits of various types and characteristics will make limestone a key asset in the future. Most of these occurrences are described by Fishl (1992).

The Giscome limestone quarry (093J 025) is located 90 kilometre northeast of Prince George near the BC Rail facilities. Dark grey fossiliferous limestone of the Mississippian to Triassic Slide Mountain Group, which crops out over a 100 by 200 metre area, grades 98% CaCO₃. Intermittent quarrying since 1990 produced calcium-rich limestone, primarily for Interior pulp mills.

The Dahl Lake quarry (093G 032), which lies 35 kilometres southwest of Prince George, processes Upper Permian fossiliferous limestone of the Carboniferous to Jurassic Cache Creek complex. Since 1968, about 550 000 tonnes of limestone have been extracted for local pulp mills, and recently 20 000 tonnes of decorative aggregate was extracted from waste rock.

CLAY AND SHALE

A total of 22 clay and shale occurrences are recorded in Quesnel Terrane rocks or in overlap assemblages on the Cache Creek Terrane. Most are stratiform fireclay deposits. Kaolinitic claystones were derived by weathering of crystalline feldspar-rich rocks and deposited in low-energy, freshwater basins. Kaolin clay is mainly used in the paper industry, although some is used in the ceramic and refractory industries. There are 4 reported occurrences of stratiform bentonite deposits in terranes of the Foreland Belt. The most prospective areas are within Upper Cretaceous to Eocene sedimentary basins along the Fraser River from Williams Lake to Prince George. Bentonite or montmorillonite clay forms when volcanic ash is deposited in low-energy shallow marine or lacustrine environments. Bentonite has a wide variety of applications and end uses, including foundry sands, drilling mud and absorbents (Moore, 2003; Crossley, 2003).

The Burnt Shale deposit (093B 047), near Quesnel has seen limited quarrying and is thought to have originally been a clay that was baked. The material is predominantly pale beige, hard, vitreous to porcelaneous, and is regarded as a pozzolan. In the past, it was used as natural pozzolan (Hora and Hancock, 1995) and currently it is currently being mined by Canada Pumice Corporation.

The Giscome Rapids deposit (093J 020) is located on the west bank of the Fraser River. The deposit has a variety of clay-types within a thick Tertiary bed that is

exposed for about 800 metres of strike length. Development work in the 1940s included the extraction of 18 tonnes of clay.

A showing of bentonitic clay also occurs near Bednesti (093G 033) adjacent to the Canadian National Railway facilities. The showing consists of cream to grey bentonite of unknown age that is exposed in 3 to 4 metre thick exposures along cutslopes.

RARE EARTH AND HIGH-TECH ELEMENTS

Niobium, rare-earth elements (REE) and yttrium are commonly associated with carbonatites and alkaline rocks (Pell, 1996 and Birkett and Simandl 1999; deposit models). Such rocks are found in the Foreland and Omineca Belts in northeast-central British Columbia. The presence of several notable occurrences makes the region highly prospective.

The Aley property (094B 027), located 140 kilometres north-northwest of Mackenzie, has an extensive exploration history. A Mississippian alkaline-carbonatite complex intrudes miogeoclinal rocks of the Foreland Belt. Exploration identified possible open-pit niobium-bearing zones that grade from 0.66 to 0.75% Nb (Pride, 1987).

The Mount Bisson alkaline complex is situated 64 kilometres northwest of the town of Mackenzie. Within it, light REE are enriched in allanite pegmatites and syenite dykes within the Wolverine metamorphic suite of the Omineca Belt.

A group of tantalum- and niobium-enriched carbonatites also occur in the Monashee Mountains north of Blue River. The Howard Creek (083D 023 and 043), Paradise (083D 006 and 022) and Verity (083D 005) prospects occur along sills that intrude mainly amphibolite-grade rocks of the Hadrynian Horsethief Creek Group. Fir deposits are unusual because of their high tantalum content (Simandl *et al.*, 2002; Dahrouge, 2002).

Carbonatite-syenite complexes and volatile-rich granites are also good exploration targets for many high tech metals and non-metals (Table 2). Regionally, these rocks occur along the western edge of the Foreland Belt, and east of the Rocky Mountain Trench. Specialty metals, such as gallium and germanium, are present in highly anomalous amounts in carbonate-hosted lead-zinc deposits such as Cay (094G 017) in the Robb Lake Belt.

The REE market is currently dominated by China and REE prices are depressed (O'Driscoll, 2003). The tantalum market was described by Simandl (2002) who noted that it is impossible to predict the market for rare earth elements in ten or twenty years.

TABLE 2. SELECT SPECIALTY MINERAL OCCURRENCES IN NORTHEAST-CENTRAL BRITISH COLUMBIA

MINFILE	NAME	STATUS	COMMODITY	HOST ROCK	CHARACTER	TECTONIC BELT	TERRANE
094B 027	ALEY	Developed Pros.	Nb, Pp, Rs	Carbonatite-hosted	Disseminated	Foreland	Ancestral NA
094B 028	ALEY DYKES	Showing	Rs, Ce, Nd, La, Th, Sr	Carbonatite-hosted	Disseminated	Foreland	Ancestral NA
093J 014	PRINCE	Showing	Nb, Rs, La, Ce, Pp	Carbonatite-hosted	Disseminated	Foreland	Plutonic Rocks
093N 012	LONNIE	Developed Pros.	Nb, Zr, Ti, Ur, Th, Rs	Carbonatite-hosted	Podiform	Omineca	Cassiar
093N 174	VIRGIL	Prospect	Nb, Zr, Ti, Ur, La, Nd	Carbonatite-hosted	Podiform	Omineca	Cassiar
083D 023	HOWARD CK. SYENITE	Showing	Ns, Sx, Nb, Ta, Ur	Carbonatite-hosted	Stratiform	Omineca	Kootenay
083D 043	HOWARD CK. CARBONATITE	Showing	Sr, Ph, Pp, Ta, La, Ce	Carbonatite-hosted	Stratiform	Omineca	Kootenay
094D 114	MCCONNELL BERYL	Showing	Be	REE pegmatite	Concordant	Intermontane	Quesnel
093O 021	LAURA	Showing	Th, Rs, La, Ce, Pr, Nd	REE pegmatite	Disseminated	Omineca	Ancestral NA
093N 201	WILL	Showing	Th, La, Ce, Nd, Yr, Ta	REE pegmatite	Layered	Omineca	Cassiar
093O 041	URSA	Showing	Th, Rs, La, Ce, Pr, Nd	REE pegmatite	Disseminated	Omineca	Cassiar
094M 022	LIARD HOTSPRINGS	Showing	Rd, Rn, Hs	Travertine	Unconsolidated	Foreland	Ancestral NA
094N 001	WISHING WELL	Showing	Rd, Ra, U, Rn, Hs	Travertine	Unconsolidated	Foreland	Ancestral NA
094E 038	TOR	Showing	Hf	Unknown	Disseminated	Omineca	Cassiar
083D 06E	FIR	Showing	Ta and Nb	Carbonatite-hosted	Layered	Omineca	Kootenay
083D 005	VERITY	Developed Pros.	Ta and Nb	Carbonatite-hosted	Stratiform	Omineca	Kootenay

VOLCANIC MATERIAL

Pleistocene lava, and associated tuffs and breccia overlie till in the south-central part of the region.

Canada Pumice Corporation mines tephra seasonally from the Nazko lava rock quarry (093B 060), 90 kilometres west of Quesnel. The company was recently acquired by Crystal Graphite Corporation. Each year the company produces between 15 000 and 25 000 cubic metres of scoriaceous lava for the agricultural, horticultural, landscaping and lightweight aggregate uses. Perlite and volcanic glass occurrences crop out primarily in the Nechako Plateau. This low-lying area is underlain by Eocene Ootsa Lake rhyolitic and dacitic flows, tuffs and breccias, with lesser andesites, basalts and conglomerates. Several recorded occurrences in the region (White, 2002) include: Uncha Lake (093F 026), Ootsa Lake (093F 028) and Cheslatta Lake (093F 028). All perlite now being used in British Columbia is imported from the United States, but ongoing development of resource roads may lead to discovery of new perlite deposits in the Nechako Plateau (Rotella and Simandl, 1999).

SILICA

Hardrock silica occurrences in British Columbia are divided into quartzite, vein and pegmatite deposits (Foye, 1987). Quartzite within the Lower Silurian Nonda quartzite is the best potential source in the region. This unit occurs east of the Rocky Mountain Trench in Ancestral North American rocks.

A folded sequence of sedimentary and volcanic rocks host the Longworth prospect (093H 038), located 80 kilometres east of Prince George. The quartzite is essentially correlative with the Lower Silurian equivalent to the Nonda Formation, and is fine-grained, massive and well-sorted. During 1985, a property evaluation produced 28 samples grading 98.84% to 99.80% SiO₂ (Foye, 1987).

The Win quartzite occurrence (093O 014) at Mount Chingee correlates with the Lower Cambrian Gog Group or the Upper Proterozoic Misinchinka Group. The unit contains a drill inferred resource of 4.5 million tonnes grading 98.03% SiO₂. Further to the southeast near Mount Kinney, the An quartzite prospect (093O 013) occurs in equivalent strata. Limited drilling suggests that there is potential for a large tonnage of high grade silica.

Alroy is an early stage silica prospect located 160 kilometres east of Prince George. Several prominent exposures of quartzite that are probably of the Cambrian Yanks Peak Formation crop out in the Fraser River valley immediately north of Highway 16. Most of these silica deposits are described by Foye (1987).

BARITE

Barite occurrences, including 3 developed prospects, are found principally in Ancestral North American rocks. Occurrences are mainly stratiform or stratabound within carbonate or fine-grained sediment sequences as described in the corresponding deposit model by Paradis *et al.* (1999). Barite is widely used as oil-drilling mud, and as filler for paper and cloth (Brobst, 1994).

The BV prospect (94N 002) is a large carbonate-hosted, high grade stratiform deposit in the Sentinel Range near Muncho Lake on the Alaska Highway. The region is underlain by Proterozoic to Middle Devonian sedimentary rocks of Ancestral North American affinity. The basal barite deposit is hosted in the Stone Formation. The inferred resource potential of the BV is 100 million tonnes grading 65% BaSO₄.

The Nonda Creek developed prospect (094K 001) is situated 14 kilometres east-northeast of the settlement of Muncho Lake. The upper section of the deposit, measures 120 metres long, 45 metres wide and 30 metres thick, and comprises 92% barite. It is considered as one of the British Columbia's highest-grade deposits.

DIMENSION STONE

Although only seven dimension stone occurrences are recorded in northeast-central British Columbia, the development potential is good, especially in the eastern region where quartzite and marble are abundant. Stone from several granite, marble, slate and quartzite prospects have physical characteristics comparable to material now being mined in southern British Columbia.

The Wishaw quartzite prospect (093H 131) near McGregor is underlain by 300 to 350 metres of pale grey, beige, pink and maroon quartzite beds of the Mahto Formation (Hora and Kwong, 1984). The unit displays intricate cross-bedding, banding and swirled patterns, making it a potentially desirable dimension stone.

The Dome Creek slate prospect (093H 028) straddles highway 16 and lies within the Hadrynian Yankee Belle Formation of the Cariboo Group. The slate is marketable because of its green color, good cleavage and strength properties. The near surface deposit covers an area of approximately 3 square kilometres.

Marble was briefly quarried at Maeford Lake (093A 081) located 100 kilometres east-southeast of Quesnel. The area is underlain by continental margin sediments of the Cunningham Formation of the Cariboo Group. During 1990, about 150 tonnes of the medium

grained milky white marble were extracted and sold locally as dimension stone.

The Aspen claims (093O 049), located west of Mackenzie, cover pale pink, coarse-grained granite of an Early Tertiary pluton. This is one of a number of small post-accretionary plutons that are attractive dimension stone targets in the Omineca Belt.

JADE (AND OTHER SEMI-PRECIOUS COMMODITIES)

The region has demonstrated potential for jade, semi-precious gemstones, like rhodonite, opal, jasper, agate. In addition, favourable areas for soapstone deposits exist southwest of Hixon, at the Trust prospect, and near Fort St. James in the Stuart Lake - Trembleur Lake and Fleming areas.

Jade (nephrite) deposits are hosted by metamorphosed mafic and ultramafic rocks associated with ancient volcanic arcs. 'Jade' may be jadeite or nephrite. Jadeite is a rock that consists essentially of the mineral jadeite, a sodium-rich, high-pressure pyroxene. Nephrite consists of acicular amphiboles of the tremolite-actinolite series that form bundles of randomly oriented and interlocking crystals. Although all commercial jade deposits in British Columbia are of the nephrite variety (Simandl *et al.*, 2000), jadeite may have formed in high-pressure eclogite-grade metamorphic rocks that crop out in the Pinchi Lake area (Simandl *et al.*, 2000). There are several recorded nephrite occurrences in the region, located mainly in the Mount Ogden and Mount Sidney Williams areas.

The Ogden Mountain (093N 165) occurrence is approximately 40 kilometres north-northeast of Takla Landing (Simandl *et al.*, 2000). Variably metamorphosed sedimentary and volcanic rocks of the Carboniferous to Jurassic Cache Creek Group are intruded by sill-like serpentinite bodies of Mississippian to Triassic oceanic ultramafites. Total production of nephrite up to 1992 was about 1441 tonnes; estimated reserves are 472 tonnes.

The Genesis deposit (093K 005) is located on O'Ne-ell Creek. The pre-Upper Triassic Trembleur ultramafic intrusions are of probable ophiolitic affinity and are related to the Cache Creek Group. The jade deposit occurs at the contact between serpentinite and a quartz monzonite intrusion. A total of 34.2 tonnes were mined in 1968. Present data suggests that about 2800 tonnes of nephrite jade and tremolite remain.

Common opal and agate occur in Triassic and younger volcanic sequences in the northern Chilcotin and southern Nechako Plateau areas. Precious opal is typically associated with Miocene volcanic sequences

where porous, pyroclastic or lacustrine rocks are interbedded with lava flows. For more information regarding this type of deposit, consult Paradis *et al.* (1999).

MISCELLANEOUS MINERALS

The area has a number of known industrial commodities, including asbestos, magnesite, graphite, phosphate, fluorite, gypsum, and mica.

Fluorite occurs mainly as stratabound carbonate-hosted deposits within the Ancestral North American rocks of the Foreland Belt. The Eaglet developed prospect (093A 046) is located near Quesnel Lake. There mineralization is contained in quartz-feldspar-mica gneiss of the Hadrynian-Paleozoic Snowshoe Group of the Barkerville terrane. The mineralized zone measures 1500 by 900 metres and has indicated probable reserves of 24 million tonnes grading 11.5% CaF₂ (Pell, 1992).

The Forgetmenot gypsum prospect (083E 001), near McBride, is hosted in Ancestral North American rocks. It is described by Butrenchuk (1987). Gypsum is intercalated with dolomite and minor limestone in the Upper Triassic Starlight Evaporite member of the Whitehorse Formation. The tabular gypsum body measures 100 by 500 metres and is up to 26 m thick. The deposit has a grade of 75 to 90% gypsum.

Mica (muscovite) occurrences are principally hosted in pegmatite veins cutting Cassiar or Kootenay terrane rocks. However, two former producers recovered mica from kyanite-sillimanite schists of the Upper Proterozoic Windermere Supergroup of the Cariboo terrane. For the geological setting of this type of deposit, see Simandl *et al.* (1999). The Canoe North Mica deposit near Valemount (083D 012) is on the northwestern margin of the Shuswap Metamorphic Complex. It is underlain by pelitic schists of the Hadrynian Lower Kaza Group. A total of 225 tonnes of mica product was extracted in 1960 and 1961. An estimated resource of 2.29 million tonnes grading 60.5% mica remains.

Cache Creek Group rocks host eight ultramafic-hosted asbestos and two magnesite showings. Deposit models for asbestos and magnesite describing the general setting were prepared by Hora (1998) and Simandl and Ogden (1999). Crystalline flake graphite showings are recorded from highly metamorphosed Cassiar terrane rocks. Detailed information is missing; however, these deposits are believed to belong to the deposit model provided by Simandl and Keenan (1998). Phosphate occurrences are stratabound, upwelling-type deposits in miogeoclinal rocks of the Ancestral North American terrane.

SUMMARY

Northeast-central British Columbia is host to a large number of industrial mineral occurrences with a wide range of deposit types and in varied geologic settings. The deposits with the best development potential are strategically located aggregate resources and barite deposits. Markets for these commodities exist in northeast British Columbia and Alberta, particularly in support of the expanding oil and gas sector. The main factor limiting the development of traditional low-cost industrial mineral deposits is the lack of a significant local market. Mining and marketing of scoria from the Nazko quarry is an example of a successful niche market development. Production of high-priced products such as jade, precious opal and emeralds is affected to a lesser extent by a limited market. In the future, with exploration resolve, technological advances and improvements in the area's diverse infrastructure network, more discoveries and expanded industrial mineral mining are anticipated.

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EMERALD AND OTHER GEM BERYL MINERALIZATION IN NORTHWESTERN CANADA

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INTRODUCTION

Emerald is green gem beryl ($\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$), in which colour is related to minor amounts of contained Chromium (Cr) or Vanadium (V). Emerald is the third most valuable gemstone (after diamond and ruby) and can be worth more than US\$100,000 per carat. Other gem varieties of beryl include aquamarine (blue), bixbite (red), goshenite (colourless), heliodor (yellow), morganite (pink), and roosterite (pink). Canada is not currently a producer of coloured gemstones, but this could change as a result of several exciting new discoveries in northwestern Canada. These, in turn, have prompted exploration expenditures of approximately \$3 500 000 in 2003 in the Yukon Territory alone.

LENED

In 1997, an occurrence of V-dominant emerald was discovered near the mid-Cretaceous Lened pluton in the southwestern Northwest Territories. Pale to medium green emerald crystals up to 3 centimetres in length occur where quartz veins cut a garnet-diopside skarn developed from a limestone of the Rabbitkettle Formation that overlies V-rich (2070-3170 ppm) black shales of the Earn Group. The proximity of the granite suggests that it is the source of the Be, although the Be content is low (6 to 7.3 ppm), but the source of the V is undoubtedly the shale. A fluid inclusion study (Marshall *et al.*, 2004) suggests that the emerald crystals formed at temperatures of 250 to 550°C and pressures of less than 3700 bars. Questions remain about the relative timing of the skarn formation, vein emplacement, and thrust faulting.

REGAL RIDGE

In 1998 a major occurrence of emerald was discovered at Regal Ridge in the southeastern Yukon Territory in northwestern Canada. The mineralogy, geology, and origin of the occurrence are described in Groat *et al.* (2002). The mineralization is associated with

quartz veins and aplite dikes that intrude metavolcanic rocks of the Yukon-Tanana Terrane. Green beryl crystals up to 4 centimetres in length are found in 12 mineralized zones within a 900 by 450 metres area. Cr averages 3208 ppm and is the predominant chromophore. Some of the smaller crystals, and sections of larger crystals, are gem-quality, and a number of small gems (up to about 2.4 carat) have been fashioned from the Regal Ridge samples.

The Yukon-Tanana Terrane in the Regal Ridge area is composed of mainly Devonian quartz-rich metaclastic rocks and carbonates, and Devonian and Mississippian metavolcanic and metaplutonic rocks that are inferred to have formed in continental magmatic arc (Mortensen and Jilson, 1985; Mortensen, 1992; Murphy and Piercey, 2000) and back-arc settings (Piercey *et al.*, 2000). The oldest rocks are in the Devonian to Mississippian Grass Lakes succession. The Fire Lake unit, a mafic metavolcanic unit composed mainly of chloritic phyllite (Murphy *et al.*, 2002), is the second-oldest unit within the succession. These rocks were thrust onto the North American miogeocline between late Triassic and earliest Cretaceous time. The Yukon-Tanana rocks are intruded by several ca. 112 Ma intrusions of the Cassiar-Anvil plutonic suite. The Tintina fault lies 14 kilometres southwest of the property.

The main host rock for the mineralization is a chlorite-plagioclase schist that is part of the Fire Lake unit (DF unit of Murphy *et al.*, 2002). Geochemical analyses show that the schist is a high-Ca boninite. The Cr in the emerald most likely came from the schist (average 960 ppm Cr). A leuco-gabbro unit (Dmi unit) is closely interfingering with the mafic schist. Variably-serpentinized ultramafic rocks occur in the western and northern parts of the map area. Murphy *et al.* (2002) suggest that these represent intrusive sills that fed the overlying DF rocks via gabbroic dikes (Dmi).

The occurrence is underlain at a depth of approximately 800 metres by a 112 Ma two-mica (biotite > muscovite) quartz monzonite, which outcrops to the east, south, and north. The intrusion, which is weakly foliated to unfoliated with shallowly dipping contacts, belongs to the Anvil plutonic suite (Mortensen *et al.*,

2000). This suite of 112-100 Ma felsic intrusions are typically rich in W, Mo, Au, and Bi. The proximity of the granite suggests that it is the source of the Be, although its Be content is low (12 to 13.2 ppm). Numerous aplite dikes from 40 centimetres to 10 metres in width occur on the property.

Quartz veins are abundant throughout the property, and the majority appears to be related to Cretaceous deformation. Early veins are typically thin, foliation-parallel, sulphide-rich, and tourmaline free. All the other quartz veins, including those that contain beryl and emerald, contain at least some tourmaline, either within the veins or in the vein selvages. The degree of alteration surrounding the veins varies from none to metre-wide rusty-weathering zones in the schist. This rustiness is likely due to weathering of finely disseminated sulphides (especially pyrrhotite) that are common in the alteration zones adjacent to the veins.

Emerald is associated with veins with several orientations. Mineralization appears to be particularly well developed where veins of the youngest generation intersect older, more deformed veins. Emeralds occur along the margins of quartz veins in highly-altered schist, as well as within the quartz veins themselves. The mineralizing event is interpreted to have occurred over a considerable period of time, but was mainly syn- to late-tectonic, and coincided with the waning stages of quartz monzonite intrusion. Late ductile deformation has also affected some of the emerald-bearing veins, as evidenced by the presence of healed fractures in emerald and micro-boudinage of tourmaline grains within vein quartz. At least two of the aplite dikes contain beryl or emerald, which confirms our hypothesis that there is a continuum from the quartz monzonite intrusion through aplite dikes to beryl-bearing quartz veins (Neufeld *et al.*, 2003).

RED MOUNTAIN

Crystals of V-dominant emerald were discovered in 1989 at Red Mountain, near Stewart on the central coast of British Columbia. The emerald occurs as small opaque crystals with numerous fractures in narrow quartz-calcite-pyrite veins that cut volcanoclastic rocks adjacent to a quartz-monzonite intrusion (Wilson, 1997). Electron microprobe analyses show 1612 ppm V and 1.04 wt.% FeO (average of six analyses), but no detectable Cr.

TRUE BLUE

The True Blue property, which is located in the Ketzza-Seagull District of the southern Yukon Territory, occurs within the Cassiar Platform and southwest of the Tintina Fault. Beryl was discovered on the property in 1976, and gem beryl in 2003 (Rohtert *et al.*, 2003). The crystals occur in a swarm of closely spaced quartz \pm siderite \pm fluorite \pm tourmaline veins that fill tension

gashes in a Mississippian-age (approximately 360 My) syenite stock. The veins range in thickness from 0.5 to 20 centimetres, and locally comprise up to 30% of the rock. The vein zone measures 700 by 200 metres in outcrop at the surface, and is exposed over an elevation range of 100 metres. Within this area, more than 100 individual occurrences have been discovered. The vein zone is developed near the upper contact of the syenite body with Lower Paleozoic pelitic and carbonate country rocks. The syenite is sodic in composition, with about 8 wt.% Na₂O, and contains moderately high concentrations of Be (up to 10 ppm) and F (up to 4000 ppm).

The beryl crystals range in size from a few millimetres to 5 by 2.5 centimetres, and in colour from pale to medium green, and from pale to dark blue. Some of the crystals, especially those occurring with tourmaline, show a blue core and a green rim. The dark blue material is noteworthy for its striking hue (which is maintained at very small sizes for aquamarine) and for its exceptionally strong dichroism. Electron microprobe analyses show high concentrations of Fe (to 5.81 wt.% FeO), Mg (to 3.27 wt.% MgO), and Na (to 2.51 wt.% Na₂O). The Fe content is among the highest ever reported for beryl. The colour is probably due to intervalence charge-transfer between Fe atoms, but the exact mechanism is unknown and is being studied.

OTHER BE AND BERYL OCCURRENCES IN NORTHWESTERN CANADA

A literature review of assessment reports and other published and unpublished reports shows numerous Be and beryl occurrences in southern Yukon and northern British Columbia. Analyses of a scapolite skarn with scheelite at the Myda claim (Yukon MINFILE 105G/071; www.geology.gov.yk.ca/minfile/, Deklerk, 2003), approximately 20 kilometres south of Regal Ridge, show 0.05 to 0.09 wt.% BeO, thought to be present in vesuvianite. Beryl has been reported from the Logtung W-Mo deposit (105B/039), the JC (Viola) Sn-bearing skarn claims (105B/040), and the Ice Lakes area (Groat *et al.*, 1995). All are just north of the British Columbian Yukon border. Beryl has also been reported from the following showings and prospects in northern British Columbia (listed west to east): Jennings River 104O/028, Ash Mountain (104O/021), Blue Light (104O/005), Gazoo (104O/045), Low Grade (104P/026), Haskins Mountain (104P/020), and Cassiar Beryl (Horseshoe Range, also called Wilson (Simandl *et al.* 2000) (104P/024). The numbers are British Columbia MINFILE property reference numbers. For on-line information, see <http://www.em.gov.bc.ca/mining/Geolsurv/minfile/>. Most of these prospects are associated with Cretaceous plutons, in particular the Cassiar batholith. The occurrences listed here (including Regal Ridge) define a Be-rich area approximately 265 (northwest-southeast) by 125 kilometres (northeast-southwest) that straddles the

British Columbia-Yukon border and the Tintina Fault. Legun (2004) used data from assessment and other published reports to define a “beryl belt” extending from southeastern to northwestern British Columbia. Within the “beryl belt” he proposed a “principal area of emerald potential” which approximately coincides with this area.

Beryl has also been found at the Pluto property in the offset part of the Yukon-Tanana Terrane southwest of the Tintina Fault, close to Dawson City (116B/134). Other Be/beryl occurrences in northern British Columbia and the Yukon, and western Northwest Territories include Mount Foster (104/M14?), Kalzas (105M/066), Emerald Lake (115O/009), and the Little Nahanni Pegmatite Group (NORMIN.DB 105ISE0015, 25, 50-56; see www.nwtgeoscience.ca). At Mount Foster colourless to light blue aquamarine occurs in mirolitic cavities in granitic rocks (Wilson, 1997). Wilson has cut several stones from this locality; the largest are 8.63 and 2.99 carats, and although the 8.63 carat stone has many inclusions, stones that weigh less than two carats are virtually flawless (Wilson, 1997).

The discovery of emeralds at Regal Ridge and Lened, and gem beryl at True Blue, along with numerous reports of anomalous levels of Be and/or the presence of beryl in northwestern Canada, suggest the potential for more emerald and gem beryl occurrences in the Yukon, western Northwest Territories, and northern British Columbia. This area could represent one or more distinct beryl/emerald camp(s), as has been recognized at other places in the world.

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KAOLIN AND SILICA RESOURCES IN ADVANCED ARGILLIC (ACID SULPHATE) ALTERATION ZONES, NORTHERN VANCOUVER ISLAND, BRITISH COLUMBIA, CANADA.

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Large Scale Advanced argillic (acid sulphate) alteration zones have been known for many years (Clapp, 1915) at Monteith Bay in Kyuquot Sound. More recently Panteleyev *et al.* (1993; 1994) described numerous large alteration zones on the north side of Holberg Inlet.

In 1999, Monteith Bay Resources Ltd., a wholly owned subsidiary of Lehigh Cement (formerly Tilbury Cement), put the high grade silica portion of the Monteith deposit into production as a silica source for the Cement Plant in Delta, British Columbia. In 2000, Homegold Resources Ltd. excavated a large bulk sample from the PEM100 quarry, Apple Bay Project on the north side of Holberg Inlet, which was barged to the Cement Plant in Delta. The material from the PEM100 is termed Chalky Geyselite, and a typical assay would be 83.26% SiO₂, 12.90% Al₂O₃ and 0.02% SO₃, 1% Fe₂O₃, 1.3% CaO, 0.24% MgO, 1% LOI; the trace element content is shown in table 1.

Large areas of clay-altered, and locally intensely acid leached siliceous rocks, occur in the belt of Jurassic Bonanza volcanic rocks that lie north of Holberg Inlet. The area of most intense hydrothermal alteration, including advanced argillic assemblages, is located in the region from Apple Bay westward to the headwaters of Hushamu Creek. The area is 15 to 30 kilometres west-northwest of the Island Copper Deposit. The alteration is most evident in the blanket-like rhyolitic Bonanza map units; however, it also occurs in the immediately underlying feldspar-phyric basic to intermediate volcanic rocks and, to a lesser extent, in some of the adjoining intrusive bodies of the Island Plutonic Suite. The relationship between regional stratigraphic map units and the hydrothermally altered rocks is discussed in Nixon *et al.* (1994).

Advanced argillic alteration zones are characterized by the presence of kaolinite, dickite, alunite and

pyrophyllite. Other associated minerals confirmed by X-ray diffraction analysis are abundant quartz; diaspore [AlO(OH)]; zunyite [Al₁₃Si₅(OH,F)₁₈Cl]; various micas, including sericite, muscovite and illite; lesser smectite; paragonite; gypsum; anhydrite; natroalunite; sulphur; rutile; and minor topaz, meta-halloysite, arenian alunite (schlossmacherite) and tridymite (Panteleyev and Koyanagi, 1993).

All clay-rich hydrothermal alteration assemblages contain silica. Most of the quartz is residual but some silica has been added. Main alteration assemblages are: quartz+kaolinite; quartz+dickite±pyrophyllite and/or kaolinite, all with or without alunite, diaspore, zunyite and minor mica; and quartz+alunite±kaolinite. The alumina content of blanket-like PEM100 deposit varies substantially. This content varies from less than 4% to more than 25% Al₂O₃. Zones with greater than 10% Al₂O₃ are relatively soft and non-abrasive.

Strongly altered rocks are bleached and chalky looking. Relict clay-altered plagioclase at Monteith Bay suggests that the PEM100 deposit was derived from tuffaceous basaltic to andesitic protoliths. Alteration in both feldspar-phyric and rhyolitic rocks is more intense than a tuffaceous basaltic to andesitic protolith and creates a mottled rock with grey-buff-pink clay patches in a grey, fine-grained to microcrystalline siliceous groundmass. The mottling consists of uneven, but generally equant, clay patches that range in size from a few millimetres to a few centimetres in diameter. In thin section, they consist of aggregates of fine-grained clay minerals, dominantly kaolinite. In some outcrops, the rocks consist, in large part, of quartz stockworks, veins and patches of pervasive silica replacement. The most intensely leached rocks are vuggy and consist almost entirely of quartz (>98%). Similar vuggy silica characterizes the siliceous residuum of intensely acid-

TABLE 1. TRACE ELEMENT CONTENT OF CHALKY GEYSERITE

Mo	Na%	Ni	P	Pb	S%	Sb	Sc	Sr	Ti%	Tl	U	V	W
2	<0.0 1	1	110	24	0.02	<2	<1	33	<0.01	<10	<10	3	<10
Zn	Ag	As	B	Ba	Be	Bi	Cd	Co	Cr	Cu	Ga	Hg	Mn
<2	0.2	6	<10	60	<0.5	<2	<0.5	<1	12	12	<10	<1	<5

*ppm except where indicated

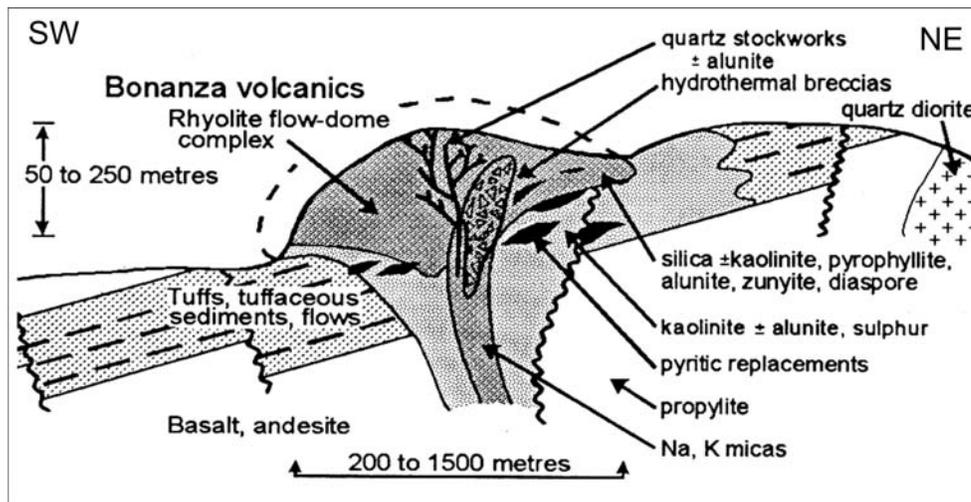


Figure 1. Schematic relationships between permeable lithologies, volcanic structures, hydrothermal conduits and mineralization in the Pemberton Hills area (Panteleyev and Koyanagi, 1993).

leached rocks in high sulphidation epithermal systems. These highly porous rocks (10 to 30% voids) consist of fine, granular, interlocking, crystalline quartz grains.

There are 9 other major zones of advanced argillic alteration within the Apple Bay Project area. Further diamond drilling and mine planning are scheduled for 2001. The PEM100 Quarry is in the final stages of mine permitting. A Memorandum of Understanding has been signed with the Quatsino First Nation.

Panteleyev and Koyanagi (1993) presented a diagram showing the schematic relationships between permeable lithologies, volcanic structures, hydrothermal conduits and mineralization in the Pemberton Hills area (Figure 1). Tuffaceous rocks in this geological setting are often deposited in a graben or similar fault-bounded basin, a caldera or series of nested calderas along the trend of the andesitic volcanic arc. In Pemberton Hills, the rhyolite assemblage that overlaps the structurally bounded, tuff-inundated basins comprises several thick flow-dome complexes with flanking welded and coarse pyroclastic deposits. Within this structural setting, the inherently high permeability of coarse subaerial pyroclastic and volcanoclastic rocks provides the most important control on movement of hydrothermal fluids and on alteration.

High and low-angle faults, the extensive systems of fractures and hydrothermally brecciated and porous leached rocks acted as effective fluid conduits.

For more information, a detail report is posted at <http://www.HomegoldResources.com>.

ACKNOWLEDGEMENTS

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INDUSTRIAL MINERAL OPPORTUNITIES IN MANITOBA, 2001

By James Bamburak and Rick Halas, Manitoba Energy, Science and Technology, Winnipeg, Manitoba, Canada

Opportunities for future industrial mineral production in Manitoba exist both from new deposits and by reactivating former mines. In many cases, both primary production and value-added production would be possible.

NEW DEPOSITS WITH PRIMARY PRODUCTION POTENTIAL

Chromite

Chromite is present in the Bird River sill, 25 km east of Lac du Bonnet, in southeast Manitoba. Gossan Resources Limited holds claims over a deposit, drilled in 1942, that contains 5 million tonnes of 7% Cr₂O₃. The deposit has an average width of 12.8 metres, is 900 metres long, and has been defined to a depth of 100 metres. Metallurgy tests indicate gravity methods can upgrade the chromite to 27% Cr₂O₃ (Gossan Resources Limited, Annual Report, 1998).

Ilmenite, Magnetite and Vanadium Pentoxide

At Pipestone Lake, Gossan Resources Limited (50%) and Cross Lake Mineral Exploration Inc. (50%) have outlined by drilling 243 million tonnes of mineralization containing 9.28% ilmenite, 23.6% magnetite and 0.28% vanadium pentoxide. The deposit has been defined to a depth of 300 metres, and is open along strike. The main, central and disseminated zones comprise the 730 million tonne deposit. It averages 70.74 metres (true width), and is 6325 m in length (Gossan Resources Limited, Annual Report, 1998).

Kaolin and Whiteware

Dawson Resources Limited is investigating kaolin from the Cretaceous Swan River Formation in the Sylvan area, north of Arborg. In 1992, the Minerals Research Laboratory (M.R.L.) of North Carolina State University conducted bench scale tests on a 90.7 kg bulk sample of the kaolinitic clay. The studies indicated that the Arborg deposit could yield approximately 23 tonnes of premium grade kaolin and 60 tonnes of container glass sand for

each 100 tonnes of raw ore mined (Schlesinger and Tanner, 1993).

The studies also showed that, with a slight reduction in heavy mineral content, the clay could be used as sanitaryware, electrical porcelain and fine dinnerware body (Schlesinger and Tanner, 1993). A whiteware market study prepared for the Department in 1996 indicated that an opportunity for growth and expansion of the Canadian Ceramic Industry existed in Manitoba. Electrical insulators, sanitaryware, stoneware and bone china were recommended products (Khan and Triple S Community Futures Development Corporation, 1996).

Marble dimension stone

Manitoba Marble Inc. has quarried Ordovician Red River Formation dolostone blocks from the Ordovician Red River Formation, 30 km south of Snow Lake for test marketing. The trade considers the stone to be "marble" and calls it "Prairie Rose Marble". In 1995, Granitic Contacts Ltd. completed a preliminary site evaluation and market analysis study for Manitoba Marble Inc. and Greenstone Community Futures to evaluate the dimension stone potential.

Potash

Potash deposits are contained within the Devonian Prairie Evaporite, and two such deposits are located south of Russell, along the Saskatchewan border. The potash deposits contain a mixture of sylvite and halite, with minor carnallite and less than 1% green clay; they are among the "cleanest" in western Canada (Bannatyne, 1971). In 1987, a comprehensive feasibility study of the Manitoba Potash Project concluded that probable mineable resources at a depth of 852 metres are 164.7 million tonnes grading 24.5% K₂O (as sylvite) (Canamax Resources Inc., Annual Report, 1988). South of the Manitoba Potash Project, Prairie Potash Mines Limited drilled 15 test holes between August 1964 and March 1966. Potentially mineable resources were estimated at 168.7 million tonnes averaging 21.7% K₂O (as sylvite) over an average thickness of 2.2 metres (Augustus Mines Limited, Annual Report, 1966). The company's leases lapsed in 1977 and the ground is currently open.

Quartz

Seller's Mountain is located in the Precambrian Shield, about 2 kilometres south of Long Lake and 150 kilometres northeast of Winnipeg in southeastern Manitoba. Robert Sellers holds mining claims and a quarry lease over the occurrence. The high purity quartz core of the main zone has a length of about 310 metres, a minimum width of 20 metres, and an observed thickness of 20 metres at its south end. A composite surface sample from the southern part of the main zone contained 98.9% SiO₂. A resource of 320 000 tonnes of high purity quartz can be inferred, if the core thickness remains at 20 metres along its length. The ultimate resource potential for this high purity quartz deposit will depend upon its geometry at depth. A second major zone containing a central vein of white, massive 'bull' quartz was found 500 metres east of the main zone, across a swamp. This zone has a length greater than 300 metres and a width of 10 to 15 metres. Unlike the main zone, the zone is orientated parallel to bedding. A spot sample contained 98.4% SiO₂ (Bamburak and McRitchie, 1994).

Silica sand

Gossan Resources Limited has mineral dispositions over a silica sand occurrence near Manigotagan. This occurrence is 15 metres (49.5 feet) thick and contains a potential resource of 45 million tonnes of silica sand. The sand is either exposed at surface or occurs beneath thin overburden. Potential uses of the silica sand are production of ferrosilicon and float glass (Gossan Resources Limited, Annual Report, 1999). W.D. Fogwill holds additional leases in the area (in partnership with H. Westdal and Associates).

Spodumene

Strider Resources Ltd. located a spodumene dyke near Wekusko Lake in Central Manitoba. A three hole drill program, in 1997, by Carta Resources Ltd. increased the drill indicated and possible resource of the deposit to 4 305 000 tonnes grading 1.30% Li₂O, over a weighted average true width of 9.99 m. An open pit could be developed on the deposit. Metallurgical studies demonstrated that a simple floatation method would produce a high-purity spodumene concentrate (Carta Resources Ltd., News Release, April 3, 1998).

Rare earths

Strider Resources Limited has identified heavy and light rare earths at Eden Lake, near Lynn Lake. A 1 kilometre long lineament contains very anomalous

amounts of yttrium, cerium, neodymium, lanthanum, dysprosium, erbium, ytterbium and lutetium. In addition, late stage pegmatite sweats and stringers contain fluorine, apatite and britholite. Mill tests on a stringer of britholite ore from a location near the north end of the lineament proved that the concentrate could be upgraded to potentially economic concentrations.

VALUE-ADDED PRODUCTION

Ferrosilicon

In 1999, Gossan Resources Limited and May Engineering Inc. of Saginaw, Michigan, announced a plan to convert the existing C\$30 million East Selkirk Smelting plant of Gossan's subsidiary, Gossan Chrome Corp., into a ferrosilicon producer (Gossan Resources Limited, Press Release August 26, 1999). No action has been taken since that time.

Float plate glass

A float-plate glass marketing study, conducted for the Manitoba Government, investigated raw material resources, such as silica sand, and conducted feasibility studies (International Technologies Consultants, Inc., 1996).

Lithium carbonate

Carta Resources Ltd. studied the feasibility of building an on-site lithium carbonate plant near Wekusko Lake. The company planned to conduct a market study to determine North American requirements for the glass, chemical, pharmaceutical industries and battery industry (Carta Resources Ltd., News Release, April 3, 1998). No action has been taken since that time.

Steel-making and paint and paper coater and filler

Gossan Resources Limited (50%) and Cross Lake Mineral Exploration Inc. (50%) carried out the necessary mineralogical, milling and furnace work to determine the economic viability of separating titanium-bearing minerals from Pipestone Lake deposit. One potential product would be titanium dioxide for the paint and paper industries; another would be magnetite and vanadium pentoxide for steel making (Gossan Resources Limited, Annual Report, 1999).

In 1992, the Minerals Research Laboratory (M.R.L.) of North Carolina State University conducted bench scale tests on a 90.7 kilogram bulk sample of kaolinitic clay from the Arborg Occurrence. The studies indicated that, with a slight reduction in heavy mineral content, the clay could be used as paper and paint filler (Schlesinger and Tanner, 1993).

Magnesium metal

Gossan Resources Limited sampled dolomite from its property near Inwood. From pilot-scale tests on the sample, Hazen Research Inc. of Golden Colorado produced a billet of commercial grade magnesium metal (99.2% Mg) using the Magnetherm process. Hazen reported that 94.6% of the magnesium could be recovered from the dolomite. Subsequently, Ballain Consulting of Colville, Washington confirmed the suitability of the dolomite for magnesium metal processing (Gossan Resources Limited, Annual Report, 1998).

Sodium silicate

In 1995, Natural Resources Canada, CANMET, under the Canada/Manitoba Partnership Agreement on Mineral Development, commissioned a study on the production of sodium silicate from silica sand. Ash Associates of Toronto, Ontario, developed the test program. Work was carried out in Ontario by I.M.D. Laboratories Ltd. and ORTECH Corporation. Results of testwork on two silica sand samples from the Winnipeg and Swan River formations indicate that solid and liquid glass that meet the industry standards for the oxides of iron, calcium, magnesium, titanium and aluminum could be produced (Ash Associates, 1996).

Sulphur

Contaminated sulphur (35 000 tonnes per year) is recovered from the two-stage zinc pressure leach facility of Hudson Bay Mining and Smelting Co., Limited in Flin Flon. The sulphur, which is presently waste, is contained in Precambrian sulphide ores that are processed to recover copper and zinc.

REACTIVATED MINES WITH PRIMARY PRODUCTION OPPORTUNITIES

Brick clay

Jurassic, Cretaceous, Pleistocene and Holocene clays have been utilized in brick making at more than 40 brick

plants in the Province since 1871. Most potential sites for future production are available for leasing.

Brines

Salt and other products from saline brines were produced from springs near Winnipegosis and Dawson Bay, and from wells at Neepawa and Brandon. Rock salt in the Devonian Prairie Evaporite, which is almost 100 metres thick and of relatively high purity, is present at depth from Roblin to Virden and to the southwest corner of the province. The depth of the salt interval increases from 762 to 1676 metres from north to south (Bannatyne, 1971). The salt is intimately associated with potash deposits.

High-purity dolomite

Drilling near Inwood, by the Manitoba Government indicated that a geological resource of 67 million tonnes of dolomite averaging 21.6% MgO with less than 0.23% residue is present within the Silurian Fisher Branch Formation (Bamburak and Gale, 1993). Gossan Resources Ltd. acquired the rights to the deposit. Additional resources of similar high-purity dolomite are indicated in the central Interlake area of the Province.

Natural cement

Cement production in the province began with natural cement produced from 1898 to 1904 from the Cretaceous Niobrara Formation at Arnold (Deerwood) on the east slope of Pembina Mountain. This operation was followed by a second plant at Babcock from 1907 to 1924. However, Gunter (1989) reported that the characteristics of the natural cement material were too variable to compete with Portland cement. Although numerous exposures of the natural cement rock occur in the southern part of the Province along the Manitoba Escarpment, there is no present production.

Non-swelling calcium bentonite

From 1939 to 1990, Pembina Mountain Clays Incorporated quarried the only non-swelling calcium bentonite in Canada. The company produced the clay from 21 sites in the Morden-Miami area. The bentonite was processed at plants in Morden and Winnipeg. With a reasonable amount of exploration activity, it is likely that new quarry sites could be identified on Crown and privately held mineral lands.

REACTIVATED MINES WITH VALUE-ADDED PRODUCTION

Bleaching agent and kitty litter

Pembina Mountain Clays Incorporated produced natural and acid-activated non-swelling calcium bentonite at plants in Morden and Winnipeg, from 1939 to 1990. Twelve grades of bentonite were sold in dry powder form primarily to vegetable oil refineries in Alberta and Ontario, where it was used as a bleaching agent to decolourize the oils. It was also used to refine waste mineral oil and tallow soaps. A small amount of kitty litter was also produced for local consumption. Currently, all natural and acid-activated non-swelling calcium bentonite used in Manitoba is imported from the southern United States.

Caustic soda and soda ash

Hooker Chemicals Canada Ltd., and predecessor Dryden Chemicals Ltd., produced caustic soda, soda ash and salt from 1968 to 1978. The caustic soda-chlorine plant, located 6 kilometres east of Brandon, was supplied from two wells that produced salt brines. The brines originated in the Winnipeg and Winnipegosis Formations, at depths of 1050.6 and 698.0 metres, respectively (Bannatyne, 1971). Production was halted due both to environmental concerns and competition from Saskatchewan (Gunter, 1989).

Container glass

The first glass container factory in Western Canada was built southeast of Beausejour by the Manitoba Glass Company in 1906. The factory drew on impure Pleistocene glacial sand from a pit located north of the plant. At its peak it employed 350 workers to produce bottles for breweries and soft drink companies in Winnipeg and Western Canada. In 1914, the operations were shut down and moved to Redcliff, Alberta, where the company was offered free land and natural gas. Now all new glass bottles are imported into the Province.

Dolime

From 1880 to 1965 the Winnipeg Supply and Fuel Company, Limited produced dolomitic lime at Stonewall from local quarries in the Ordovician Stonewall Formation, and production continued until 1967 from the Lillies Farm (Gillies) quarry in the Gunton Member of the Stony Mountain Formation. Silurian dolomite, quarried at

Hilbre, was calcined at the Faulkner plant of Continental Lime. Silurian dolomite, quarried at Inwood by Building Products and Concrete Supply Limited, was calcined adjacent to the quarry to produce dolomitic lime. The operation closed in 1967 (Bannatyne, 1971). No dolime is currently produced in the Province.

Lightweight aggregate

Kildonan Concrete Products Limited made concrete block and redi-mix concrete from clinker. Pleistocene lacustrine clay, deposited in glacial Lake Agassiz, was extracted from 1955 to 1997, next to Kildonan's plant in St. Boniface. Echo-Lite Aggregate Ltd. began production of lightweight aggregate in 1961. Presently all lightweight aggregate is imported into the Province.

Portland cement

Portland Cement production began in Manitoba in 1913 at Fort Whyte, in south Winnipeg. Lafarge Canada Inc. produced Portland cement from calcined high-calcium limestone from its Steep Rock and Lily Bay quarries at its Fort Whyte plant until 1987, and employed 85 to 100 people (Shetty, 1994). Inland Cement Ltd. produced Portland cement at its Tuxedo plant, in south Winnipeg, from 1965 to 1992. Output of the Steep Rock quarry was also sold to Inland Cement Ltd. for its Winnipeg cement plant from 1965 to 1992. In response to poor demand for cement (equivalent to only 85 days of production during 1993), Inland's plant was shut down and hundreds of jobs lost. This decreased demand was due to the effects of recession in the construction industry. Operations were consolidated in Edmonton (Shetty, 1994) and all cement used in the Province is transported across Saskatchewan to Winnipeg for distribution.

Salt

Monkman's salt works, north of the town of Winnipegosis, produced a small amount of salt from evaporation of brine from springs in 1818 and 1874. The salt was used locally for preserving meat and fish. Similarly, in 1941, a small amount of salt was produced by the Northern Salt Company, Limited from a brine spring near Dawson Bay on Lake Winnipegosis. The Canadian Salt Company produced salt at Neepawa using the vacuum pan evaporating process on brine starting in 1932. The brine was recovered in two wells from depths of 548 and 455 metres, respectively (Bannatyne, 1971). Annual salt production ranged from 18 100 to 22 700 tonnes. The plant became uneconomic and closed in 1970 when cheaper salt could be obtained as a by-product from

solution mining of potash in Saskatchewan (Gunter, 1989).

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INDUSTRIAL MINERALS IN WASHINGTON STATE

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Washington is endowed with a diverse suite of industrial minerals, an excellent transportation infrastructure (including the Columbia River), deep water ports at Seattle and Tacoma, and a state history in which natural resource production has figured prominently. Abundant reserves support the current production of aggregates, dolomite, limestone, diatomite, silica, olivine, ball and refractory clay, decorative stone, peat, dimension stone, pumice, gypsite, and crystals. However, limestone and several other industrial minerals are now produced at levels below historic highs because of material imported from alternative sources in Canada, Mexico and around the Pacific Rim. Vast reserves of magnesite exist, and smaller commercial deposits of barite, feldspar, refractory clays, talc, pigments, and saline compounds have produced in Washington State in the past; these are presently inactive.

The value of annual mineral production in Washington since the mid-1980's has been in the five to six hundred million dollar range. For many years gold and magnesium metal from dolomite (which was produced by Northwest Alloys) were the major contributors to the total value. Today, aggregate production contributes an ever increasing proportion to the total value. This trend will continue if projections that the current population of 5.6 million Washington residents will nearly double by 2045. The most recent federal statistics estimate that the value of mineral production for 1998 was \$US609.5 million. Aggregate production accounted for one-half of this, one-quarter came from production of metallic minerals, including magnesium metal production from dolomite, and the rest was from all other industrial mineral production.

Washington is growing and expanding, so demand for the indigenous products sand and gravel, rock, and decorative stone is also expanding. Unfortunately, urbanization related to that growth has resulted in paving over of some of the best round-rock resources in the state. Legislation, such as the Growth Management Act, has

required the designation of mineral resource lands of long-term economic significance. This statute was intended to insure a supply for the next two decades, but despite these better planning measures, local opposition frequently has prevented mining. In many cases, permitting of essential new aggregate resources has required several years lead-time or has been impossible. Barging of aggregates has great potential but the infrastructure needed to transport sand and gravel from tidewater to areas throughout the Interstate 5 growth corridor is currently inadequate. Consolidation of aggregate producers has been a significant trend throughout the state in the past few years; companies have become fewer and larger and many are under European ownership.

Several value-added industrial mineral products, including ground calcium carbonate for paper coating and some refractory products, continue to flourish. Exploration drilling is currently underway on the Idaho side of the eastern Washington kaolin/halloysite "clay belt". Virtually all industrial production capacity is being seriously impacted by the current electricity shortage, which has been a windfall to some and a crisis to other industries. This energy shortage comes at a time when there is a serious debate over the impacts of hydroelectric dams on anadromous salmonids. As salmon runs diminish, and new listings of endangered species emerge, creative solutions will be needed to address these and other complex issues to insure that viable extractive industries are maintained in Washington State. A new licensing program for geologists came into effect July 1, 2001. These Earth Scientists and other workers must continue to address all potentially negative environmental impacts related to exploitation of public resources.

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A REVIEW OF RECLAMATION LAW AND THE PERMITTING PROCESS FOR SURFACE MINING IN COLORADO

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ABSTRACT

The rapid urban growth and sparse ground waters of the semi-arid Colorado landscape, combined with development traditions and a historic mining past, led to a unique legal structure for the process of citizen involvement in mine permitting. The gravel industry prodded the Colorado legislature to deal with the loss of aggregate resources due to expanding suburban neighborhoods during the 1960s and early 1970s. Although the State enacted regulations affecting surface mining, including the Colorado Mined Land Reclamation Act (1973 as amended) and the Colorado Land Reclamation Act for the Extraction of Construction Materials (1995), it is the local governments that have the most land use powers. Multiple levels of government, a lack of binding master plans and penalties, and a conflict between the desire to both have a robust economy and restrict urban growth, led to disjointed planning policies (including those for resource conservation).

The population of Colorado is expected to nearly double to 6.4 million residents by the year 2025. Most of that growth will be in the Denver metropolitan area. Transportation issues that include the largest highway and light-rail construction project in state history cannot be resolved without mining. The aim of this report is to provide industry, land planners, and citizens an analysis of Colorado statutes; and to update the works of Flynn (1991), Schwochow (1980), and Imhoff (1976) that relate Colorado legislation and the mineral resource industry.

Attention is focused on four selected counties—Boulder, Clear Creek, Jefferson, and Weld (Figure 1). Boulder is known as an area with strict growth control and a reputation for environmental activism. Clear Creek County, on the Colorado Front Range west of Denver, is in stark contrast; it has a number of abandoned and operating mine operations (precious metals and aggregate). Jefferson County has many municipalities located within the Denver metropolitan area, and is faced with aggregate shortages alongside demands for increased housing. Major potential aggregate resources and land for future suburban growth appear to be in Adams and Weld Counties, an agricultural region that may soon follow the past development pattern of Jefferson County.

INTRODUCTION

This report compares the State of Colorado surface mined land rules and regulations with select county policies and zoning. It limits its scope to construction materials as defined by the Colorado Land Reclamation Act for the Extraction of Construction Materials—meaning rock, clay, silt, sand, gravel, limestone, dimension stone, marble or shale extracted for use in the production of non-metallic construction products (Section 34-32.5-101, et seq., C.R.S. 1984, as amended). Interested individuals should contact the appropriate state and county departments for further information or changes regarding these laws and rules.

A 1961 survey of sand and gravel resources available to metropolitan Denver reported that about four times as much aggregate had been lost to urban expansion than had been consumed in construction (Inter-County Regional Planning Commission). In 1967, Sheridan illustrated historic land conflicts between the aggregate industry and the expanding Denver urban area. He correctly forecast the future dependence of Denver upon other county resources and the need to move northward

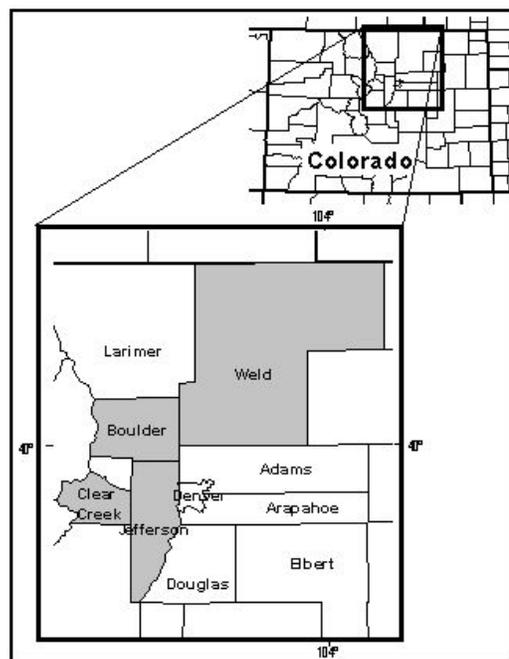


Figure 1. Map of Colorado highlighting the four counties selected for this report.

to mine deposits containing lower quality sand and gravel. The State-directed County planning commissions (with populations of at least 65 000) in Colorado prepared resource conservation plans in the 1970s. Unfortunately, some considered the mineral resource policy developed to avoid sterilization of deposits due to urban encroachment on commercial mineral deposits. Stearn (1979) and Schwochow (1980) noted problems caused by lack of State funding, personnel shortages in cities and counties, and the lack of penalties for noncompliance. Schwochow suggested the bill “. . . failed to preserve what was left of the high-quality gravels due to local governments’ noncompliance and delays in adopting the required master plans” (1980, page 29). At that time, the city of Denver supplied nearly 90 percent of the area’s sand and gravel requirements. By 1955, the city’s support had dropped to zero. Nearly forty years later, the aggregate industries continue to set record production for the Denver metropolitan area and seek to recover high-quality reserves before they are covered by rapid suburban development. Weld and Morgan Counties have major sources of aggregate and industry operators are striving to lease agricultural land and gain mineral rights. Remote rock quarries in the mountains, and pits along St. Vrain and Boulder Creeks may also provide future material.

THE STATE OF COLORADO PERMITTING PROCESS

The State of Colorado (and thus applicants for mining operations) is subject to applicable federal laws, including the National Environmental Policy Act of 1963, and the Clean Water, Clean Air, Endangered Species, and National Historic Preservation Acts. In 1973, the Colorado Legislature passed House Bill 1529 (Section 34-1-304, C.R.S. 1973) and the Colorado Mined Land Reclamation Act (Section 34-32-101 *et seq.*, C.R.S. 1973 as amended). The Colorado legislature wanted to identify aggregate resources, require mining permits, and establish guidelines for the reclamation of surface-mined lands. Copies of specific laws and regulations are located among the “Colorado Revised Statutes” at certain libraries, or are available for a small fee from the Division of Minerals and Geology (Department of Natural Resources, 1313 Sherman Street, Denver, Colorado 80203).

All mining and reclamation in Colorado is under the direction of the Colorado Mined Land Reclamation Board (or The Board). The Board is appointed by the Governor and composed of representatives from the mining industry and conservation or agricultural groups. The Board oversees operation of the Mined Land Reclamation Division (with responsibility for mine permitting) within the Colorado Department of Natural Resources. The Minerals Program at the Colorado Division of Minerals and Geology (CDMG) is funded largely through permit and annual fees paid by the operators—the Program gets very little General Fund money (State tax dollars). The

Program is also supported by State Severance Tax money (also paid by the industry) (Pineda, CDMG, 2001, written communication). The State requires a permit fee, reclamation plan, and financial or performance warranties. If the operator is a state or county government, only a performance warranty is required. The financial warranties are set high enough for a “worst case scenario”, ensuring that reclamation work can be completed. Thus, funds to reclaim the largest number of acres disturbed in one year of the mining plan need to be posted.

All mine operators must obtain a state permit for extraction of minerals (including sand and gravel, stone, precious metals, oil shale) and disturbance of soils. Sites do not require a reclamation permit in cases where material is not sold or hauled off-site, material moved constitutes a foundation excavation with an approved building permit, or water or road tunnel development is involved. Three types of permits are required, depending on the size of operation and type of material removed per year. For construction materials they are: (1) Limited Impact 110 Operations, (2) Special 111 Operations, and (3) Regular 112 Operation (Table 1). Hard rock operations cannot apply for a Special 111 Operation and as a general rule, the larger the operation, the tougher the regulation and the higher the concern with impact. The application is approved or denied within thirty days of filing, except in complex cases where the review period may be extended by an additional sixty days. There are financial civil penalties for mine operators who fail to obtain a permit. In addition, the Regular 112 permit requires photographs of the area’s condition prior to mining to be filed. All operators must submit an annual report and fee to the CDMG. The annual report must describe, in general terms, the mining and reclamation activities conducted over the preceding year (Pineda, 2001, written communication)

According to Pineda, the CDMG encourages public participation during the permitting process. Pineda notes that comments from the public may result in permits that incorporate stipulations that address citizen or public concerns. Colorado law also provides for public comment during bond release and for citizen complaints. The CDMG is currently reviewing the rules and regulations in regards to some of the hearing processes and should be consulted for any updates.

Historically, Colorado water rights have been distinct from ownership of land due to the high demands for water for agriculture and mining in this arid region. Thus, water rights are purchased separately. In 1989, the Colorado Legislature passed Senate Bill 120 that requires any gravel pit that exposes groundwater to the atmosphere after December 31, 1980, to replace all out-of-priority depletions of groundwater. Guidelines for substitute water supply plans are submitted to the Office of the State Engineer. A requirement for plans and fees are added if the gravel pit operation exposes groundwater in an over-appropriated stream system.

TABLE 1. THREE TYPES OF PERMITS FOR CONSTRUCTION MATERIAL MINING BY THE STATE OF COLORADO. (BASED ON INFORMATION FROM THE STATE OF COLORADO, 1993, 1995.)

Permit Type	LIMITED IMPACT 110	SPECIAL 111	REGULAR 112
Plan of Operation		Sole purpose of obtaining materials for highway or related construction under federal, state, or municipal/county control. Short time.	
Size	Less than 10 acres.	Less than 30 acres.	Affects 10 acres or more.
Public Notice	Post sign at site. Notice to County Commissioners, Soil Conservation District. One notice in local paper.	Post sign at site. Notice to County Commissioners, Soil Conservation District.	Post sign at site. Notice to County Commissioners, Soil Conservation District, City Manager, County Planning Dept. Newspaper notice published once/wk for 4 weeks.
Public Comment	Written comments due within 10 days of newspaper notice.	Written comments received within 5 working days of filing.	Written comments due 20 days after last date of publication. May attend Informal Conference in person. Written comments raised orally at the Conference submitted within 5 working days.

LOCAL LAW AND CONTROL

The permitting and regulation of non-coal mining operations varies greatly from city to county according to hundreds of zoning and land use regulations. After World War I, population growth, suburban development, and political self-determination played a role in increasing county government and services. Despite this, a number of steps are the same throughout Colorado that impact the grassroots level. A reclamation plan and permit (with exceptions already noted) are required for the life of the mine. Applicants in Colorado must notify the local county government, local municipalities within two miles, and all landowners within two hundred feet of the mine's affected land. The State also publishes notice of the operation in a local newspaper once a week for 2 weeks prior to an application hearing. Section 34-32.5-109(3), C.R.S. makes a mining operator responsible for assuring that the mining operation and post-mining land use comply with any master plan for extraction and local land use regulations. Some counties (for example Clear Creek) require only that the operation pass local zoning ordinances: they leave mining regulation to the state.

Table 2 is a comparison of non-coal surface mining issues and how they are dealt with at the State and local government level. This table is based on analysis of Colorado State statutes (1993, 1995); planning and zoning responsibilities of Boulder (2000), Jefferson (2001), and Weld (2000) Counties; and the Interstate Mining Compact

Commission, 1997. The issues raised are not in order of importance and many policies include standards to minimize negative impacts. For example, the federal government has established air pollution standards, whereas county preventative measures for fugitive dust may include wetting down, detouring, paving, speed control, disturbing less soil, and revegetation. Some of the language used by both the State and counties tends to be generic, enabling interpretation of what is appropriate usage for a particular site.

BOULDER COUNTY

Boulder County has a population of 258 234 in an area of 742 square miles (National Association of Counties—NAC, 2001) of prairie, forest, and tundra. Although the public perceives Boulder as the only Colorado community to effectively control growth, municipalities within the county retain their own zoning prerogatives. So the City of Boulder (around 80 000 people) has insulated itself against sprawl with open space, mountain parks and a land use regulation that provides for a long-term growth rate no greater than one percent per year. The county has been criticized for its high median home prices. In contrast, neighbouring Boulder County towns such as Broomfield, Lafayette, Longmont, and Louisville are exploding in size. The county prepared a Comprehensive Plan with a Mineral Resource Areas Map and a Geologic

TABLE 2. REGIONAL AND LOCAL ISSUES IN MINING FROM A STATE AND COUNTY PERSPECTIVE.

ISSUE	STATE OF COLORADO POLICY	RESPONSIBLE STATE AGENCY	COUNTY POLICY	RESPONSIBLE COUNTY
Mining Proposal	State CMLRB reclamation permit for mining operations. Legal description, index map, premining plan & affected lands, mining plan, reclamation plan, proof of mailings & filings.	<i>Colo. Dept. of Natural Resources</i>	Special Use Review; Affected land reclaimed in cooperation with the CMLRB. Zoned mining. Planned Development District application (if mining proposal outside the Mineral Conservation Zone District); Reclamation study. Special Review Permit; CMLRB Reclamation Plan; Environmental Impact Statement.	<i>Boulder</i> <i>Clear Creek</i> <i>Jefferson</i> <i>Weld</i>
Site Location	Plan of Operation (permit)* or minerals agreement if on federal lands or Indian tribal lands. Compliance with local county/municipal approval and permits.	<i>Appropriate federal agency such as the U.S. Bureau of Land Management, U.S. Forest Service*</i> <i>Colo. Dept. of Natural Resources</i>	Proof of Filing. Variances, county zoning and land use permits, building permits. Protect Natural Areas. Federal and state permits required for mining operation.	<i>Local County Clerk and Recorder</i> <i>Boulder</i> <i>Jefferson</i>
Visual Quality			Protect and preserve Natural Landmarks. Visual impact study; Open Space resources study. Screening of the proposed use from adjacent properties.	<i>Boulder</i> <i>Jefferson</i> <i>Weld</i>
Geologic Hazards	Geochemical stability and characteristics of the site.	<i>Colo. Dept. of Natural Resources</i>	Geologic report.	<i>Jefferson, Weld</i> (Permit needed if site in geo hazard area).
Archeological or Historical Significance	Compliance with State and federal regulations.	<i>Colo. State Historical Preservation Office</i>	Historic resources, archeological, and paleontological study.	<i>Boulder, Jefferson, & Weld</i>
Water Rights	Compliance with Colorado water laws.	<i>State Engineer at the Colo. Div. of Water Resources</i>		

ISSUE	STATE OF COLORADO POLICY	RESPONSIBLE STATE AGENCY	COUNTY POLICY	RESPONSIBLE COUNTY
Water Quality and Quantity	Compliance with State and federal water quality standards.* (No unauthorized release of pollutants to surface drainage system or ground water).	<i>Water Quality Control Commission at the Colo. Dept. of Health. Environmental Protection Agency*</i>	Preservation and conservation of groundwater quality. Meet and maintain State water quality standards, meet county criteria.	<i>Boulder & Weld</i>
	Ambient groundwater data. Hydrologic impact evaluation, hydrograph.	<i>Colo. Dept. of Natural Resources</i>	Water quality and quantity study submitted to State Engineer for review.	<i>Jefferson</i>
Air Quality	Compliance with State and federal air quality standards.* Fugitive Particulate Emission Permit.	<i>Air Pollution Control Division at the Colo. Dept. of Health</i>	Meet and maintain State air quality standards, meet county criteria.	<i>Boulder, Jefferson, & Weld</i>
			No objectionable dust permitted if property abuts residential use.	<i>Clear Creek</i>
Wetlands	Dredge and Fill Permit.* Stream channel reconstruction.	<i>U.S. Army Corps of Engineers* Colo. Dept. of Natural Resources</i>	Wetland conservation.	<i>Boulder & Jefferson</i>
Grading/ Erosion Control	Final topography appropriate to final post land use. All affected land protected from slides and surface areas stabilized. Lakes or ponds have specified ratios for slopes.	<i>Colo. Dept. of Natural Resources</i>	Restrictions on post-mining uses and grading plans for final land contours.	<i>Boulder, Jefferson, & Weld</i>
Waste Material	Refuse disposed of in an unsightly and nondeleterious manner.	<i>Colo. Dept. of Natural Resources</i>	On-site sewage disposal	<i>Boulder, Jefferson, & Weld</i>
Vegetation	Type of present vegetation. Post-mining vegetation (a diverse, effective, and long-lasting vegetative cover capable of self-regeneration and at least equal to the surrounding area cover).	<i>Colo. Dept. of Natural Resources & Soil Conservation District</i>	Revegetation plan	<i>Boulder</i>
			Vegetation study; Soil report. Specifications for landscaping. Soil report; vegetation replaced to minimize erosion.	<i>Jefferson</i> <i>Weld</i>
Overburden and Backfill	Map of general type, thickness, and distribution of soil. (Topsoil segregated from spoil and preserved, inert and clean structural fill generated outside the site may be used for backfill with approval).	<i>Colo. Dept. of Natural Resources</i>	Sufficient arable soil for respreading over excavated area.	<i>Weld</i>

ISSUE	STATE OF COLORADO POLICY	RESPONSIBLE STATE AGENCY	COUNTY POLICY	RESPONSIBLE COUNTY
Drill or Auger Holes	Plugged with non-combustible material, prevent polluting drainage.	<i>Colo. Dept. of Natural Resources</i>	Core drilling sample report.	<i>Jefferson</i>
Wildlife	Compliance with federal law.* Safety and protection of wildlife on site shall be taken into account; habitat diversity encouraged. Endangered species protection.*	<i>Colo. Division of Wildlife regional office**</i>	Wildlife Impact Report Wildlife study. Conservation of critical habitats.	<i>Boulder</i> <i>Jefferson</i> <i>Weld</i>
Blasting/Noise Health and Safety	Compliance with standards for acceptable noise levels. On-site standards to regulate the health and safety of employees and visitors.	<i>Colo. Dept. of Natural Resources;</i> <i>Mine Safety & Health Administration (MSHA)*</i> <i>Occupational Safety and Health Administration*</i>	Noise impact criteria. No objectionable noise or odor if property abuts residential use. Noise and blasting study (must meet County, State, and federal regulations); Fire protection study. Radiation study. Safety fencing as deemed necessary. Noise standards modified to be compatible with adjacent land uses.	<i>Boulder</i> Clear Creek <i>Jefferson & Weld</i> <i>Jefferson</i>
Mineral transportation	Load limits and truck safety standards (except for federal highways*).	<i>Colo. Dept. of Transportation</i>	Traffic impact study; Road access requirements, hours of operation limited.	<i>Boulder, Jefferson, & Weld</i>

* Administered by the federal government.

** Department of Wildlife statement not required for Limited Impact Operations.

Hazards and Constraint Areas Map. Aggregate resource areas do not include lands defined and mapped as: critical wildlife habitat, agricultural lands of National and Statewide importance, and designated “Natural Landmarks” and “Natural Areas” (Boulder County, 2000). “Natural Landmarks” are “. . . prominent landscape features that distinguish a specific locality in Boulder County and are important because of the views they afford, their value as scenic vistas and backdrops, and the intrinsic value they hold . . . (Boulder County, 2000, p. 3). Such landmarks include Big Elk Park, Boulder Falls, and the Flatirons. The landscapes may have additional cultural, ecological, or geological attributes. “Natural Areas” are landscape areas recognized for one or more unique characteristics of natural beauty, geology, soils, vegetation, or historical significance (Boulder County, 2000). Examples of such areas include: Eldorado Canyon, Heron Rookery, South Boulder Creek, and Rabbit Mountain.

CLEAR CREEK COUNTY

Occupying an area of 396 square miles with a population of 8 448 people (NAC, 2001), Clear Creek County is the smallest one to be considered. Beginning with a gold rush in 1859, Clear Creek towns considered mining as a boon, not a problem. Developments produced gold, silver, copper, lead, and other metallic minerals. There are over 8000-patented mines in the county and active tours are a local industry. Unusual zoning regulations in Clear Creek County give the county the power to protect mineral reserves. The county created a special extraction district in which mining is regarded as the highest and best use of land in the district. Almost a quarter of the county is zoned for mining (Imhoff, 1976). Aggregate operations must occur in areas zoned for mining or industrial use (quarries fall into the latter category). There are no special permits or regulations

required at the local level if the area is zoned for mining; it is basically a State process.

JEFFERSON COUNTY

Jefferson County, on the west side of Denver, comprises approximately 772 square miles and 492 528 people (NAC, 2001)—the most populous of the four counties. Once an agricultural area, the county is now largely suburban residential, business, and industrial. The county created a Mineral Extraction Policy Plan in 1977 and a Mineral Conservation Plan for conservation of a mineral resource. In an area designated for mining, agricultural use, public parks and/or recreation areas are allowed as long as they do not preclude the extraction of commercial mineral deposits. In future, no additional lands can be zoned as Mineral Conservation. New mining applications outside those regions already zoned Mineral Conservation are processed under Planned Development Mining Regulations (Field, Jefferson County Planning and Zoning Department, 2001, oral communication). More than 20 years ago, the county noted that only 8 300 acres of land with good quality quarry aggregate and 16 400 acres of good quality sand and gravel existed in the 220 700 total acres of available for resource extraction (Jefferson County, 1977).

The Jefferson County Mineral Extraction Policy Plan (1977) established a point system (between “0” and “100”) for evaluating mine sites according to their ability to conform to County goals. The ratings are not used as final approval criteria but rather provide a reference point for review. Points are awarded for such characteristics as visual impact, unique vegetation, wildlife habitat conditions, archaeological sites, historic sites, significant geologic features, geologic hazards, and quality of mineral resource. Higher points indicate a site more desirable for mining.

In 1987, the “Report of the Jefferson County Aggregate Resources Mining Roundtable” was released to the public. It identified nine potential areas for monitoring and enforcement of aggregate mining operations: air (dust), water, noise (operations and transportation), impact on wildlife and vegetation, impact on historical, archaeological and palaeontological sites, impact on property values and the economy. The report also noted that there are no existing federal or State standards to address the impact of aggregate mining on open space, tourism, recreational resources, or unique geological formations.

WELD COUNTY

Weld County, which is the largest county examined in area, encompasses 3993 square miles and has a population of 152 189 (NAC, 2001). Only Weld and Pitkin counties in Colorado have a structural “home-rule.” All 63 counties in Colorado have statutory authority,

subject to the same authorities and restrictions provided for by the State. Home rule statutes provide authority for local governments to legislate with respect to local property, municipal or corporate affairs, and administrative procedures. In the case of Weld County, their charter allows for reorganization of county government. For example, there is an oversight board that reviews the county commission.

Basically, the County relies upon Colorado State law for mining regulation. Weld County has a comprehensive planning plan and a mineral extraction plan. However, agricultural land is still considered a prime resource and is generally not rezoned for industrial use. With the push for both aggregate resources and urban expansion into this county from the metropolitan areas, it is just a matter of time before County Commissioners will have to deal with more requests for land use changes as it evolves from a rural community to an urban one. Aggregate producers are racing to lease properties in the County, forecasting shortages of reserves in Jefferson County.

SUMMARY

Nearly all the regional and local issues surrounding mining involve social and environmental restrictions, such as meeting requirements and standards set by the state and/or county to address negative impacts. Efforts by the State attempt to preserve and conserve natural resources, such as air, water, wildlife, and vegetation. Human resource issues like health and safety are addressed under federal and local planning efforts. Citizens raise the same concerns at all mine permit hearings, regardless of the site location: noise, dust, increased traffic, and visual impact.

Noise and dust are relatively easy to mitigate while traffic and visual impact are more difficult. Haulage roads through neighbourhoods do bring increased traffic and road wear, and new interchanges or paved roads are costly. The negative visual impact of a mine, which generates tremendous citizen opposition and emotion, can rarely be dealt with quantifiably. Jefferson and Boulder Counties attempt to determine site suitability (including the visual impact of a mining operation upon unique landscapes such as hogback ridges, valleys, or scenic overlooks). Jefferson County uses a numerical point system as a guideline, whereas Boulder County has designated Natural Landmarks and Natural Areas. In time, scenic and geologic features may become the subject of more intense scrutiny. An attempt is being made to preserve agricultural lands (and natural resources such as sand and gravel); in these mining is viewed as an interim use.

Today’s demand for aggregate mining mirrors population growth, which led to the construction boom and created job opportunities in the Denver metropolitan area during the past decade. Economic considerations,

such as the costs and benefits of mining as a land use, are usually limited to information such as haul costs and road impact. The economic benefit is usually not assessed against the environmental cost. Clear Creek County appears to take mining, which is the driving force of its economy, as the best land use.

There are a number of checks and balances in the permitting process, although critics may call it duplication of effort. Local government grants permission to mine, and some counties (such as Jefferson and Boulder) mirror the State reclamation requirements. The State does not grant permission to mine; CDMG issues reclamation permits and ensures that mining and reclamation are completed according to the approved plan submitted by the operator. Pineda of the CDMG states “It is a delicate balancing act for the Division, local governments and other State agencies. It is important that the public understand the different government processes in order to effectively participate in the process” (2001, written communication).

Although public hearings afford an opportunity to deal with site issues, zoning processes may fail to account for the macro or regional landscape. Cities expand within a county that may not be able to provide for urban services. The county deals with the impact of trucks from a mine operation, but not the impact when its final destination is in another county? It is urbanization itself, and the need for basic infrastructure support like highways, housing and sewers, that drives our mineral resource needs. This leads to mining, and impacts upon the environment. Government at the state and local level has attempted to eliminate irresponsible mining operations and to encourage resource conservation.

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INDUSTRIAL MINERAL ACTIVITY IN OREGON

By Ronald P. Geitgey, Oregon Department of Geology and Mineral Industries, Portland, Oregon, USA

Non-fuel mineral production in Oregon consists entirely of industrial minerals. The state has no active metal mines. The estimated annual value of this production is about US\$300 million, of which 70% is construction aggregate and the remainder a dozen commodities that supply primarily local and regional markets.

Construction aggregate products include crushed quarry rock (primarily basalt) and sand & gravel (produced from in-stream sites, floodplains and terraces). Production from active stream channels is under pressure from salmon recovery efforts. Land use conflicts are increasing, and as a result more aggregate must be transported longer distances to markets by rail and barge. Consolidation of operations continues and a few large companies now control most of the production capacity. Additional construction products include Portland cement, common brick, cinders for road surfacing and ice control, and pumice, both for lightweight concrete blocks and horticultural potting soils. Oregon perlite is used for soil conditioning, fireproof doors, and ceiling tile manufacturing. One diatomite operation produces filter aids and another operation processes and packages cat litter and absorbent products. Bentonite clay from three sites is used as sealant for water wells and civil engineering purposes. Zeolite (clinoptilolite) from two locations is used in absorbent and cation exchange applications. Gemstone production includes agate, jasper,

precious opal, and Oregon sunstone, which is a transparent calcic plagioclase with a coppery schiller. Other commodities include emery for nonskid surfaces, dune sand for container glass, soapstone for sculpture, air abrasives from nickel smelter slag, and various types of rough and split stone for building and decorative uses.

Several industrial mineral occurrences have potential for new or renewed production. Dune sands and massive quartzite bodies are being evaluated as possible feedstocks for proposed float glass plants along the Interstate Highway 5 corridor. Feldspathic sands in both coastal dunes and uplifted submarine canyon fill deposits have the potential to produce quartz and feldspar products of very uniform grain size. Heavy mineral sands in raised terraces along the southern coast contain ilmenite, chromite, zircon, and garnet. Lake Abert, an alkali lake, has significant reserves of sodium carbonate brine. Nepheline syenite occurrences near the central coast have some potential for traditional nepheline markets but may be more suitable for dimension stone or silica-free air abrasives. Although freshwater diatomite resources have been identified in southeastern Oregon, development is hampered in part by lack of infrastructure. As with many western states and provinces, Oregon has large identified reserves of natural zeolites but total production remains low and zeolites continue to be a commodity in search of a bulk market.

MAGNESIUM METAL – SOURCES, PROCESSES, AND MARKETS

By Brian Coope, Industrial Minerals Consultant, UK

MAGNESIUM MINERALS

Magnesium is the eighth most abundant element in the earth's crust, but is very underused compared to iron and aluminium, the other abundant metals. For each tonne of magnesium produced in the world there are more than 60 tonnes of aluminium and in excess of 2000 tonnes of iron and steel.

Magnesium occurs in wide range of minerals, and some of the most common are presented in Table 1: Of these minerals, magnesite, dolomite, carnallite, lake brines, and serpentine all provide feed for commercial operations. Until the recent closure of Dow's Freeport plant, seawater also played a significant part in the magnesium raw material supply equation. In the near future both brucite and bischofite could be included.

BRINES – MAGNESIUM CHLORIDE AND CARNALLITE

Production of magnesium metal by electrolysis utilizes magnesium chloride or the mixed

magnesium/potassium chloride salt, carnallite, as electrolyte. Magnesium chloride is the second most common salt in seawater (after sodium chloride) and is thus available as a virtually inexhaustible resource. The process to produce concentrated magnesium chloride from seawater is multi-stage: first involving precipitation of magnesium hydroxide using lime, followed by conversion to magnesium chloride by reaction with hydrochloric acid, and subsequent purification, concentration, and dehydration stages. Until it closed in 1998, the Dow Chemical operation at Freeport Texas was the only large-scale magnesium plant based on seawater.

Meanwhile other brine-based operations have been able to achieve cost savings by using a more concentrated feed and reducing the number of stages of processing. Magnesium-rich brines from the Great Salt Lake in the United States provide feed for the Magcorp operation in Rowley, Utah. The brines are concentrated by solar evaporation and desulphated with calcium chloride solution.

The Norsk Hydro operation at Porsgrunn in Norway now uses magnesium chloride brine derived from solution mining of carnallite beds in the Zechstein salt formation

TABLE 1 MAGNESIUM MINERALS

Mineral	Chemical formula	Weight % Mg
<i>Oxide and carbonate (sedimentary & metamorphic)</i>		
Magnesite	MgCO ₃	28.8
Dolomite	CaCO ₃ .MgCO ₃	13.2
Brucite	Mg(OH) ₂	41.7
<i>Chlorides and sulphates (evaporites)</i>		
Bischofite	MgCl ₂ .6H ₂ O	12.0
Carnallite	KCl.MgCl ₂ .6H ₂ O	8.8
Kieserite	MgSO ₄ .H ₂ O	20.2
Epsomite	MgSO ₄ .7H ₂ O	9.9
Langbeinite	K ₂ SO ₄ .2MgSO ₄	11.7
Seawater	MgCl ₂	0.13-0.14
Lake brines	MgCl ₂	0.8-4.0
<i>Silicate minerals (metamorphic)</i>		
Olivine	(Mg,Fe) ₂ SiO ₄	20-30
Serpentine	H ₄ Mg ₃ Si ₂ O ₉	26.3
Talc	Mg ₃ Si ₄ O ₁₀ (OH) ₂	19.2

in the northern Netherlands. The operator, Nedmag, uses a proportion of the brine to produce high purity magnesia at its Veendam plant. The Porsgrunn formerly used magnesium chloride brine obtained from carnallite by Germany's potash producer, Kali + Salz at Saldetfurth.

From the Dead Sea in Israel, existing operations extract carnallite by solar evaporation and produce potash, magnesia (from magnesium chloride brines), and bromine compounds. The operating company had the choice of using carnallite or magnesium chloride brines but opted for carnallite because costs are lower and the process is more efficient. Plants producing magnesium metal in Russia are also based on carnallite, which is obtained as a by-product from the potash processing operations of Silvinit at Solikamsk.

MAGNESITE

Magnesite is the highest grade of magnesium ore of widespread occurrence. Recently, the United States Geological Survey estimated world reserves of magnesite to be 2 500 million tonnes (on a contained Mg basis) without including estimates for Australia or Canada.

Inferred reserves of magnesite ore at both the Kunwarara deposit in Queensland and the Leigh Creek deposit in South Australia exceed 500 million tonnes, and other substantial deposits exist in Queensland, Western Australia, and the Northern Territory. Meanwhile, including estimated resources (Table 2) for Canada and Australia, the total world resource estimate becomes 2 690 million tonnes of reserves and 3739 million tonnes of reserve base. Most of the countries in Table 2 appear to be capable of producing magnesium metal from magnesite ore,

so why is there currently only one plant in the world producing magnesium-from-magnesite, and why does the operation actually import its magnesite raw material? The answer is power and location. The Norsk Hydro plant at Becancour in Quebec was built during the late 1980s and the site was chosen because cheap electricity is available and it is close to the United States, the world's major market. Chinese magnesite was chosen on the grounds of purity, consistency, and cost.

Both leading projects in Australia are based on magnesite that will be converted to magnesium chloride

TABLE 2. WORLD MAGNESITE RESERVES -- MILLION TONNES

	Reserves		Reserve base	
	MgCO ₃	Mg	MgCO ₃	Mg
Australia – e	608	175	1215	350
Austria	52	15	69	20
Brazil	156	45	226	65
Canada – e	52	15	83	24
China	2604	750	3472	1,000
Greece	104	30	104	30
India	104	30	156	45
North Korea	1563	450	2604	750
Russia	2257	650	2535	730
Serbia	17	5	35	10
Slovakia	69	20	104	30
Spain	35	10	104	30
Turkey	226	65	556	160
USA	35	10	52	15
Others	1458	420	1667	480
WORLD TOTAL	9340	2690	12 982	3739
* -- Source: US Geological Survey e – This paper				

for electrolysis. These are the AMC Stanwell project in Queensland, and the Samag project in South Australia.

BRUCITE

Brucite would produce ore with the highest magnesium content, but commercial deposits of brucite are rare. However, it should be noted that Russia's two main magnesium producers, Solikamsk Magnesium Works and Avisma, have been carrying out trials on brucite from the Kuldur deposit in Siberia and propose to base new plant units on the material. Both companies intend to use chlorine and potassium chloride generated from existing production units to convert the brucite to synthetic carnallite. This would allow them to expand without aggravating their existing chlorine disposal problems.

SERPENTINE

The Magnola plant, which is currently coming on stream at Danville, Quebec, Canada, is based on a serpentine feed material from the tailings produced by decades of asbestos mining. The serpentine tailings, which contain an average of 24% Mg, are leached with hydrochloric acid, and then filtered to remove iron and silica compounds. The resulting brine is subjected to a series of purification steps to remove nickel, boron, manganese, and other elements before it is dehydrated in a spray drier and chlorination.

The potential of this process has led to interest in tailings from other asbestos mines – notably at Cassiar in western Canada, Woodsreef in Australia, and Asbest in Russia.

DOLOMITE

Although dolomite is clearly lower in magnesium content than the magnesium minerals just described, the calcium component provides an “in situ process chemical” in metallothermic reduction processes. In its

simplest form the process involves the reaction between calcined dolomite (magnesia plus calcia) and ferrosilicon to yield magnesium metal and a slag of calcium iron silicates.

Dolomite is one of the most abundant of all industrial minerals, and although the feed for magnesium metal production must be of high purity, worldwide there is no shortage of suitable material. Other factors, such as sources and costs of energy and ferrosilicon, and proximity to market are major considerations in the siting of any dolomite-based magnesium project.

CURRENT RAW MATERIAL SOURCES

In 1999, the estimated primary magnesium production of 440 000 tonnes was derived 52% from dolomite, 38% from brines and carnallite, and 10% from magnesite from the sources listed below:

- Magnesite – Norsk Hydro Canada
- Dolomite – Pechiney, NorthWest Alloys, Timminco, Brasmag, Chinese producers
- Brucite – Solikamsk (trials)
- Bischofite – proposed for Kalush
- Carnallite – Norsk Hydro Norway, Solikamsk, Avisma
- Lake brines – Magcorp, Dead Sea Magnesium, Minhe Magnesium

MAGNESIUM SHIPMENTS AND WESTERN WORLD PRODUCTION IN 2000

According to International Magnesium Association (IMA) data, Western production of primary magnesium was 210 300 tonnes in 2000, down by 42 100 tonnes (20%) from the previous year. Total Western World shipments were down to 367 000 tonnes (from 375 000 tonnes in 1999) and the die-casting sector was down to 111 000 tonnes (from 133 000 tonnes in 1999), as shown in Table 3.

TABLE 3 -- IMA SHIPMENTS 2000 -- BY END USE AND REGION ('000 TONNES)

	USA & Canada	W Europe	Asia/Oceania	Other	Total
Al alloys	73.4	52.2	30.1	9.4	165.1
Die Casting	57.6	36.0	12.6	4.5	110.7
Desulphurization	26.7	21.8	2.5	0.6	51.6
Other	19.0	12.9	5.3	2.3	39.5
Total	176.7	122.9	50.5	16.8	366.9

However, it should be pointed out that IMA changed its data collection definitions in 2000 to exclude ingot produced by primary magnesium producers from diecaster scrap. Production is about 33 000 to 35 000 tonnes annually, predominantly by Norsk Hydro at its plants in Canada (Becancour) and Norway (Porsgrunn). Previously, these tonnages were included in IMA's primary magnesium shipments data.

If the 2000 data is adjusted to account for this production, then Western World production was 244 000 tonnes, total shipments were 402 000 tonnes, and shipments to the diecasting sector were approximately 145 000 tonnes.

To evaluate growth of the magnesium market over the past decade, the combined version is more useful (Figure 1). Average annual growth from 1990 to 2000 has been 4.8% per annum. Clearly growth in the die-casting sector has been the most spectacular; it was 15% per annum in 1990 and 1992, and has been 20% per annum from 1993 to 2000.

FUTURE GROWTH

Some forecasts suggests that total demand for primary magnesium will reach 800 000 tonnes by the year 2010, of which the magnesium alloy sector – die-casting and wrought magnesium -- will account for 465 000 tonnes (58% of total). Total magnesium alloy demand will be much higher than this of course but Class 1 scrap will account for a further 100/150 000 tonnes.

WESTERN WORLD PRODUCTION VERSUS CHINA AND RUSSIA

One of the other major features of magnesium shipments has been the rise of China as a supplier to Western markets. Shipments from China and the CIS (mainly Russia) to Western markets reached 157 000 tonnes in 2000 and thus accounted for 39% of total shipments (adjusted IMA data). China accounted for an estimated 130 000 tonnes and Russia the remaining 27 000 tonnes. China's production served aluminium alloys, desulphurization, and "other markets", whereas the higher grade Russian product was predominantly used in magnesium alloys (diecasting and wrought magnesium) plus some to aluminium alloying markets.

According to the Chinese Magnesium Association, Chinese production reached 193 000 tonnes in the year 2000. Exports consisted of more than 90 000 tonnes primary magnesium and 40 000 tonnes magnesium granules.

FUTURE SUPPLY

There are no brownfield capacity expansions under construction at the present time – apart from the potential increased capacity from Magcorp's electrolytic cell replacement program. Capacity expansion plans mooted or announced by Norsk Hydro, Dead Sea Magnesium, Solikamsk, and Avisma are all on hold or have been shelved.

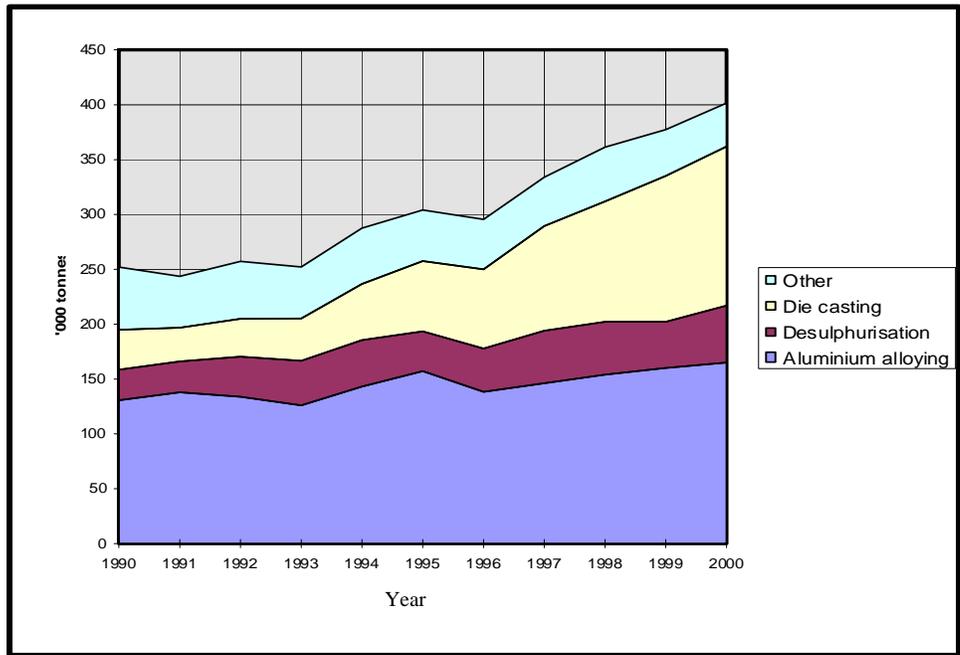


Figure 1. World Primary Magnesium Shipments – by end-use

Over 20 new greenfield magnesium projects have been proposed during the past three years. The most advanced projects appear to be:

- Noranda's Magnola plant in Quebec, Canada, is mechanically complete (63,000 tpa capacity) and is currently undergoing commissioning. However, the process is behind schedule because of problems with impurities in the cells, which have reduced output. The plant was scheduled to be at full capacity towards the end of 2001 but by the end of March only 12 out of 24 cells were operating. It appears that significant process adjustments will be required to overcome the problems. Production in 2001 is expected to be in the 20 000 to 30 000 tonne range.
- Both AMC's Stanwell project in Queensland, Australia, and Pima's Samag project in South Australia are expecting to complete financing arrangements during 2001 (AMC in the second quarter and Pima in the fourth quarter). Both companies have important offtake agreements to underpin future sales. Both plants could start commissioning during 2003/2004.

These three projects will add just over 200 000 tpa of new capacity to the market, equivalent to 40% of total world market in 2000. For this reason there is likely to be a breathing space before any other major project reaches the starting blocks.

RECYCLING

Secondary magnesium will play an important role in the overall supply picture in the future. Recycling reduces the requirement for primary metal but the practice is already well-established for magnesium (and actually enhances its desirability as a material of choice for automotive and other mass-produced goods. It should be

noted that only Class 1 scrap can be used for diecasting alloys.

PRICES AND THE TWO-TIER MARKET

The magnesium market is a two-tier market. There is a market high purity magnesium market for structural applications (including diecasting) – and a bulk standard market covering applications ranging from aluminium alloying to desulphurization. China is now the main factor in the supply of material to this sector of the market. The high-grade market is concerned with long-term contracts and a significant content of quality assurance, technical input, and service in the price make-up. The differential between high grade/contract price and standard grade/spot price has been 50% or more in the past but a level of around 25% premium would appear most likely for the immediate future.

It is instructive to compare the prices published in the main trade publications, Metal Bulletin (MB) and Platt's Metals Week, with actual transactions. In the absence of terminal markets the published prices are based on what producers and traders tell the journals concerning recent transactions. The spot price basis means that these prices can be very different to the actual levels at which the bulk of shipments are being transferred (mostly under long term contract). One measure of the latter is the average import value for the annual shipments by major supply countries extracted from trade data. These are presented in Figures 3 and 4 for the United States and Europe, respectively.

In the United States, the average import value for Canadian magnesium was actually fairly close to the Metal Week spot Western quotation since 1996, and the Russian AIV has been fairly close to Platt's Metals Week's spot dealer import price quotation. The price for Canadian metal has been consistently 40-50% higher and

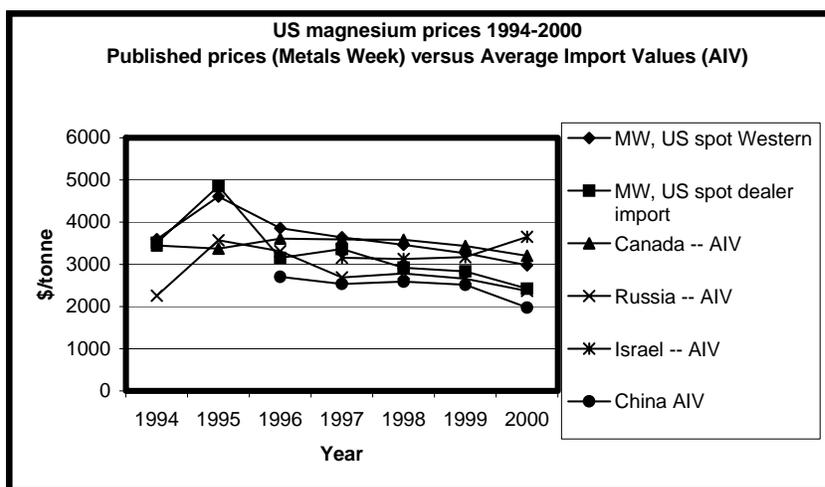


Figure 3. United States magnesium prices from 1994-2000

the Russian price around 25% higher than the prices of Chinese magnesium.

In Europe the Norwegian AIV price levels have been higher than MB's free market price quotation by more

than 40% in most years. The Russian AIV price level actually coincided with MB free market price in 1999 but is usually higher by 15 to 25%.

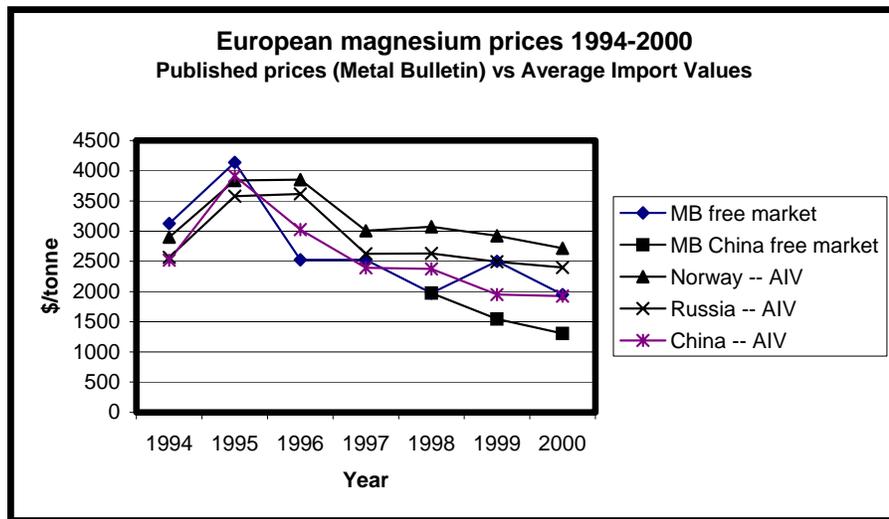


Figure 4. European magnesium prices 1994-2000

MAGNESITE AND RELATED OPPORTUNITIES IN BRITISH COLUMBIA, CANADA

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BACKGROUND

Magnesite is an industrial mineral used in the production of calcined, dead and fused magnesia as well as magnesium metal. In 1998, the total world magnesite production was estimated at 18 million tonnes (Coope, 1999). In that year, about 8.7 million tonnes of magnesia were produced from natural magnesite and about 1.8 million tonnes were produced from seawater or brines.

North America is a major importer of magnesia products. In 1991 it brought in more than \$US 43 million worth of magnesium oxide in which MgO contents exceeding 94%, \$US 12.5 million of other magnesium oxides, and \$US 5 million worth of magnesite.

Worldwide, the use of magnesium for automotive part die casting and steel desulphurization continues to expand. Mg-metal production for 1998 was estimated at 452 500 short tonnes. If current trends continue, by the year 2003 more magnesium will be used in die casting than in aluminum alloying (Brown, 1999). Although British Columbia has important magnesite resources (Figure 1) and access to the abundant, competitively priced energy required to transform magnesite into value-added products such as magnesium and magnesia, only the Mount Brussilof deposit is in production.

BRITISH COLUMBIA'S MAGNESITE

More than 70 magnesite occurrences have been reported in British Columbia (Figure 1). Most of the significant deposits are hosted by sedimentary rocks that were deposited in shallow marine environments.

Most of the promising sparry magnesite deposits are hosted by sedimentary rocks of Precambrian to Cambrian age in southeastern British Columbia. The deposits are strata-bound and are associated with palaeobathymetric highs of probable tectonic origin. The Mount Brussilof deposit is hosted by the Cambrian Cathedral Formation, which is composed of shallow-marine platformal carbonates that were deposited along the Cathedral escarpment (bathymetric high). Magnesite deposits of the Brisco-Driftwood Creek and Cranbrook areas follow the palaeobathymetric Windermere high. Those in the Brisco-Driftwood Creek area are hosted by the Precambrian (Helikian) Mount Nelson Formation, and those in

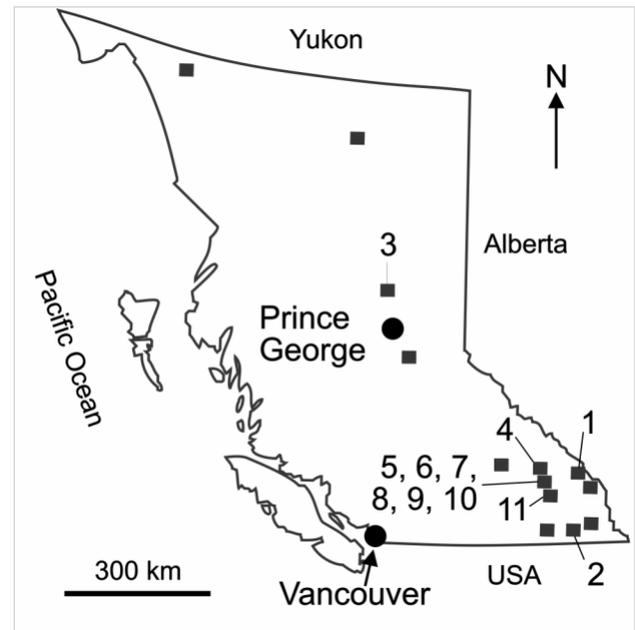


Figure 1. Location of sediment-hosted magnesite deposits in British Columbia. 1-Mount Brussilof (Baymag Mines Co. Ltd.); 2-Marysville; 3- Anzac; 4-Driftwood Creek; 5- Jab; 6-Topaz Lake, 7-Clealand Lake, 8-Bots Lake, 9-Dunbar Creek; 10-Red Mountain, 11-Invermere.

the Cranbrook area by the Cambrian Cranbrook Formation. These undeveloped deposits have lower MgO and higher SiO₂ and CaO contents than the Mount Brussilof deposit. However, they share a low FeO content, and some have dimensions of potential economic interest.

MOUNT BRUSSILOF

Baymag Mines Co. Ltd. owns the world-class Mount Brussilof magnesite deposit. The deposit is located 35 kilometres northeast of Radium Hot Springs. It supplies raw material for high quality caustic and fused magnesia. The ore is so pure that a combination of selective mining and blending precludes the need for upgrading to meet industry specifications (Knuckey, 1998). In 1980, proven and probable geological reserves were 9.5 million tonnes grading over 95% MgO in calcined product, sufficient for a mine life of over 150 years, (Schultes, 1986). Magnesite-bearing strata have been traced for at least 13

kilometres along strike. The Mount Brussilof deposit provides all the present Canadian magnesite production. Baymag Mines Company Ltd. has a capacity of up to 100 000 tonnes per year of high-quality calcined magnesia and 14 000 tonnes per year of fused magnesia. In the past it also supplied magnesite for magnesium metal production.

The deposit is located within the foreland tectonostratigraphic belt and a palaeotopographic high commonly referred to as "Kicking Horse Rim," east of a Cambrian Cathedral palaeo-escarpment. The rocks east of the escarpment host the magnesite mineralization, and were deposited in a shallower marine environment than their stratigraphic equivalents to the west.

Magnesite ore is coarse, white or light grey in colour and buff when weathered. Textures do vary widely (Simandl and Hancock, 1992). Minor impurities in magnesite ore comprise isolated dolomite crystals, calcite, and dolomite veins and coarse pyrite pyritohedrons or octahedrons. Pyrite stockworks/veins, and subvertical fractures filled by a mixture of beige-coloured ankerite, calcite, chlorite, coarse radiating or single quartz crystals are separated from ore by selective mining.

Replacement features include coarse, white carbonate crystals oriented perpendicular to fracture planes or partings, and lenses of fine-grained dolomite enclosed by sparry carbonates. Bipolar growths of zoned magnesite crystals, magnesite pinolite, rosettes and coarse carbonate crystals with lozenge-shaped cross-sections are also interpreted as diagenetic or metasomatic replacement textures.

OTHER SPARRY MAGNESITE DEPOSITS

The Marysville deposit, which was originally owned by Cominco Ltd., was acquired subsequently by Stralak Resources Inc., and optioned recently to a private exploration company based in The Bahamas. The deposit is located 16 kilometres northwest of Cranbrook and extends for at least 8 kilometres along strike; maximum thickness is estimated at 24 metres. Between 1938 and 1961 the deposit was investigated by trenching, test pitting, underground testing, diamond drilling and geological mapping. The magnesite horizon is within the Cambrian Cranbrook Formation, which consists mainly of quartzites (Hancock and Simandl, 1992).

The Anzac deposit is located 122 kilometres north-northeast of Prince George, in the Misinchinka Ranges of the Rocky Mountains. The magnesite showing is within the Lower Cambrian Gog Group. The property was staked and mapped by MineQuest Exploration Associates Ltd. for Norsk Hydro in 1986. Six magnesite outcrops are located along a strike length of 5 kilometres with apparent thicknesses ranging from 3 to 11 metres (Hancock and Simandl, 1993).

The Brisco-Driftwood Creek deposit is within the Mount Nelson Formation, which was traditionally assigned to the Purcell Supergroup of Middle Proterozoic age. However, it is possible that this formation correlates with the Windermere Supergroup of Late Proterozoic or Early Cambrian age. Magnesite crops out sporadically along a strike length of 5 kilometres. The sparry carbonate zone has a maximum apparent thickness of 175 metres. The deposit was initially explored by Canadian Occidental Petroleum Ltd. (Simandl and Hancock, 1992). The claims lapsed, and the deposit is now owned by three British Columbia prospectors.

The Jab, Red Mountain, Topaz Lake, Cleland Lake, Dunbar Creek, Invermere, Hellroaring Creek and Botts Lake magnesite occurrences are less well known. They are believed to be on the same stratigraphic horizon as the Brisco-Driftwood Creek deposit. Most of them are covered by a thin layer of overburden and their size is not well constrained (Simandl and Hancock, 1992). Magnesium-rich portions of the deposits are almost entirely magnesite with minor concentrations of pyrite, iron oxides, dolomite, calcite, chert, chlorite and mica (Simandl and Hancock, 1996).

GEOCHEMISTRY

Major oxide analyses were carried out on magnesite-bearing rocks from Mount Brussilof, Anzac, Driftwood Creek, Jab, Marysville, Topaz, Cleland Lake and Botts Lake deposits (Figure 2). Although the chemical compositions of samples from these deposits is similar to those from the Mount Brussilof deposit, Mount Brussilof samples generally have higher MgO and lower iron and silica contents. In some cases, this could be due to weathering processes. All deposits appear to have median CaO contents comparable to those from Mount Brussilof; the major impurities are SiO₂ and CaO. The sparry magnesite samples are characterized by low FeO, MnO, Al₂O₃, TiO₂, K₂O and Na₂O contents (Figure 2). The total iron content (reported as FeO) decreases with increasing MgO content of the rocks from limestone to magnesite. Magnesite-bearing rocks from the Mount Brussilof deposit average 18 ppm boron, results from the other deposits are even lower.

SUMMARY

Ore from the Mount Brussilof deposit is selectively mined then blended. It does not require any further upgrading to produce high quality calcined and fused magnesia. Other sparry magnesite deposits in British Columbia have slightly lower MgO grades, and slightly higher SiO₂ contents than Mount Brussilof. However, iron and manganese concentrations in the magnesite crystal lattices

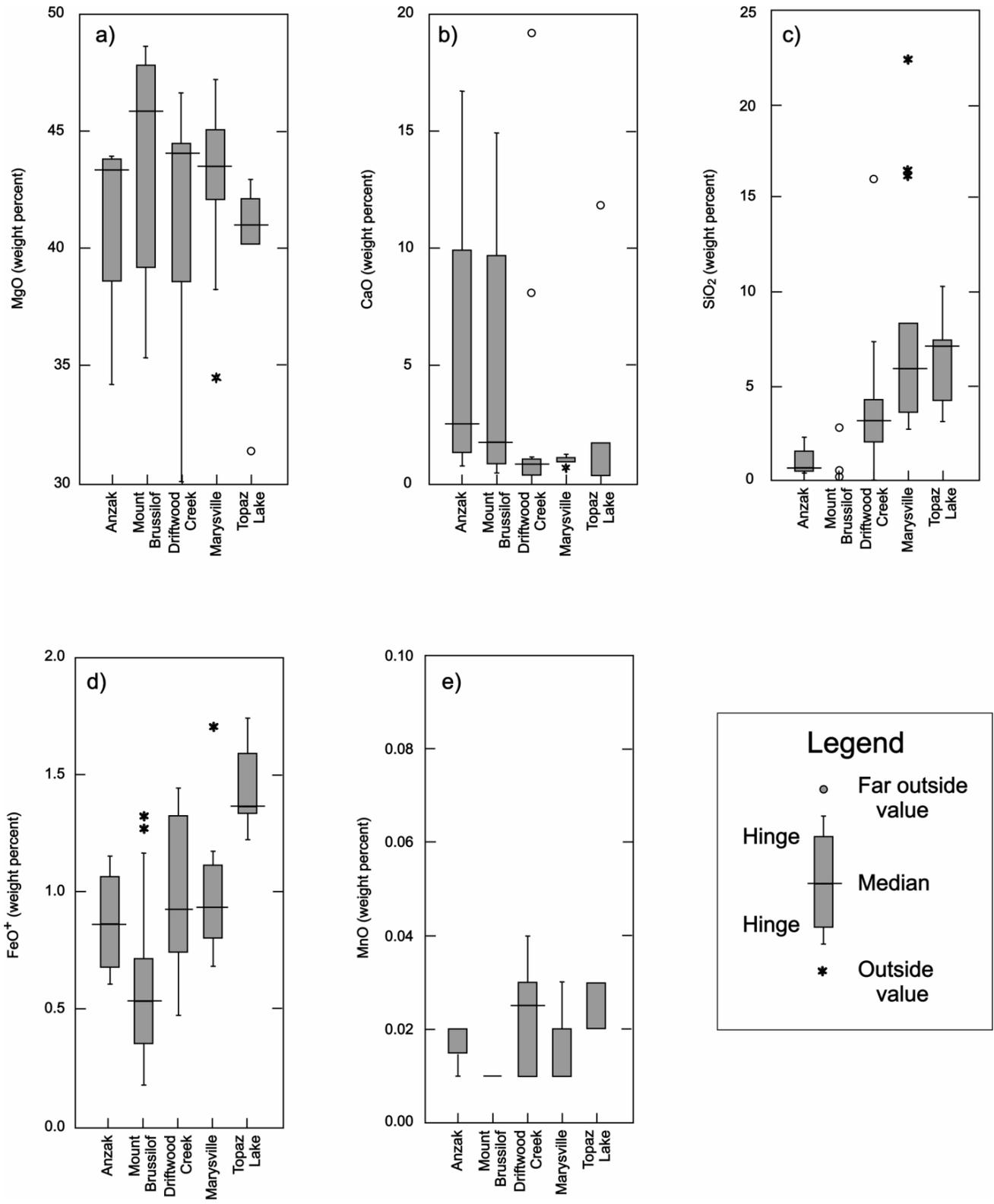


Figure 2. Composition of magnesite-bearing samples from selected magnesite deposits in British Columbia (total iron reported as FeO) Modified from Simandl (2002).

in these deposits are very low, a positive feature. As well, the boron content of these rocks is low. Most of the

deposits are coarsely crystalline, so conventional processing methods could probably remove mineral

impurities and produce high-purity product. There may be no beneficiation required to produce magnesium metal, electrical-grade fused magnesia, or magnesia products for environmental and agricultural applications. The overall characteristics of magnesite-rich rocks from British Columbia compare favorably with those of ores from European sparry magnesite deposits.

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HYDROMAGNESITE IN BRITISH COLUMBIA, CANADA

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INTRODUCTION

Hydromagnesite occurrences in British Columbia have been recognized since the beginning of the 19th century (Reinecke, 1920; Young, 1915). However, the known occurrences of hydromagnesite lack the size to compete with the large sparry magnesite deposits in British Columbia (Grant, 1987; Simandl *et al.*, 1996) as potential sources of raw materials for the production of industrial grade caustic, dead-burned and fused magnesia, or magnesium metal.

In British Columbia, exploration and/or re-evaluation of known hydromagnesite occurrences may result in discovery of deposits with potential as sources for natural flame retardants. Rapid growth of the inorganic natural flame retardant market and close collaboration with existing users with captive markets are needed to successfully explore and exploit these resources (Simandl, *et al.*, 2000).

FLAME RETARDANTS

Flame retardants are materials incorporated or applied to products, including plastics and textiles, to increase their resistance to fire. According to the Danish Environmental Protection Agency, at least 350 substances are used as flame retardants.

In the mid 1990s, 70% of the flame retardants consumed in the United States were inorganic. Aluminum hydroxide (ATH), accounted for more than 50% of the total. More recent data indicates that each year flame retardant markets in the United States and Europe consume 344 800 and 339 900 tonnes, respectively (Weber, 2000).

The flame retardant efficiency of ATH, magnesium hydroxide ($Mg(OH)_2$), and similar materials, like hydromagnesite and huntite, is based largely on their endothermic decomposition into an oxide and water. The released water vapor isolates flames and dilutes flammable gases. Magnesium-based compounds are relatively new in the flame retardant market. ATH, which becomes unstable above 200°C, is only applicable to polymer systems compounded and processed at low

temperatures, such as production of polyvinyl chloride, ethylene vinyl acetate copolymer, and polyethylene. In contrast, $Mg(OH)_2$ is stable up to 340°C, so it can be applied during production of polypropylene, nylons and thermoplastic polyesters such as polyethylene terephthalate, polyamide and polybutylene terephthalate. In addition to mined and processed brucite, $Mg(OH)_2$ can be extracted from brines or sea water, or can be manufactured synthetically from magnesite and other Mg-rich minerals, such as serpentinite. The market for $Mg(OH)_2$ is estimated at 10 000 to 15 000 tonnes for Europe and the United States combined. The price for synthetic $Mg(OH)_2$ is generally US\$1800 to 2700 /tonne.

There is no published market data for milled natural huntite-hydromagnesite ore used as a flame retardant, but it is expected to be much lower than that for $Mg(OH)_2$.

HYDROMAGNESITE / HUNTITE

There are a number of hydromagnesite ($Mg_4(OH)_2(CO_3)_3 \cdot 3H_2O$) and huntite ($Mg_3Ca(CO_3)_4$) occurrences worldwide. The major impurities in these deposits are magnesite, aragonite, calcite and dolomite. Only a few of these occurrences are exploited for their flame retarding properties.

Ore from the Serbia basin of Kozani provides a well documented example. Georgiades *et al.* (1996) report that it consists of a mixture of huntite and hydromagnesite with very low iron content ($Fe_2O_3 < 0.03\%$), high whiteness (~95%) relative to chemically produced MgO, the ore contains less than 8% total impurities (aragonite, calcite, magnesite, and other materials).

An average mineralogical composition, based on XRD and chemical analysis data of current ores is as follows: huntite (46%), hydromagnesite (46%), magnesite (4%), aragonite (3%), calcite (1%). A typical chemical analysis of the ore is MgO (38.0%), CaO (9.5%), H_2O (9.1%), CO_2 (43.4%) and LOI (52.5%).

In the Serbia basin of Kozani, beds with known ratios of huntite/hydromagnesite are selectively mined and blended to obtain a marketable product of constant composition and quality. Primary processing consists of

crushing to less than 10 millimetres and drying to less than 1% moisture. Final processing consists of de-agglomeration and air classification to obtain desirable particle shape and particle size distribution. Depending on the specifications of the final product, additional drying and surface treatment may be required (Georgiades *et al.*, 1996).

The typical end product from this locality has a huntite/hydromagnesite ratio of 1:1 and 50% of the particles are between 0.5 and 0.7 microns in diameter. Material with high huntite content is ground finer, with 50% between 0.3 and 0.4 microns. Generally, 97% of particles in both products are below 5 microns and the TAPPI brightness is over 95% (Georgiades *et al.*, 1996). The stability of the product is intermediate between that of $Mg(OH)_2$ and ATH.

HYDROMAGNESITE IN BRITISH COLUMBIA

Grant (1987) reviewed earlier reports by Reinecke

(1920) and Cummings (1940) that documented hydromagnesite occurrences in British Columbia. The early reports considered the deposits chiefly as a potential source of magnesia because the flame retardant market did not exist at that time. Renault and Stead (1991) described the geological setting and sedimentation within Cariboo area playas and saline lakes where deposits of this type are found. This study indicates that hydromagnesite-magnesite in these environments can be found: 1) as major constituents in carbonate playa basins where they precipitated subaqueously or in zones of shallow groundwater discharge; 2) in mudflats surrounding closed perennial lakes; and 3) in marshy valley-bottoms and in saline mudflats of ephemeral lake complexes. In the latter environment they occur in peripheral mudflats or near spring water discharges.

Although the detailed genesis of hydromagnesite-magnesite accumulations in British Columbia is beyond the scope of the present study, the reader is invited to consult Renault and Stead (1991) and Calvo *et al.* (1995) for more information. Huntite was first reported in British Columbia deposits in the early 1990s (Renault, 1993).

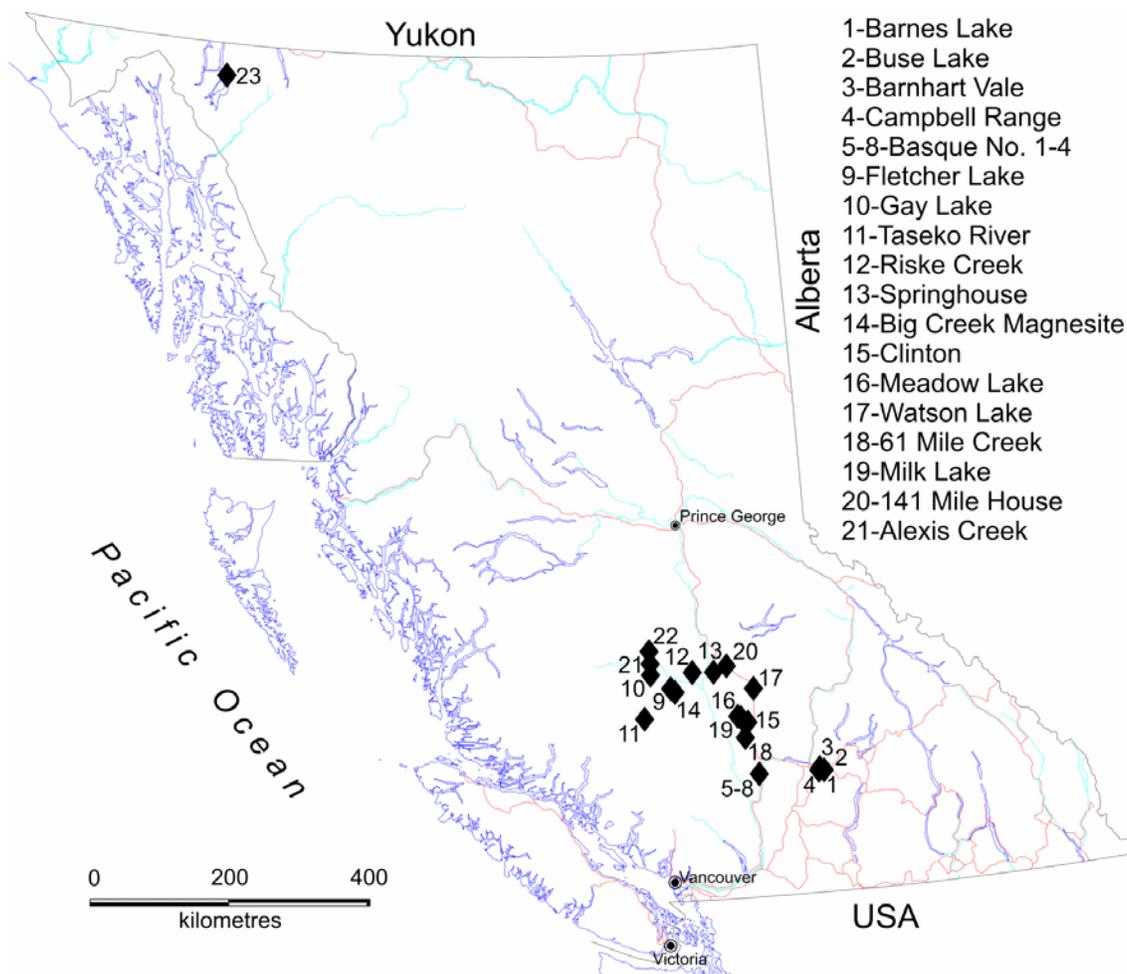


Figure 1. Hydromagnesite Occurrences in British Columbia.

The early reports that attempted to characterize hydromagnesite deposits in British Columbia predated discovery of huntite by Faust (1953).

All known British Columbia hydromagnesite occurrences reported in the Minfile website (www.em.gov.bc.ca/Mining/Geolsurv/Minfile/default.htm) are listed in Table 1 and located on Figure 1. Information about thickness, mineralogy, continuity and the extent of the British Columbia hydromagnesite occurrences is incomplete. In many cases loss on ignition data [H₂O+ analyses], which are an essential factor in estimating hydromagnesite and huntite content, are not available. In most reports, a description of the analytical method is not given and no scanning electron or modern X-Ray diffraction data was available.

TABLE 1. HYDROMAGNESITE OCCURRENCES IN BRITISH COLUMBIA . FOR DETAILS, PLEASE CONSULT THE MINFILE WEBSITE

<http://www.em.gov.bc.ca/Mining/Geolsurv/Minfile/default.htm>

OCCURRENCE	MINFILE NUMBER
61 MILE CREEK	092P 078
BARNHART VALE	092INE049
BUSE LAKE	092INE048
CAMPBELL RANGE	092INE050
SPRINGHOUSE	092O 088
141 MILE HOUSE	093A 156
ATLIN	104N 079
BIG CREEK MAGNESITE	092O 089
CLINTON	092P 072
MEADOW LAKE	092P 074
RISKE CREEK	092O 087
WATSON LAKE	092P 077
ALEXIS CREEK (L.561)	093B 041
ALEXIS LAKE (L.2833)	093B 056
BARNES LAKE	082LNW082
BASQUE NO. 1, 2, 3 and 4	092INW043, 44, 45 and 46
FLETCHER LAKE	092O 084
GAY LAKE	092O 085
MILK LAKE	092P 173
TASEKO RIVER	092O 086

SUMMARY

If current upward trends in the application of flame retardants continue, the improved market potential for hydromagnesite products may justify reassessment of selected known occurrences and exploration for new deposits. British Columbia hydromagnesite deposits do represent primary exploration targets for producers with a captive flame retardant market.

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FLUID INCLUSION EVIDENCE FOR THE GENESIS OF THE MOUNT BRUSSILOF MAGNESITE DEPOSIT, BC, CANADA

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ABSTRACT

The depositional environment of carbonates hosting the Mt. Brussilof deposit supports evaporitic origin for magnesite but it does not preclude either late diagenetic or hydrothermal origin. Textural evidence indicates either diagenetic recrystallization of sedimentary magnesite precursors or hydrothermal origin for the magnesite ores. Fluid inclusion studies reveal involvement of two independent but coeval fluids. One fluid inclusion population, found in quartz growth zones, is a CO₂-bearing saline brine represented by three-phase fluid inclusions. The other population found in magnesite and dolomite veins, is represented at room temperature by two-phase brine inclusions containing no CO₂. Petrographic work indicates that both fluid inclusion populations coexisted at the temperatures and pressures of fluid inclusion trapping. The intersection of the two isochoric constraints from the coeval fluid generations is consistent with maximum formational temperatures between 195 to 305°C and maximum pressures of approximately 2650 bars, corresponding to burial depths on the order of 8 km. This study is consistent with sedimentary/diagenetic formation of magnesite followed by a relatively minor hydrothermal overprint. Vein-forming carbonates, mainly sparry dolomite with minor magnesite are part of the hydrothermal overprint.

INTRODUCTION

There are a number of large, sedimentary-hosted, potentially economic magnesite deposits in British Columbia (Simandl and Hancock, 1996; Simandl, 2002). Only one of these, the Mount Brussilof mine (owned by Baymag Inc.), is currently in production. The mine is located in the southeastern part of the province, approximately 35 kilometres northeast of Radium Hotsprings, within the Foreland tectonostratigraphic belt and Kicking Horse Rim. The western margin of the Kicking Horse Rim coincides with the Cathedral paleoescarpment (Figure 1) along which there are a number of magnesite and Mississippi Valley Pb-Zn showings (Simandl and Hancock, 1991). The rocks within the pit consist mainly of light coloured, nearly monomineralic, coarse textured magnesite ore (Figures 2, 3, and 4). Gangue minerals are either disseminated within magnesite, fracture related or found as open space fillings (Simandl and Hancock, 1999).

Three genetic models are commonly suggested to explain the origin of sparry magnesite deposits (Simandl

and Hancock, 1999). These are: replacement of dolomitized, permeable carbonates by magnesite due to interaction with a hydrothermal fluid (Lugli *et al.*, 2000; Singh and Sharma, 1997; Kralik and Hoefs, 1978, Morteani *et al.*, 1982; Aharon, 1988, Simandl *et al.*,

1991); diagenetic recrystallization of a magnesia rich protolith deposited as a chemical precipitate in marine or lacustrine settings (Fritz and Simandl, 1993; Pohl, 1990; Pohl and Siegl, 1986) and direct precipitation from hydrothermal fluids (Fallick *et al.*, 1991; Halfon and Marcé, 1975). Field and macroscopic textural observations at the Mount Brussilof deposit indicate that in most cases, magnesite textures can be interpreted as late diagenetic replacement or as hydrothermal in origin. Structural and stratigraphic settings are described in the section on regional geology suggest sedimentary origin for the magnesite protolith. It is likely that the primary sediments consisted of fine-grained magnesite, hydromagnesite, huntite or other low temperature magnesia-bearing minerals and that these minerals recrystallized or were converted into magnesite during the late diagenesis.

REGIONAL GEOLOGY

The Mt. Brussilof deposit is hosted within the Middle Cambrian Cathedral Formation (Figure 1). The Cathedral formation is approximately 340 metres in thickness and is comprised of white, grey and buff coloured limestone and dolomite with minor quartz and pyrite veins and disseminations (Simandl and Hancock, 1991). The Cathedral conformably overlies the Naiset formation (Figure 5). Conformably overlying the

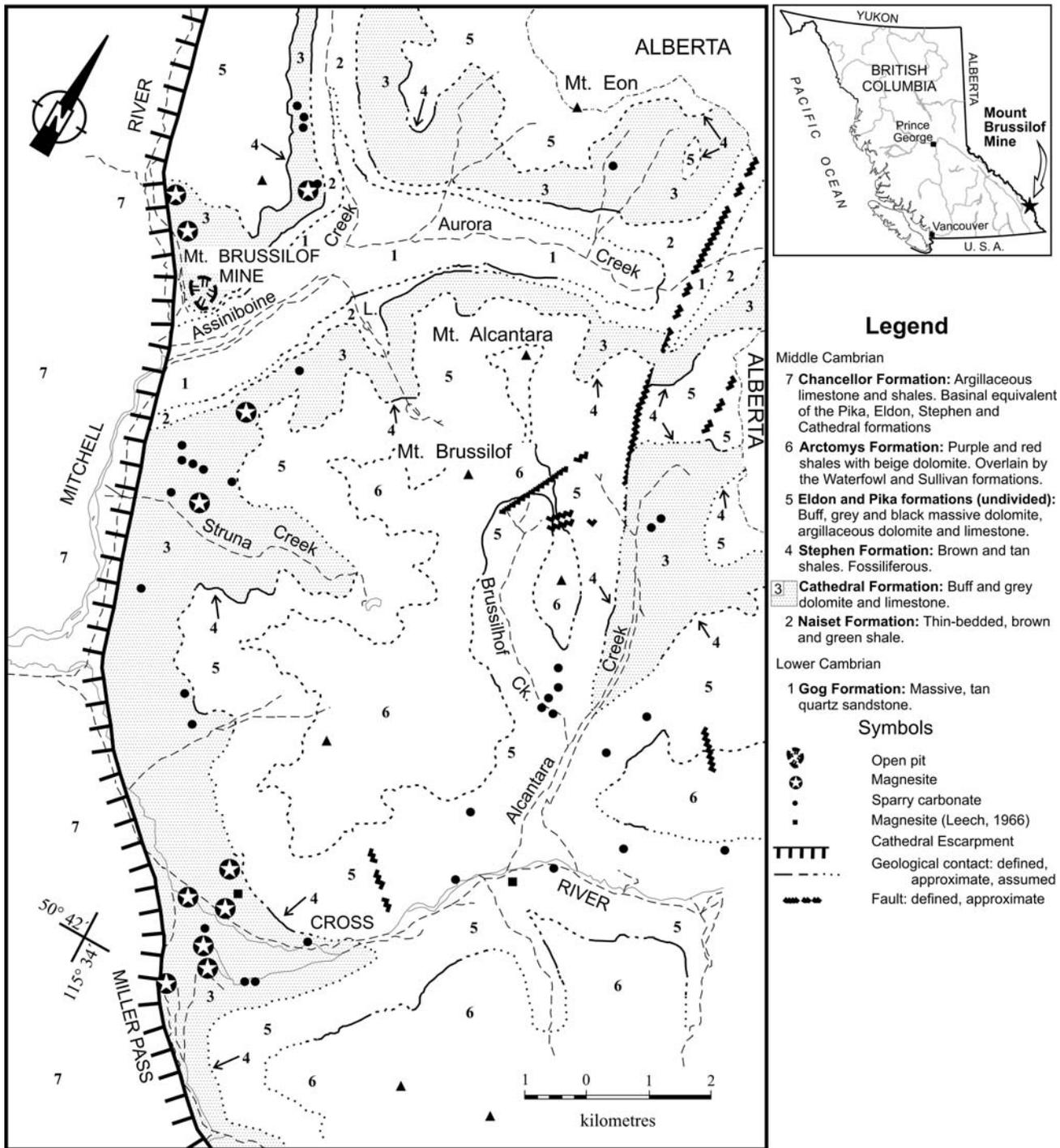


Figure 1. Geology map of the Mount Brussilof area, showing the location of the Mount Brussilof mine and other magnesite deposits in general proximity to the Cathedral paleoescarpment and Kicking Horse Rim (after Simandl, 1991).

Cathedral Formation are the Middle Cambrian Stephen, Eldon, Pika, Actomys and Chancellor formations. Rock types in these formations vary from shales and argillites to limestones, and are locally fossiliferous. The entire Middle Cambrian succession unconformably overlies Lower Cambrian massive quartz sandstones of the Gog Formation. Rocks outcropping west of the Cathedral Escarpment (Figure 1) are strongly deformed, but those to the east are not (Simandl *et al.*, 1991). The Cathedral, Eldon, and Pika formations have poorly developed cleavage, while the rocks of the Stephen and Naiset Formations have well developed foliation. In Mount Brussilof area, magnesite showings are restricted to the Cathedral Formation and up to now, magnesite has not been found west of the Cathedral escarpment (Figure 1). Fine-grained dolostone and late sparry dolomite are present on both sides of the Cathedral Escarpment (Simandl *et al.*, 1991). The magnesite host rocks are carbonates of the Cambrian Cathedral Formation, which were deposited in a relatively shallow marine environment (Fritz and Simandl, 1993). Where the field relationship between sparry dolomite and sparry magnesite is clear: the sparry dolomite appears younger than sparry magnesite.

This study is based upon fluid inclusions, field and microscope observations. The veins and other open space fillings sampled and studied consist of dolomite, magnesite and quartz (Figure 6). The veins show no evidence of deformation. Vein width varies from centimetres up to tens of centimetres. Dolomite is the dominant vein mineral, but in thin sections, in most cases, it is difficult to distinguish between dolomite and magnesite without an electron microscope or microprobe. The majority of crystals within the veins are idiomorphic and range in size from few millimeters to several centimeters in length. In some cases the carbonates and quartz crystals show growth zones. Fluid inclusions from within selected growth-zoned crystals have been examined and analyzed in detail (Figure 7). In a few cases magnesite has been observed as overgrowths on existing dolomite crystals. That particular paragenesis was not previously observed at Mount Brussilof.

Fluid Inclusion Data:

Samples of typical magnesite ore were not studied because fluid inclusions that they contained were too small (less than 5 microns in diameter). The four samples studies for fluid inclusions are from the late quartz-carbonate veins. Two samples are zoned quartz crystals and the other two samples are carbonate samples from the vein. One carbonate sample is a clear crystal of magnesite. The other carbonate sample is a composite sample taken from the vein wall. It consists of a cloudy sparry dolomite overgrown by a clear

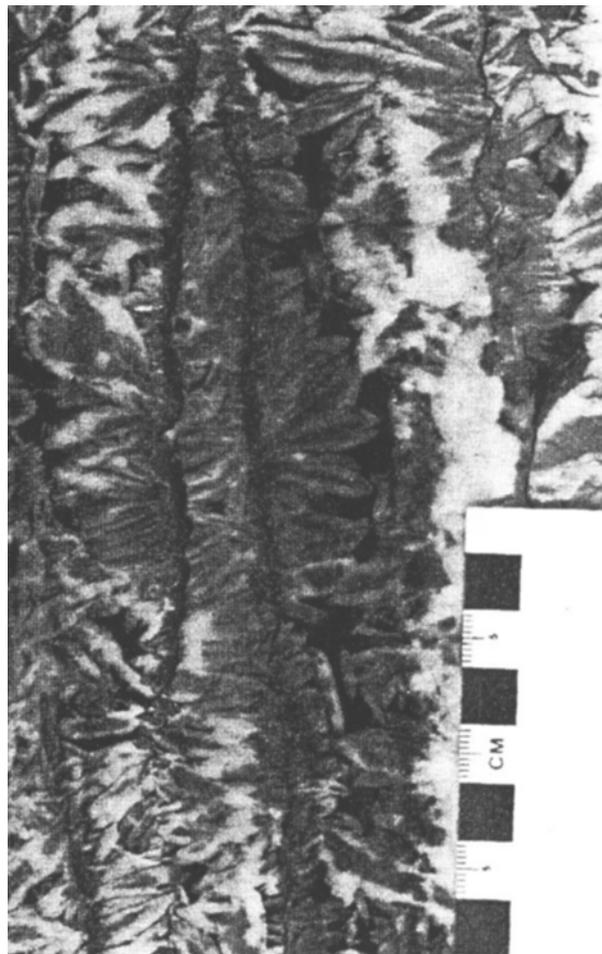


Figure 2. Zebra banding in magnesite, vestigial silty dolomitic protolith (black) with zoned magnesite crystals (white and light grey).

magnesite rim. Drusy quartz (Table 1) hosts Type 1 three-phase fluid primary inclusions that range up to 120 micrometres across with variable shapes. These inclusions occur within healed fractures, as isolated inclusions, and along growth zones. The contained phases are an aqueous phase, a liquid carbonic phase, and a vapour carbonic phase. At room temperature the carbonic vapour and carbonic liquid phases occupy approximately 7 and 1 percent, respectively, of the inclusion volume. When these inclusions are cooled, they nucleate a clathrate at an average temperature of -31°C followed closely by the nucleation of ice at approximately -35°C . Continued cooling results in nucleation of solid CO_2 at approximately -90°C . No additional phases nucleated when samples were further cooled to -195°C . Subsequent warming of the fluid inclusions causes the solid CO_2 to melt at temperatures near the CO_2 triple point (-56.6°C). Continued heating resulted in the melting of ice at temperatures above -29°C ; with final ice melting temperatures in the range of -8.5 to -3.5°C . Clathrate melting (Figure 8) takes place over the temperature interval from 7.5 to 8.9°C .



Figure 3. Stylolite-like fractures, with pyrite and calcite. Recrystallized pyrite and calcite along the stylolites is indicative of fluid flow. 1-dollar coin for scale.

SAMPLE DESCRIPTIONS

Homogenization of the carbonic phases to carbonic vapour occurs in the temperature interval 28.2 to 29.8°C. Total homogenization to the liquid occurs over the temperature range 190 to 210°C. These data are consistent with fluid compositions of $X\text{-CO}_2 = 0.010$, $X\text{-H}_2\text{O} = 0.975$ to 0.983 and $X\text{-NaCl} = 0.007$ to 0.015 (2.2 to 4.8 wt% NaCl equivalent). Raman microprobe analyses of the carbonic phases of these inclusions indicate that N_2 , CH_4 and H_2S concentrations are below the detection limit.

Inclusions in the magnesite (Table 2) are mainly two-phase fluid (Type 2) with rare three phase fluid inclusions (Type 1). The dominant two-phase fluid inclusions (Type 2) are comprised of a vapour and an aqueous phase. The vapour phase occupies

approximately 10 % of the inclusion volume at room temperature. Upon cooling, these inclusions nucleate ice at approximately -45°C. Further cooling to -195°C does not cause any additional phases to nucleate. Upon heating, the ice begins to melt at temperatures above -30°C, with the final disappearance at temperatures in the range of -4 to -5°C (Figure 9). Further heating results in a continual decrease in the size of the vapour bubble until total homogenization occurs at temperatures of 170 to 190°C. Many of the larger fluid inclusions decrepitate or stretch upon heating. To obtain reliable measurements, we concentrated on a number of smaller inclusions with similar phase ratios that were located away from the polished surfaces and defects within the magnesite. These microthermometric data correspond to compositional ranges of 6.4 to 7.8 wt% NaCl equivalent.

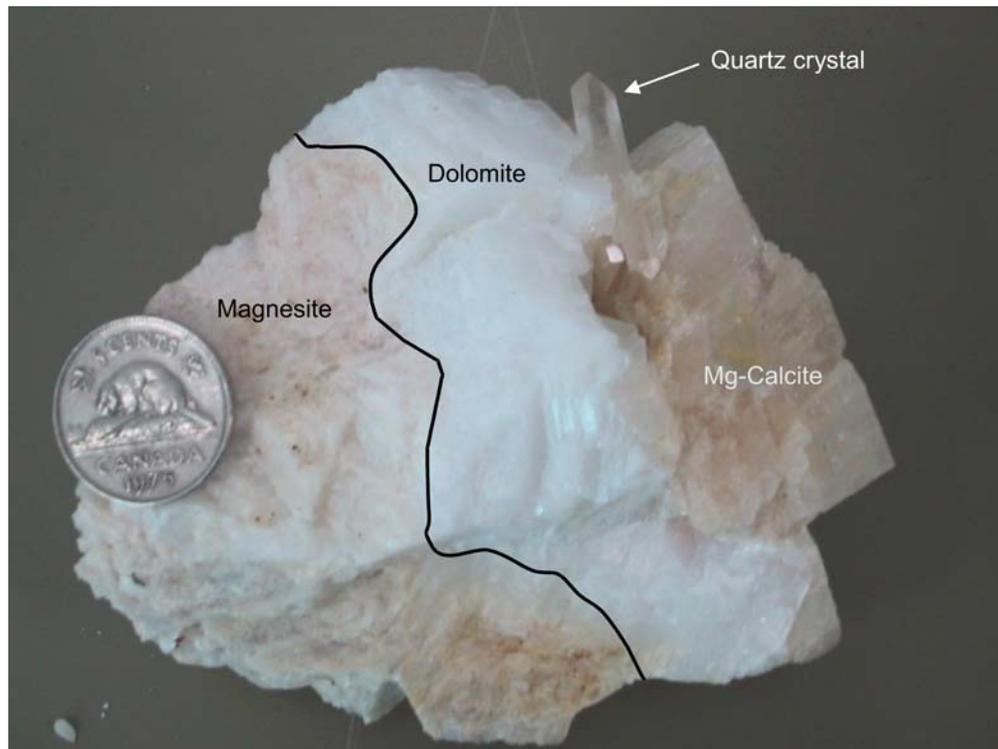


Figure 4. Quartz-carbonate fracture filling in magnesite. The central vein consists of quartz crystals in vug and vein-like settings. There is a white halo of dolomite forming a fairly sharp boundary with the magnesite host-rock. 5-cent coin for scale.

DISCUSSION

Both Type 1 and Type 2 fluid inclusions display total homogenization (Figure 10) to the liquid phase. This negates the possibility that the two fluids are conjugates of a boiling (immiscible) system, therefore boiling should not be considered as a possible mechanism for ore genesis in the Mt. Brussilof deposit. As has been shown, the two fluids more likely coexisted within the Mt. Brussilof rocks but originated from different sources. The compositions of fluid inclusions can be used to calculate minimum and maximum isochores for each fluid inclusion population. Isochores for the fluid inclusions in magnesite have been calculated using the equation of state of $H_2O-NaCl$ (Zhang and Frantz, 1987) and those representing the fluid inclusions in the quartz-carbonate veins have been calculated using the Bowers and Helgeson (1983) equation of state for $H_2O-NaCl-CO_2$. These isochores are shown on Figure 11.

Due to petrographic and field relations, Type 1 and Type 2 fluids are deemed to have coexisted in pressure-temperature space at the time of fluid inclusion trapping. This provides a unique opportunity to derive pressure-temperature constraints using the intersection of the isochoric limits obtained from the two fluid inclusion populations, which represent a non-boiling but probably mixed fluid system. As can be seen from

figure 11, the fluid inclusion isochoric data do not constrain lower temperature and pressure limits of the two fluid types. The lower pressure-temperature constraints are derived from the minimum (total) *homogenization* temperatures and pressures along the liquid vapour curve for $H_2O-NaCl$. This yields a minimum temperature limit of approximately $195^\circ C$ and a corresponding minimum pressure constraint of about 10 bars (Fisher, 1976). The maximum limit can be obtained where the two isochores diverge at higher pressure and temperatures (Figure 11). This places the maximum pressure and temperature estimates at 2650 bars and $305^\circ C$, respectively. Based on this data, the maximum burial depth of the Mt. Brussilof deposit was approximately 8 kilometres, which is consistent with the current tectonic models for the Cordillera (Wheeler and McFeely, 1991)

SUMMARY

Previous studies described the geological setting of the Mount Brussilof deposit and textural features compatible with either sedimentary, late diagenetic or hydrothermal origin (Simandl *et al.*, 1991; Simandl and Hancock, 1991 and 1999). The present study confirms that magnesite may have formed from Mg-rich magnesite precursors of sedimentary origin and that

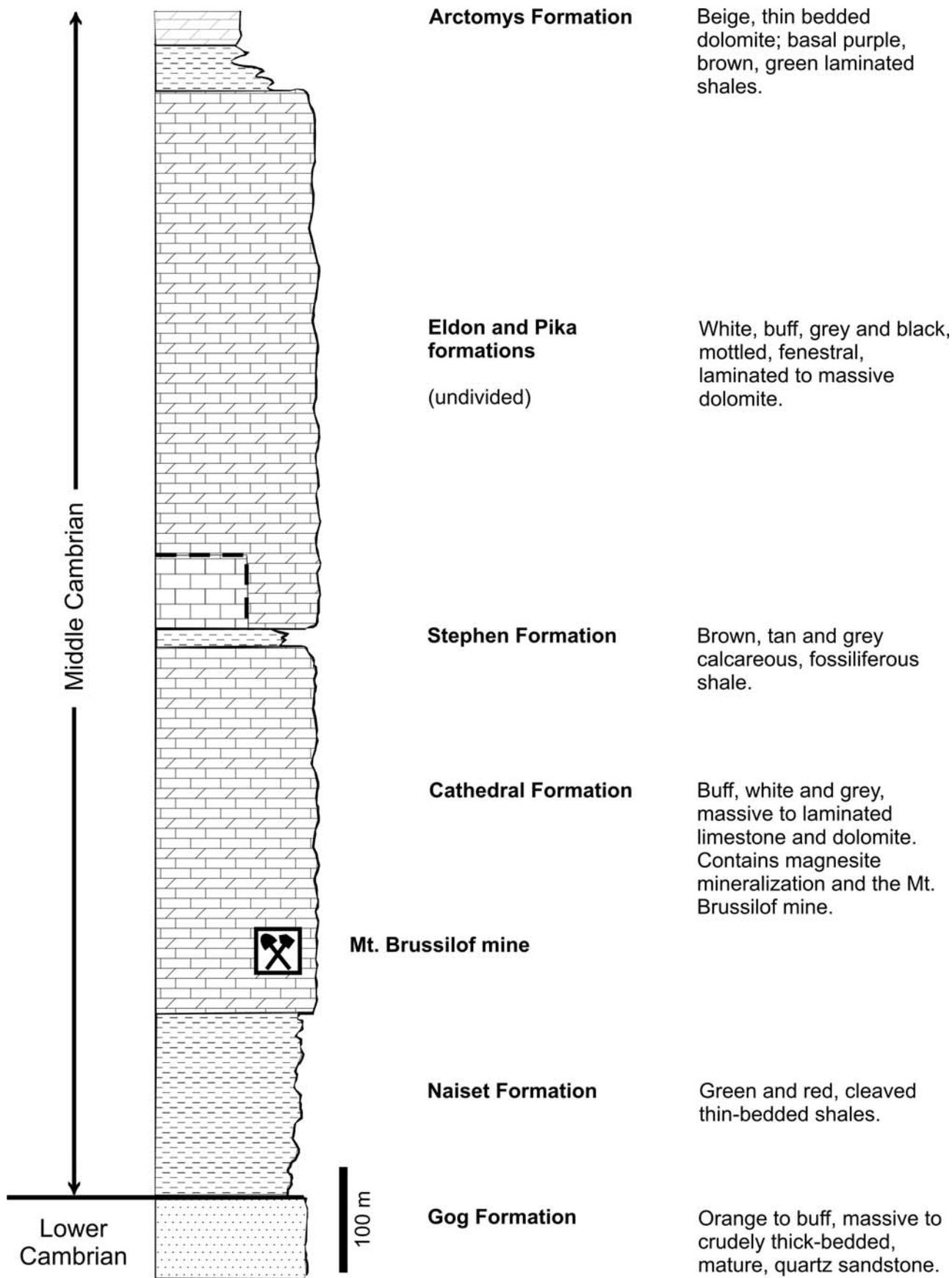


Figure 5. Stratigraphic column from the Mount Brussilof area (after Simandl, 1991)

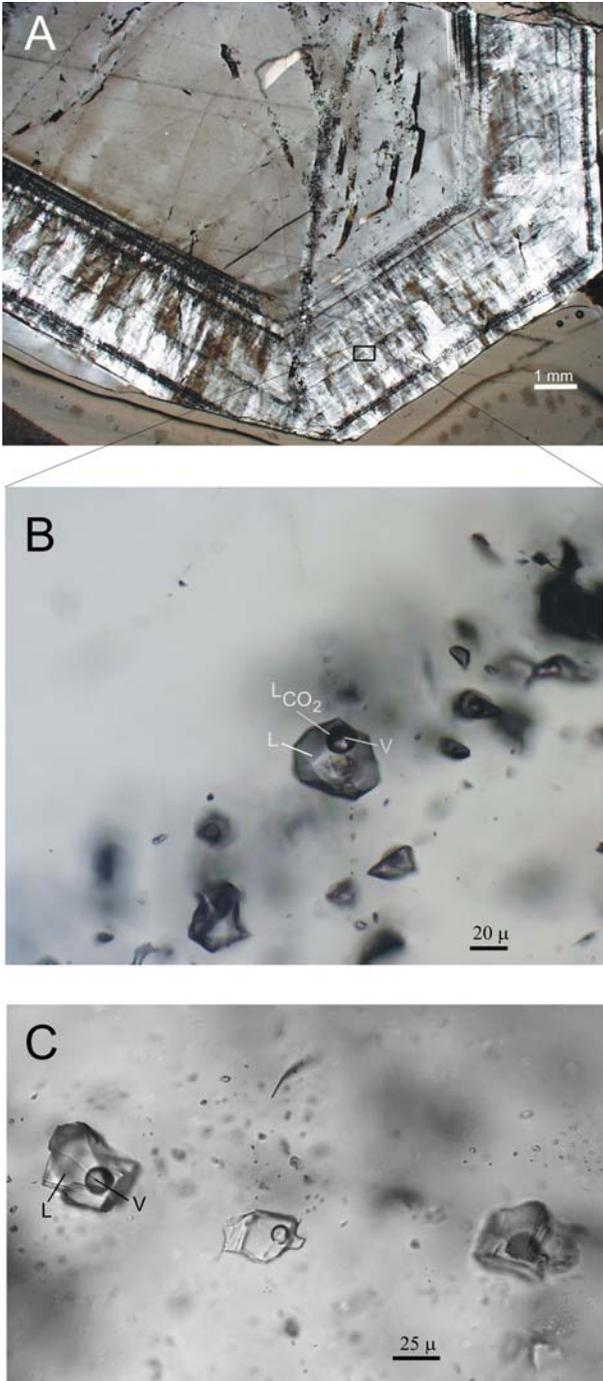


Figure 6. Photomicrographs. A: Zoned quartz crystal similar to that shown in Figure 5; B: Enlargement of the rectangle shown in photomicrograph A. The growth zones are delineated by linear arrays of fluid inclusions. These inclusions comprise three phases at room temperatures, CO₂ vapour (V), Saline brine (L), and liquid CO₂ (L-CO₂); C: Two phase fluid inclusions in dolomite at room temperature comprised of a saline brine (L) and a water vapour (V).

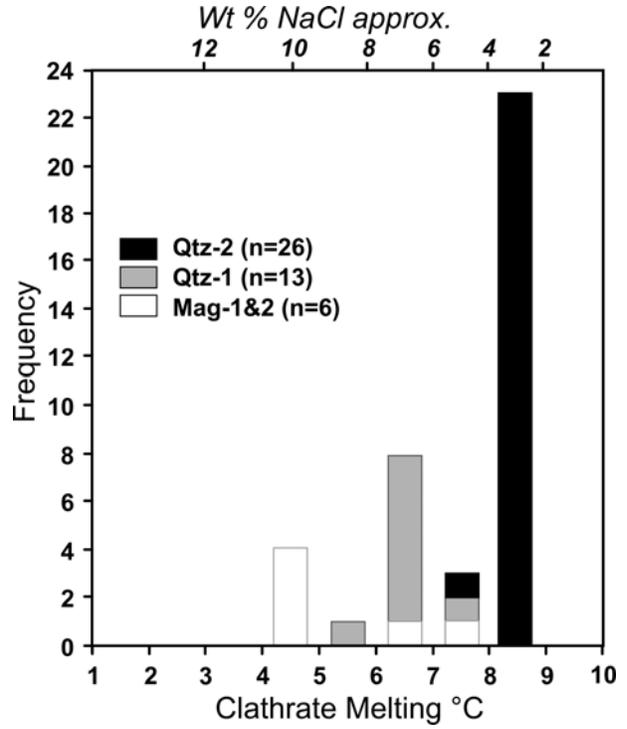


Figure 7. Clathrate melting histogram for the three-phase CO₂-bearing fluid inclusions in quartz and dolomite. Qtz: quartz data, Dol: dolomite data, n: number of measurements.

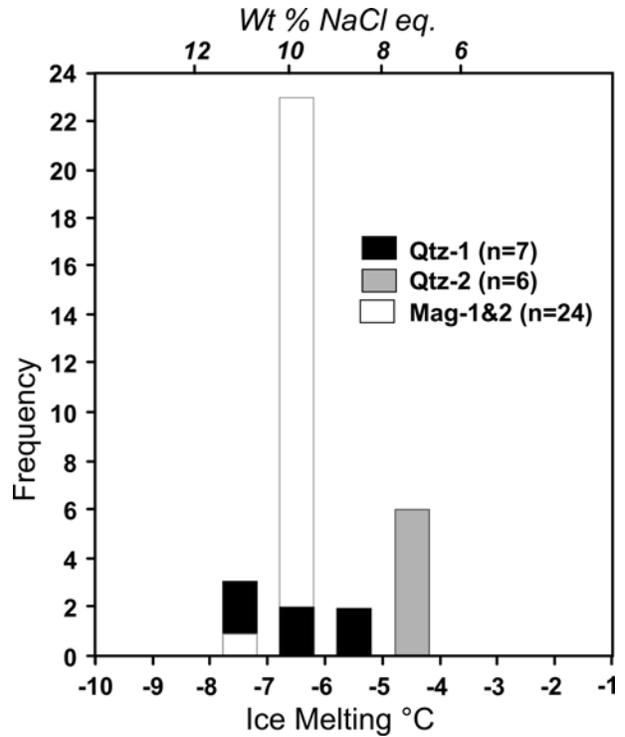


Figure 8. Ice Melting histogram of the microthermometric data from the two-phase inclusions in dolomite and quartz.

TABLE 1. MICROTHERMOMETRIC DATA FOR FLUID INCLUSIONS HOSTED IN QUARTZ CRYSTALS

Sample #	TM _{CO2}	TE	TM _{ice}	TM _{da}	TH _{CO2-v}	TH _{tot}	Sample #	TM _{CO2}	TE	TM _{ice}	TM _{da}	TH _{CO2-v}	TH _{tot}
Qtz-1-1		-45	-6.6	6		199	Qtz-2-1	-56.0	-29	-4.2	8.9		208
2			-0.8	6		195	2	-56.8	-20	-4.8	8.3	28.2	s 203
3			-3.5			s	3		-30	-4.9	8.3	29.2	s 204
4	-60	-23	-8.2	7.2		s	4	-56.5	-27	-4.7	8.3		
5			-5.3	6.4		190	5	-56.3	-29	-5.0	8.3	29.3	206
6			-6.4	6.7		214	6n	-56.6	-27	-5.0	7.5	29.8	210
7			-5.8	6.8		201	7	-56.7	-20	-4.6	8.6	28.9	206
8	-57	-33	-6.0	7.2	26		8	-56.5	-27	-4.9	8.3	28.9	208
9			-6.5				9	-56.5	-26	-4.8	8.3	28.8	208
10		-23	-5.6				10		-4.9	-4.9			191
11		-18	-5.8	5.1	26.1		11		-4.7	-4.7			192
11b		-27	-5.7	6.8			12		-23	-4.8			194
12		-24	-7.8				13		-20	-4.4	8.5		s
13		-38	-7.9				14a		-17	-4.8			199
14		-17	-4.6				14b		-17	-4.0			140
15		-20	-6.2	6.1			14c		-17	-4.2			186
16		-38	-8.8				15	-55.7	-17	-5.1	8.3	28.8	
17		-25	-7.9	6.7			16	-55.7	-18	-4.9	8.2	29.1	
18		-19	-8.2				17	-55.7	-30	-4.8	8.3	29.5	
19		-20	-6.0				18	-56.0	-31	-4.6	8.4	28.7	
20		-23	-5.0				19a		-17	-4.6	8.4		
21		-22	-6.9				19b		-17	-4.8	8.4		
22	-58.6	-23	-8.3				19c		-17	-4.9	8.3		
23			-7.8				20	-55.7	-17	-5.1	8.1	29.2	
24		-21	-7.0				21	-55.4	-18	-4.7	8.4	28.0	
25		-34	-6.8				22		-17	-4.6	8.4		
26		-27	-7.5				23		-17	-4.8	8.2		
27			-7.3				24		-20	-4.3	8.5	28.4	
28			-7.3				25		-18	-4.4	8.5	28.9	
29		-27	-7.6				26	-55.7	-17	-4.9	8.3	29.2	

TM = Melting temperature, TH = Homogenization temperature, TE = Eutectic temperature, V = vapour, all temperatures in °C, S = stretched, N = necked down, CLA = Clathrate

TABLE 2. MICROTHERMOMETRIC DATA FOR FLUID INCLUSIONS HOSTED IN MAGNESITE

SAMPLE #	TE	TM _{ICE}	TM _{CLA}	TH _{TOT}	SAMPLE #	TE	TM _{ICE}	TM _{CLA}	TH _{TOT}
MAG-1-1	-20	-4.9		133	MAG-2-1	-27	-6.0		
2	-25	-4.8		L >200	2	-17	-4.8		
3	-30	-4.8		188	3	-21	-6.6		
4	-17	-4.8		S	4	-30	-5.9		
5	-35	-4.7		S	5	-22	-6.8		
6	-18	-4.7		176.6	6	-27	-6.8		
7	-30	-4.9		>200	7		-6.5		
8	-20	-4.0		>200	8	-27	-5.3	7.9	
9	-14	-6.4		309	9	-27	-6.1		
10	-16	-6.4			10	-31	-6.7		
11	-21	-6.5		D	11		-6.7		
12	-21	-5.1			12		-6.8		
13	-24	-5.8		D	13	-20	-6.8		
14	-20	-5.6			14		-6.8		
15		-5.2		D	15	-15	-4.2		
16	-24	-5.2		297	16	-29	-6.8		
17		-4.5		D	17	-26	-6.2		
18	-16	-6.0		D	18	-25	-6.3		
19	-16	-6.0		276	19	-23	-6.7		
20	-19	-6.0		238	20	-31	-6.6		
21	-22	-6.1		D 341	21	-27	-6.6		
22	-28	-5.0		286	22	-18	-6.5	4.8	
23	-22	-4.4		D	23	-17	-6.5	4.8	
24	-22	-4.5		D	24	-20	-6.5	4.9	
25	-21	-4.7		D	25	-18	-6.4		
26	-25	-4.5		D	26	-15	-6.5		
27	-28	-4.3		D	27	-25	-6.4		
28	-28	-4.6		280	28	-16	-3.1		
29	-19	-7.3	6.7	D 305	29	-12	-2.8		
30			4.7		30	-22	-7.1		

TM = Melting temperature, TH = Homogenization temperature, TE = Eutectic temperature, all temperatures in °C, S = stretched, D = decrepitated, L = leaked, CLA = clathrate

these precursors may have been converted to sparry magnesite during diagenesis it also establishes the maximum pressure/temperature conditions for magnesite formation. Microscopic studies in at least one thin section identified textures indicating replacement of sparry dolomite by magnesite. The volume of this late hydrothermal magnesite (which post-dates sparry dolomite) appears to be minimal compared to the volume of magnesite ore that is interpreted to pre-date sparry dolomite. Sparry dolomite is widely distributed through the area and it is probably genetically related to Mississippi Type Pb-Zn deposits that are known to occur in this area (Simandl *et al.*, 1991).

The two distinct, intersecting fluid inclusion populations identified in this study are consistent with a fluid system that has not boiled and also place pressure-temperature constraints on both hydrothermal conditions and the coeval emplacement of quartz-carbonate veins. These constraints yield potential maximum temperatures of magnesite formation of 305°C with a corresponding pressure maximum of 2650 bars, which indicates burial depths on the order of 8

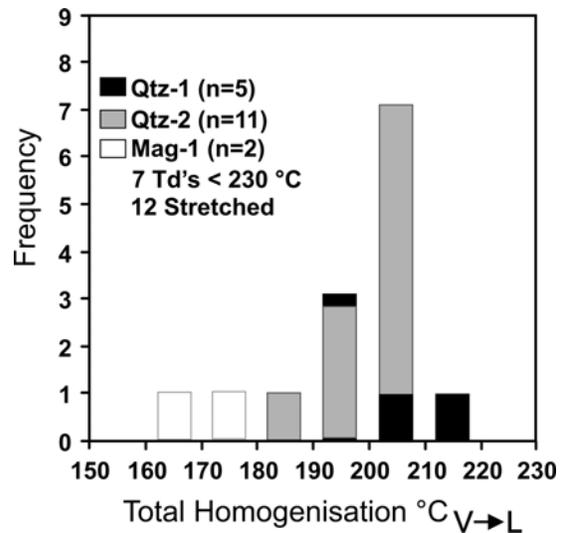


Figure 9. Total homogenization temperature histogram of the microthermometric data from the two-phase and three-phase fluid inclusions hosted within quartz and magnesite. All fluid inclusions measure homogenized to the liquid phase, with 7 inclusions decrepitating (Td) and 12 inclusions stretching. Data from the stretched and decrepitated fluid inclusions is not shown on the diagram.

kilometres. Minimum fluid inclusion homogenization temperatures of 195°C provide a minimum temperature limit of inclusion entrapment and diagenetic recrystallization or hydrothermal magnesite formation. Salinities of the magnesite-hosted two-phase fluid inclusions range from 6.4 to 7.8 wt% NaCl equivalent. Carbonic fluids responsible for emplacement of the quartz carbonate veins were not derived locally. They likely originated from an external source, suggesting nearby igneous or hydrothermal activity.

Exploration programs in southeastern British Columbia should be designed to be effective regardless of the origin of magnesite and compatible with both, the sedimentary/ diagenetic and hydrothermal hypotheses.

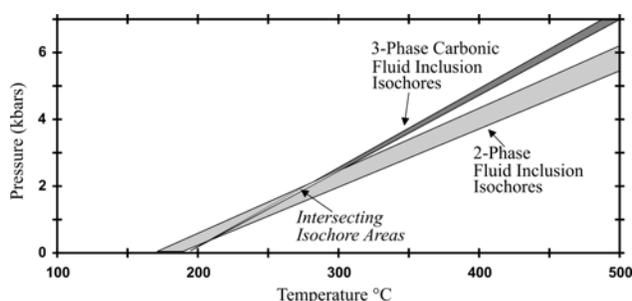


Figure 10. Pressure-temperature diagram showing the different isochoric constraints from the two fluid inclusion populations. The dark grey area represents the isochoric constraints derived from the three-phase carbonic fluid inclusions. The medium grey area portrays the constraints for the two-phase fluid inclusions. The light grey area represents the intersection of the two isochoric constraints.

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SHORT-WAVE INFRARED SPECTROSCOPY (SWIR) IN MAGNESITE EXPLORATION

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INTRODUCTION

Short-wave infrared spectroscopy (SWIR) analysis with field-based spectrometers is widely used in exploration for a variety of mineral deposits (Thompson *et al.*, 1999). This manuscript reports the results of an orientation study conducted for the purpose of evaluating the applicability of SWIR technology in exploration for magnesite deposits. Magnesite is used mainly in production of caustic, dead burned and fused magnesia (MgO), and magnesium metal. These products have a wide range of industrial, chemical, environmental and agricultural applications (Simandl and Hancock, 1996; Brown, 1999; Coope, 1999). Magnesite deposits in British Columbia belong to sparry variety as defined by Simandl and Hancock (1999) and are spatially associated with the sparry dolomite bodies. Several field methods developed in the past to distinguish between magnesite and dolomite during exploration programs (Simandl *et al.*, 1993), have limitations. The use of SWIR spectrometers provides a rapid and non-destructive field test for the presence of high-grade magnesite.

ORE AND HOST ROCK CHARACTERISTICS

In British Columbia, Precambrian to Cambrian sedimentary rocks host sparry magnesite deposits, mainly within dolostones (Simandl and Hancock, 1996; 1999). Magnesite-rich rocks that form deposits are typically white, light grey and massive or are characterized by sparry, pinolitic and zebra textures. Typically, major impurities are quartz and dolomite, while minor quantities include pyrite, calcite, clay and iron oxides, chlorite, calcite, mica, palygorskite and aragonite. These impurities occur as fracture fillings, in vugs, or along bedding planes. The MgO and CaO proportions in sparry magnesite are variable. MgO content is the most important parameter in exploration for magnesite deposits.

The dolomite host rocks are either the planar or sparry variety. Planar dolomite, which is the most common host to magnesite deposits, is texturally and mineralogically heterogeneous on the hand specimen scale. Textures may be massive, thick bedded to thinly

laminated, brecciated, stromatolitic or oolitic. Locally the rocks display prominent partings. The dolomite host consists predominantly of dolomite but may also contain some magnesite or calcite.

METHODOLOGY

Seventeen samples, including eleven magnesite-bearing rocks and six dolomites, were chosen from the Mount Brussilof, Anzak, Driftwood Creek, Topaz, Red Mountain and Boots Lake deposits in British Columbia. The samples were cut and approximately 2 kilograms sent for chemical analysis by XRF. A flat slab was kept for reference and analyzed using the PIMA-II short-wave infrared spectrometer. The instrument has an internal light source, allowing collection of laboratory quality data in the office or the field.

Short-wave infrared spectroscopy detects the energy generated by vibrations within molecular bonds. These bonds have bending and stretching modes within the 1300 to 2500 nanometre region of the electromagnetic spectrum. SWIR is particularly sensitive to certain molecules and radicals, including CO₃. The positions and shapes of absorption features in the spectrum are a function of the molecular bonds present in the mineral. The CO₃ molecule has a large decrease in reflectance value in the 2310 to 2360 nanometre range that shifts in position as a function of carbonate mineral chemistry. The major carbonate mineral compositions are shown on Figure 1.

RESULTS

Results of analyses of the 17 samples are summarized in Table 1, which includes sample type, major element analyses and the position of the dominant carbonate feature in the 2300 nanometre range. Feature positions were calculated using a hull subtraction. Representative spectra are shown on Figure 2. Overall, the magnesite samples exhibit a very narrow range of wavelength values, from 2298 to 2303 nanometres with most having a value of 2298 nanometres. The only exception is the sample from the JAB deposit that contains talc and exhibits an apparent feature position of 2308 nanometres.

TABLE 1. A REPRESENTATIVE ANALYSIS IS SHOWN FOR EACH SAMPLE. MgO AND CaO VALUES WERE DETERMINED ON A BULK SAMPLE BY XRF.

Spectrum	Sample No.	Deposit	Rock Type	Wavelength	MgO %	CaO %
Carb001b	A24/11-220c	Anzak	Dolomite	2307	26.16	25.76
Carb002c	B34/06-307	Topaz	Magnesite	2299	41.03	0.31
Carb003a	B35/17-314	-----	Dolomite	2319	20.39	29.65
Carb004b	B38/03-331	Red Mtn	Magnesite	2298	40.14	0.32
Carb005a	B40/04-346	JAB	Magnesite (plus talc)	2308	41.85	0.35
Carb006a	B41/02-358A	Clelland L.	Magnesite	2298	41.12	1.14
Carb007a	B44/01-386	Botts L.	Si, Mg-rich Dolomite	2301	28.8	10.64
Carb008b	D29/14-259	Driftwood Cr.	Mg-rich Dolomite	2316	30.08	19.21
Carb009b	D33/05-290	Driftwood Cr.	Magnesite	2303	38.3	0.83
Carb010c	D49/01-449	Driftwood Cr.	Magnesite	2296	38.62	0.1
Carb011a	M7/5-32	Marysville	Magnesite	2298	42.14	1.03
Carb012b	P52A	Baymag	Magnesite	2299	48.34	0.43
Carb013a	Bay-00-11	Baymag	Magnesite	2298	46.77	0.4
Carb014c	Bay-00-12	Baymag	Dolomite	2318	21.15	28.17
Carb015a	Bay-00-13	Baymag	Dolomite (low reflect)	2207	22.09	25.63
Carb016a	Bay-00-14	Baymag	Magnesite	2298	44.25	0.55
Carb017b	Bay-00-15	Baymag	Magnesite	2298	46.27	0.46

Dolomite samples are generally less reflective than the magnesite and have poorer spectra. One analysis was dropped (Bay-00-13) because of a very low reflectance response either due to a lack of carbonate in the analyzed sample or possible pyrite contamination that reduced the overall signal. The dolomite samples have wavelength positions greater than 2306 nanometres and in the pure dolomite samples typical values range from 2313 to 2319 nanometres. One sample with a large amount of Si in the chemical analysis has a wavelength position of 2302 nanometres, either reflecting contamination, or the presence of Mg-rich carbonate.

DISCUSSION AND CONCLUSIONS

The results of this reconnaissance study show that there is good correlation between MgO content, determined by XRF major oxide analysis, and the wavelength positions determined with the PIMA-II spectrometer. In addition, microprobe analyses of the magnesite from British Columbia sparry magnesite deposits shows remarkably uniform chemical composition on the crystal scale, consistent with the observed narrow range in wavelength positions in this study. The correlation is not as good for the dolomite samples, due to greater variability in bulk chemistry, textural variability and possible mineral mixtures. The following conclusions can be drawn from this preliminary study:

- Spectral analysis successfully identifies magnesite with the dominant feature exhibiting a very narrow

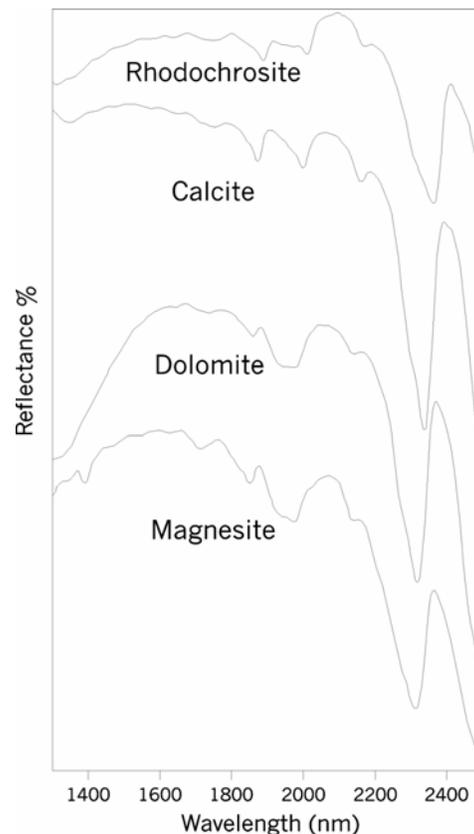


Figure 1. Representative spectra for calcite group carbonates showing variation in the dominant feature position (references from SPECMIN™; Hauff, 2001). Reflectance offset for clarity.

range of values from 2298 to 2302 nanometres (within instrument error).

- Dolomite samples have wider range of values for the 2300 nanometre position, correlating with a broader range in composition. The dolomites typically have values ranging from 2306 to 2319 nanometres.
- The observed variations provide a technique for use in exploration for magnesite deposits. Future work should include analysis of a much larger sample set in order to verify these results with greater statistical confidence.

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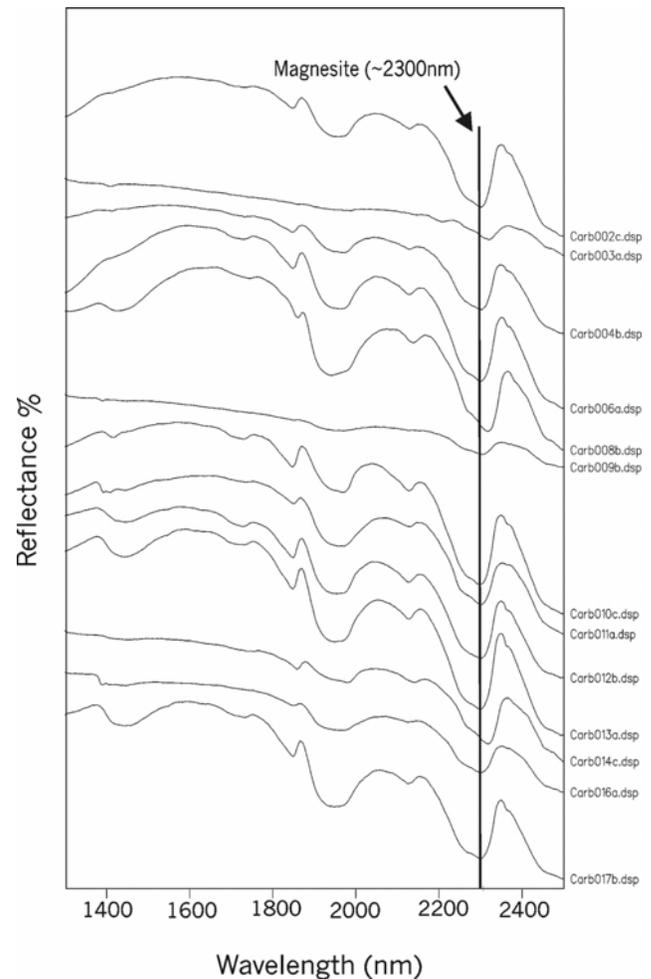


Figure 2. Representative spectra for magnesite and dolomite samples from deposits in British Columbia. Spectra with minima to the right of the magnesite line represent dolomite samples. Reflectance curves offset for comparison of spectra.

DRIFTWOOD CREEK MAGNESITE

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The Driftwood Creek magnesite deposit is the largest of a northwest trending cluster of similar magnesite occurrences hosted by Helikian age Mount Nelson Formation. The property is located 30 kilometres northwest of the Canadian Pacific rail line in Brisco, British Columbia. The Driftwood Creek deposit contains a resource estimated at 20 to 30 million tonnes of raw magnesite within several west-northwest trending stratabound lenses that are up to 200 metres wide.

The Brisco and Driftwood Creek deposits are hosted by dolomites of the Helikian Mount Nelson Formation of the Purcell Supergroup within the Purcell anticlinorium; they are situated west of the Rocky Mountain Trench fault (Simandl and Hancock, 1991). Mount Nelson is unconformably overlain by the Toby Formation of the Windermere Supergroup. The unconformity records the East Kootenay orogenic event, which consisted of regional uplift and metamorphism dated at 750 to 850 Ma, and submarine volcanic activity within the Purcell anticlinorium (Pope, 1989). The magnesite deposits are located within an area that was affected by low-grade regional metamorphism. The Driftwood Creek deposit occurs in the middle dolomite sequence of the lower Mount Nelson Formation.

In 1978, Kaiser Resources Ltd. performed a program of drilling, geological mapping and sampling. Results of the program indicated that there are approximately 22 500 000 tonnes of magnesite-bearing rock within the claim group (Morris, 1978). In 1987 and 1988, Canadian Occidental Petroleum Ltd. carried out detailed geological mapping and sampling of the prospect. Numerous faults were mapped in the area of the magnesite lenses (Rodgers, 1989). Older Mount Nelson Formation strata were thrust northeast over younger rocks of the Horsethief Creek Formation and resulted in the formation of two sets of cross faults that trend north-south and northeast-southwest. Cross sections show that the thickest part of the magnesite body is located along a ridge top near a topographic high. Surface exposure there exceeds 200 metres in width. The thickest part of the magnesite occurrence is flanked by a stratabound dolomite breccia

that is interpreted to be a dissolution breccia and collapse breccia.

Magnesite and sparry carbonate form stratabound lenses that are characterized by coarse to sparry crystals. Vestiges of hemispherical stromatolites are visible in the fine grained magnesite bearing rocks, and a stromatolitic horizon underlies the magnesite. Cherty dolomite overlies the magnesite. Although quartz veins and stringers 1 to 3 centimetres in width occur sporadically throughout the entire stratigraphic column, they are locally concentrated near fault zones and/or chert-bearing stratigraphy. Chert nodules and quartz veinlets up to 2 centimetres in width are the main impurities in the magnesite. Field relationships support a dolomite replacement origin. Trenching and diamond drilling intersected a pink granitic intrusion, which may have been a heat source for hydrothermal replacement of dolomite by magnesite. As is typical for macrocrystalline magnesite deposits, the coarse grained textures of the magnesite zone indicate that recrystallization occurred during regional metamorphism. Eleven 3.0 metre wide channel samples across a 33.0 metre outcrop exposure within the central "core" or thickest exposure of the magnesite horizon returned values of 44.3% MgO, 1.1% SiO₂ and 50.6% LOI.

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CLASSIFICATION OF MAGNESITE DEPOSITS WITH EMPHASIS ON THE MOUNT BRUSSILOF AND KUNWARARA TYPES

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Major magnesite deposits are hosted either by ultramafic or sedimentary rocks. Ultramafic rock-hosted magnesite ores consist mainly of talc-magnesite rocks (Simandl and Ogden, 1999) or they form “Kraubath-type” high-grade magnesite veins and stockworks (Zachman and Johannes, 1989; Paradis and Simandl, 1999).

Sedimentary-hosted magnesite deposits, discussed below, are either so-called “sparry” (Mount Brussilof - type) or “nodular/cryptocrystalline” (Kunwarara - type) deposits. Well-documented examples of sparry magnesite deposits are the Eugui deposit in Spain (Lugli *et al.*, 2001), the Mount Brussilof, Driftwood Creek and Marysville deposits of southeastern British Columbia (Simandl and Hancock, 1996; Simandl *et al.*, 1996), and the Veitsch deposit in Austria (Pohl and Siegl, 1986). Typically, sparry magnesite deposits are stratiform or lens-shaped and hosted by carbonates deposited on the continental platform. In many cases the magnesite-bearing horizon can be traced for several to tens of kilometres along strike (Simandl and Hancock, 1999). Most bodies are a few to tens of metres thick. The magnesite rocks are characterized by pinolitic, zebra-like (Figure 1) or xenotopic textures, and monopolar and antipolar growths (Pohl and Siegl, 1986; Simandl and Hancock, 1991, 1999; Lugli *et al.*, 2001). Typical grades for sparry magnesite deposits are 90 to 95% magnesite with resource estimates ranging from several million to hundreds of millions of tonnes. Although magnesite in some of these deposits has elevated iron content, magnesite from British Columbia deposits have very low iron in its crystal structure (Simandl and Hancock, 1996). High iron content adversely affects the refractory properties of the final product.

At Mount Brussilof (Figure 2), which is the only magnesite deposit currently in production in Canada, the high-grade ore is delineated by closely spaced drill holes, sampled, and selectively mined by open pit. Computer modeling, followed by controlled blasting maximizes the blending potential of the ore. Six daily production piles exist at any given time on the mine site. Subsequently, the ore is trucked to the processing plant where it is blended again if required (Knuckey, 1998). Typical grades of marketed products are given in the Table 1.

The Kunwarara orebodies in Queensland (Figure 3) are economically significant parts of an extensive nodular/cryptocrystalline deposit. The deposit is

subhorizontal, extends over 63 square kilometres, and averages more than 10 metres in thickness within a



Figure 1. Sparry magnesite, zebra texture, Mt. Brussilof Mine.

tertiary sedimentary basin. Magnesite ore is overlain by dark humus-rich clay sediment. The waste to ore ratio is 0.4 to 0.5. Proven reserves at sites KG1, KG2 and KG3 orebodies are estimated at 18.6 million tonnes and the total resource is estimated at 75.8 million tonnes, including the nearby Oldman deposit (Queensland Metals Corporation Ltd, 2000). Magnesite nodules make up 20 to 95% by volume of the ore and range from 1 millimetre to 50 centimetres in diameter. They consist of either bone or porous magnesite. Analyses of nodules (four representative samples) collected by Burban (1990) indicate 94.4 to 98.2% MgO, 0.82 to 2.04% CaO, 0.69 to 2.76 % SiO₂, 0.17 to 0.29 % Fe₂O₃, 0.08 to 0.29% Al₂O₃, and 0.06 to 0.2 % MnO on LOI free basis. The boron content averages 0.002%. Mining is carried out by open pit; no blasting is needed. The ore is washed, crushed, screened, and further upgraded by scrubbing, heavy media separation and cyclones. If necessary, it is sorted



Figure 2. Mt. Brussilof, sparry magnesite deposit, southeastern British Columbia.

optically. Other Kunwarara-type deposits are Yaamba and the Triple Four deposits. The latter is reported to consist of 77 million tonnes of material containing 35 million tonnes of magnesite.

Unbeneficiated magnesite nodules contain 92.3% MgO (Anonymous, 1987). After processing, similar to the Mount Brussilof operation, the ore is carefully stockpiled and blended.

Mining of the nodular ores of the Kunwarara deposit is inexpensive because blasting is not required; however, ore processing from this type of deposit is more complex than for ore from Mount Brussilof-type deposits. Both deposit types provide sources of raw materials for calcined, deadburn and electrofused magnesia, magnesium hydroxide, and other value-added products. They have also proven to be good starting

TABLE 1. CHEMICAL COMPOSITION (WT %) OF SELECTED PRODUCTS MARKETED BY BAYMAG INC.

Product	Fused MgO ¹	Baymag 30 ²	Baymag 40 ³	Baymag 96 ⁴	Baymag 58 ⁵
MgO*	97.2	97.2	97	97	96.5
CaO*	1.7	1.8	1.9	1.8	2.2
Fe ₂ O ₃ *	0.5	0.6	0.6	0.6	0.6
Al ₂ O ₃ *	0.2	0.1	0.1	0.2	0.2
SiO ₂ *	0.4	0.3	0.4	0.4	0.5
LOI		2	5		0.1
Mg					58.2

1. Magnesia carbon bricks and other high performance refractory applications where resistance to chemical attack is needed.
2. Acid neutralizer in manufacturing of MgO compounds, water treatment agent, gas desulphurization and fuel additive.
3. Applications where high reactivity is critical.
4. Cellular acetate, specialty refractories, Epsom salt, mag-sulfate cements
5. Mainly in animal feed industry.

* Reported on loss free basis in wt%.



Figure 3. One of the Kunwarara mines, Queensland, Australia (nodular magnesite deposit).

material for production of magnesium metal.

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ENVIRONMENTAL RISK ANALYSIS AND AGGREGATE MINING

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ABSTRACT

Environmental risk analysis has a vital role to play in protecting the environment from the impacts of mining. It is also a valuable tool that can be used by the aggregate industry to demonstrate that it can manage environmental issues and produce acceptable levels of environmental protection. Traditionally the concept of risk management has been applied to natural and man-made hazards. A potential environmental impact commonly is considered to be any action that may cause harm to the environment. Risk is the likelihood of the harm becoming actual. Commonly, risk is expressed in terms of consequences and the likelihood of the consequences being realized.

Environmental risk analysis uses a systematic approach to identify potential environmental impacts and hazards, their consequences, and the likelihood that they will happen. Through the analysis, environmental risks are evaluated and opportunities for risk reduction identified.

Risks exist because there are uncertainties. The uncertainty of ignorance occurs because potential hazards and risks have not been evaluated. The uncertainty of unknown occurs because our knowledge is limited. The uncertainty of disagreement exists when experts cannot agree or when experts and the thoughtful laypersons do not agree. This can be caused by lack of data, misconceptions, and mistrust. The uncertainty of linguistics exists because we often refer to events or quantities in imprecise terms, or in specialized jargon familiar only to people in our profession. The uncertainty of performance occurs because people make mistakes. The uncertainty of unpredictability occurs because some things, such as weather and earthquakes, are inherently unpredictable, and because nature is in a constant state of change.

Potential environmental impacts associated with aggregate mining, like noise, can be measured and expressed in quantitative terms, such as how loud and how long the noise exceeds the background level by a specified amount. Other potential impacts, such as sinkhole collapse due to quarry dewatering, result from a series of cascading impacts. These impacts are difficult to measure quantitatively and, therefore, must generally be expressed in qualitative terms. One way to qualitatively assess such impacts is to characterize their nature in terms such as: the range of the impact, the timing of the impact, the duration of the impact, the magnitude of the impact, the ability to predict the impact, and the ability to control the impact.

INTRODUCTION

Solum certum nihil esse certi

The only certainty is uncertainty

Pliny the Elder, *Historia Naturalis*

The environment today has a higher political profile than ever before, and protection of the environment has become a significant priority for society. The community expects and demands that environmental considerations be integrated into mining operations, and that the community not be left with a legacy of environmental damage created by the mining industry. Many people do not understand the environmental issues associated with mining, and understand even less the risks they pose.

Every action in life has a risk. Almost everything we do, or do not do, affects our risk exposure. For example, what we eat, how we travel, what physical activity we engage in, and how much sleep we get can directly influence the type, consequences, and likelihood of positive or adverse outcomes.

The aggregate industry is an extractive industry, and aggregate resources cannot be obtained from the landscape without causing changes. Aggregate extraction occurs in an environment that can only be partially defined in physical, chemical, biological, and anthropogenic terms. Consequently, a degree of uncertainty exists about the type and extent of adverse environmental impacts that the mining will have. If potential risks are not carefully characterized, then reliable prediction is difficult and greater levels of uncertainty about environmental risk are introduced. In addition, and perhaps of greater significance, an aggregate mining operation causes changes in the physical, chemical, biological, and anthropogenic characteristics of the area being mined, which could modify the expected environmental impacts of the mining should they occur.

Environmental risk analysis has a vital role to play in minimizing the impacts of mining on the environment. Thus it can be a valuable tool for the aggregate industry to use to anticipate problems and demonstrate that it is managing environmental issues to ensure that levels of environmental protection are acceptable. Environmental risk analysis uses a systematic approach to identify and

evaluate potential environmental impacts, the consequences of those potential impacts, the likelihood of those potential impacts happening, and ways to reduce the severity of those impacts.

Modern risk assessment has its roots in probability theory and in the causal linkages between adverse health effects and hazardous activities (Mileti, 1999). The concept of risk management traditionally has been applied to hazards to society created by human activity, such as dam failures or nuclear power plant failures; hazards to humans created by other humans, such as risk of being a victim of crime or being in a fatal traffic accident; and hazards to humans due to natural events, such as lightning strikes, earthquakes, floods, landslides, diseases, and so forth. Over the last twenty years, the concept of risk management has also started to be applied to hazards to the environment, such as the risk that human activities will cause water pollution, impact natural areas, or disturb wildlife.

Risk analysis is a subset of the risk assessment process, and risk assessment is an essential part of an overall environmental management system that can be fully integrated within an aggregate mining operation. This discussion focuses on issues relevant to environmental risk analysis.

TERMS USED IN RISK ANALYSIS

Terminology used in risk analysis varies between countries and authors, and the terms ‘analysis’ and ‘assessment’ are sometimes used interchangeably in the literature on risk. There has been considerable debate about how each term should apply to environmental risk management. Some consider ‘analysis’ to include everything that is done to establish an understanding of risk and its characteristics, and ‘assessment’ to be limited to the comparison with specific criteria. Others consider ‘assessment’ as the wider term and ‘analysis’ as a part of the process. The diverse origins of risk management theory, and wide variety of disciplines involved led to the differences in terminology. The debate is essentially semantic, and although the specific terms are not important, the substance is. The core of risk methodology is the analysis – breaking down the systems, hazards, and risk attributes into their constituent elements and examining and testing those elements, their linkages, and their interactions (Dryden and Beer, 1999).

In this discussion, a *potential environmental impact* is considered to be any action that might alter the environment. An *initiating event* causes a potential environmental impact to happen. A *consequence* is the intermediate or final outcome of an event or situation. An *environmental risk* describes the consequences if the impact becomes real, and the *likelihood* that the impact will become real. There can be environmental risks without any environmental consequences actually

occurring. The question is, can the operator successfully manage the risks?

Risk analysis means the systematic use of information to identify hazards and to estimate, quantitatively or qualitatively, the likelihood and consequences they will be realized. *Environmental risk analysis* separates risk to the environment from other mining risks, such as occupational safety and health issues, which are not included in this discussion.

Environmental risk assessment is a larger process that includes risk analysis, as well as the systematic application of policies, procedures, and practices to identify potential environmental impacts; analyze the consequences and likelihoods associated with those impacts; estimate risk levels; assess those levels of risk against relevant criteria and objectives; make decisions; and act to reduce risk levels.

An *environmental management system* includes environmental risk assessment, and is an overall, fully integrated system within an aggregate mining operation that has organizational structure, assigned responsibilities, and defined practices, procedures, policy, goals, and objectives (Welch, 1998).

Risk analysis techniques can be used to identify and characterize environmental impacts, can be part of a larger risk analysis process, or can be part of an integrated environmental management system. This discussion focuses only on issues relevant to identifying and characterizing environmental impacts.

UNCERTAINTY - WHY THERE ARE ENVIRONMENTAL RISKS

Risks exist because there are uncertainties. If we knew with absolute certainty the consequences of an action, there would be no risks. Uncertainty is a factor of the world in general, including aggregate operations.

Uncertainty creates a situation in which risks can either be overstated or understated depending on motives or choice (Mileti, 1999). There is also the possibility that risk assessments will suggest that uncertainty is due to the lack of data or the quality of the data, when in fact it is due to a difference in professional judgment. Some risk assessments give the impression of better knowledge and certainty than actually exists. Uncertainty may also create the perception that certain risks exist even if they have not been analyzed.

There have been a number of attempts to create taxonomies of different types of uncertainties, including those by Morgan and Henrion (1990), Wilson and Shlyakhter (1996), Dryden and Beer (1999), and Beer and Foran, (2000). The types of uncertainties that are most applicable to environmental risk analysis are:

- Uncertainty of ignorance

- Uncertainty of unknown
- Uncertainty of disagreement
- Uncertainty of linguistics
- Uncertainty of performance
- Uncertainty of unpredictability.

The *uncertainty of ignorance* occurs because hazards and risks have not been investigated – we do not know because we did not ask (Dryden and Beer, 1999). This uncertainty commonly leads to the question “What if something goes wrong that you failed to anticipate?” A comprehensive environmental management system should strive to eliminate the uncertainty of ignorance.

The *uncertainty of unknown* occurs because our knowledge is limited – we asked but we could not determine the answer (Dryden and Beer, 1999). For example, we do not fully understand how ground shaking caused by blasting may impact rock stability. This uncertainty commonly requires using conservative estimates as a precautionary measure. The uncertainty of unknown stems, in part, from the fact that mining involves development in only partially defined environments. It also stems from the fact that engineering and the natural sciences are not always exact sciences. Engineering testing protocols, design, and construction techniques are continually improving, as are scientific sampling, testing, interpretation and judgment. A comprehensive environmental management system should strive to identify and manage the uncertainty of unknown.

The *uncertainty of disagreement* commonly exists when experts do not agree, or when experts and thoughtful laypersons do not agree. Disagreements between experts and thoughtful laypersons are attributed to numerous causes; typically they are based on lack of data, misconceptions, or mistrust (Margolis, 1996). The scientific method, including gathering data, analyzing data, and comparing alternative theories, usually leads to consensus among unbiased scientists. However, there are times when disagreement among experts continues to exist, especially when data are incomplete or difficult to obtain (Morgan and Henrion, 1990), or when ardent opponents with their own agendas misrepresent facts to make their point.

The *uncertainty of linguistics* exists because we often refer to events or quantities in imprecise terms (Morgan and Henrion, 1990), or because we speak in technical terms that are not clearly understood by others outside our profession (Arbogast, 2001). For example, “the flow of a spring” is an imprecise quantity. “The net flow of a spring on January 1, 2001 between 1200 and 1300 hours, local time” is more precise.

The *uncertainty of performance* occurs because people make mistakes, including human error in calculations, design, sampling techniques, or interpretations. Performance issues are commonly

addressed with quality control procedures or with environmental management systems.

Many natural activities such as weather and earthquakes are inherently unpredictable and create the *uncertainty of unpredictability* (Dryden and Beer, 1999; Beer and Foran, 2000). Further, natural systems are in a constant state of change, either through natural processes or due to human activity. The uncertainty of unpredictability commonly is addressed by utilizing probabilistic methods, and by employing monitoring and response programs.

THE AGGREGATE INDUSTRY AND ENVIRONMENTAL RISK

Aggregate resources cannot be obtained from the landscape without changing it. During mining, decisions are constantly being made in response to the intended or unintended effects of the mining operation. By its nature, aggregate extraction involves development in three dimensions. Unfortunately, we cannot completely characterize what is below the land surface, and there is always a degree of uncertainty about the type and extent of potential adverse impacts. For example, many hydrologic processes that can be affected by aggregate mining operations underground where they cannot be observed, and some types of impacts on the groundwater system occur far from the operation. To further complicate matters, the physical, biological, and cultural characteristics of an area either impacted by or impacting an aggregate operation are continually changing, and those changes may influence the environmental impacts of mining. For example, an environmentally sound crushed stone operation in a karst area could start causing damage to the environment if the nearby groundwater system is modified by natural conditions, such as a prolonged drought, or by human activity, such as increased groundwater withdrawal by a nearby water-well field. Our inability to completely understand natural systems and the uncertainty associated with possible changes over time introduces environmental risk.

Environmental disturbance caused by aggregate mining can be due to engineering activities carried out during aggregate extraction or processing. The most obvious impact is the conversion of land from undeveloped or agricultural status to an open pit or quarry. This major impact may be accompanied by loss of habitat, noise, dust, vibrations, chemical spills, erosion, sedimentation, changes to the visual scene, and abandonment of the mined site without remedial action. 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. Generally, they can be restricted to the immediate vicinity of the aggregate operation by employing responsible operational practices that use modern engineering

techniques and technology. Descriptions of common impacts are presented in Barksdale (1991), Kelk (1992), Smith and Collis (2001), Lüttig (1994), Bobrowsky (1998), Primel and Tourenq (2000) and Langer (2001).

Mining aggregate can lead to serious and obvious environmental impacts in some situations, but others are not obvious, particularly in geologic environments such as active stream channels, slide-prone areas, and karst areas. These environments are dynamic and respond rapidly to outside stimuli, including aggregate extraction. In these situations, aggregate mining may alter sensitive parts of the natural system at or near the site, and create *cascading environmental impacts*. For example, aggregate mining in a karst area might lower the water table, which could remove the buoyant support to rock that overlies water-filled caverns or other solution features. This might result in collapse of the land above the caverns and the creation of a sinkhole.

Mining aggregate might be acceptable in some environmentally sensitive areas, but should be conducted only after careful risk analysis, and then only with extreme prudence. Failure to do so can lead to serious, long-lasting, and irreversible environmental consequences, not only near the operation but also at locations some distance from the site.

A number of factors go into minimizing environmental risks from mining aggregate. Meeting conditions required to obtain mining permits, and enforcement of government regulations and requirements play a major role in preventing common environmental risks. Economics and the desire for safe operations are also strong incentives for environmental compliance. Even with no incentives, the chance of good luck may allow an operation to work without causing any serious environmental problems. However, a carefully conducted environmental risk analysis lessens risk and is essential to a proactive environmental management system.

IDENTIFYING AND CHARACTERIZING POTENTIAL ENVIRONMENTAL IMPACTS

Commonly, factors and their interactions that cause environmental risks are inadequately understood (Cross, 2000). Risk analysis involves breaking the hazard and risk attributes of the system down into their constituent elements, then exploring, examining, and testing those elements and their linkages and interactions (Mileti, 1999). It is not possible to examine every possible risk in all possible combinations of any complex system. Careful scenario development does, however, enable most risks to be reasonably considered (Dryden and Beer, 1999). Risk analysis should address not only real or actual risks, but also perceived risks.

The process should be as simple as possible, but must not be oversimplified. Identifying potential environmental risks starts out with the assumption that what can go wrong will go wrong. Perceived environmental impacts can be eliminated after they are considered if it is clear that their consequences would be insignificant or if they are unlikely to happen.

Environmental risk identification should be a structured process. It must systematically work through the elements of the planned or existing aggregate operation to discover and evaluate any aspects of the mining operation that could lead to significant adverse outcomes. This process should consider impacts beyond the obvious ones, because less common factors often result in environmental problems (Dryden and Beer, 1999).

The traditional risk model is linear. However, natural systems should be studied holistically because a system is different from the sum of its parts (Mileti, 1999). Thus, environmental risk models need to take a more systems-based approach to understanding the complex interactions between humans and the natural environment.

Langer and Kolm (2002) designed a holistic systems analysis method (Figure 1) to characterize natural and human systems, identify potential aggregate mining impacts to those systems, and evaluate the extent of those impacts. The method is iterative, and generally follows that employed by process geomorphologists. The process begins with a definition of the problem. The analysis and the models that are built drive the problem, not vice versa (Morgan and Henrion, 1990). The problem definition is refined as the understanding of the system improves by incorporating more detail on those parts of the system that have been shown to be important, and by simplifying those that are less important.

The process continues with data collection, and conceptualization and characterization. The systems analysis method includes an integrated analysis of various systems that make up the environment, including land surface, geomorphic, subsurface, and groundwater systems. The process is iterative, and is repeated at any time the characterization reveals the need.

Identifying and evaluating potential impacts requires understanding about how the various parts of the natural system (including the human part) create and transmit impacts, and the resulting condition of the impacted system. The process begins by selecting a method of mining and processing aggregate based on the characteristics of the site. Rerunning the site characterization process using the new parameters created by the mining method identifies potential environmental impacts of the mining. By comparing the “before mining” and “during mining” scenarios, it is possible to determine how the systems will be affected by mining and how the systems will change. The possible changes are evaluated to decide whether the impacts are acceptable or whether

mitigation is needed. For example, risk analysis may show that draining a pit in order to extract sand and gravel from beneath the water table causes unacceptable risks to nearby wetlands whereas extracting the material from a flooded pit by using a dragline does not create serious risks.

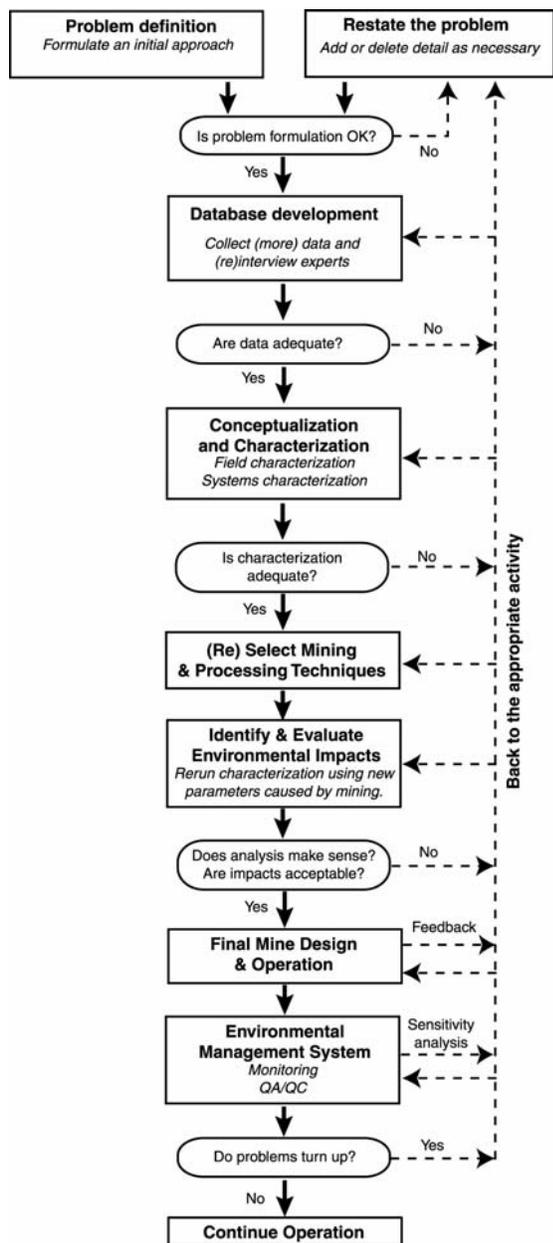


Figure 1. - Diagram showing systems analysis of potential environmental impacts from aggregate mining.

The systems analysis approach emphasizes process and response, and recognizes multiple and interrelated causal factors. This is of particular interest when systems are open to potential changes. The approach is continually adjusted based on feedback from previous iterations. There is a marriage between hierarchical systems analysis and risk analysis because there is much common ground

between the process and response analysis used in hierarchical systems and the initiating events and consequences analysis used in risk analysis.

The data collection phase forms the basis of all subsequent analysis and is critically important. A wide range of data sources can be used for analyzing both likelihoods and consequences. Data types include data on the natural systems (derived from site characterization), as well as data about the mining and processing methods, reliability and failure statistics for equipment, and the possibility of human error.

There are well-established databases for equipment, like drill rigs, trucks, and crushers that are based on industrial experience. For other analyses, sources of high quality data may not be available and it may be necessary to compile, manipulate, or extrapolate data. Before the operation starts up, this may be done by referring to experience in other similar regions, although care is needed to ensure that the data applies to the new mine site (Dryden and Beer, 1999). Later, data collected at the mine site would be used to refine estimates based on the general data.

The experience of facility or company personnel can be invaluable, especially if other independent and applicable data is not available. However, analyses indicate that people generally give much more accurate and consistent responses to questions about likelihoods of component events than for the entire system. Therefore, the emphasis during risk analysis should be on the variables, not the specific consequences or likelihoods (Dryden and Beer, 1999). Various techniques to obtain this type of information include questionnaires, interviews and group sessions.

INITIATING EVENTS, CONSEQUENCES, AND LIKELIHOOD ANALYSIS

The term *initiating event* refers to the action that triggers an environmental impact. In some situations, one action can cause one or multiple events, and determining the cause and effect are relatively straightforward. For example, clearing the land can create noise and dust. In other situations, two or more actions combine to initiate one or multiple events. For example, clearing the land, by itself, has no direct impact on erosion. However, a later major rainfall can result in rapid erosion and sedimentation.

Logic trees are an analytical method used to try to understand the roles of components in causing environmental impacts. In this method the sequence of events are organized and the role and relationship of the variables affecting the outcome established (Dryden and Beer, 1999). Figure 2 shows a sample logic tree for sinkhole collapse related to changes in the water table.

Logic trees may be *consequence-driven* (such as in Figure 2), and show the events leading to one consequence, or can be *event-driven*, and show the consequences that may result from one initiating event.

Both humans and nature can cause initiating events. As related to aggregate operations, potential human initiating events include drilling, blasting, excavating, quarry or pit dewatering, in-quarry or in-pit transport of material, crushing, screening, and washing material.

Human activity outside a quarry or pit can also initiate events. For example, paving over an area that was in its natural state could increase runoff and flood an otherwise dry quarry. Other off-site human activities that may trigger events include other mining, construction, blasting, agricultural activities, and changes in uses of the land. Some human initiating events can be predicted and plans can be made to deal with them. However, many are not planned and some happen after the environmental analysis is conducted. Predicting this type of event is very difficult.

Natural initiating events include climatic events (droughts, heavy precipitation, and precipitation during critical times such as when fish spawn), seismic activity, landslides, natural ground-water level changes, and natural fluvial processes. Most natural initiating events are difficult to predict but historical events can be considered in planning.

Initiating events due to mining can involve choices. For example, if a quarry intercepts the water table, the operator can either mine the wet material or dewater the quarry. Dewatering could impact the water table level elsewhere and become an initiating event.

A cascading environmental impact can also be the initiating event for a subsequent impact. For example, excavating rock in a karst area might intercept a natural conduit, which might cause flooding of the quarry. Further, the operator might decide to dewater the flooded quarry, which might lower the ground-water level, and result in a loss of buoyant support and sinkhole collapse (Figure 2).

The results of environmental risk estimation or characterization indicate the likelihood of possible adverse outcomes by combining the outputs from the consequence and likelihood analyses. *Risk estimation* is the term usually applied when the analysis has a substantial quantitative component, *risk characterization* is used when the analysis is largely qualitative (Dryden and Beer, 1999).

Risk estimates can be described in terms such as the likelihood of a specific environmental impact occurring per unit of time, per unit of area mined, or per unit weight or volume of material produced. In instances where rare or endangered species or sensitive ecosystems are involved, the relevant measure may be the probability that the aggregate extraction will affect the species or ecosystems during the life of the operation. In some

circumstances, the operator might need to define a method of measuring the potential risk that meets the special or unique circumstances of the particular case. Commonly, quantified risk levels are presented graphically as risk contours, color bands, or three-dimensional depictions.

Risks related to cascading environmental impacts are seldom quantifiable. Qualitative rankings assigned to them often are based on pairs of terms describing consequences and likelihoods. The known factors that influence likelihood and consequences can be analyzed to arrive at the terms like those used in Figure 3. The analyst ranks and weights various properties to factor knowledge and experience into the process.

Consequences and likelihoods are seldom as simple as shown in the matrix (Figure 3), and commonly require more detailed descriptions (Cross, 2000). Consequences can be expressed in terms of the extent, timing, duration, and severity of the impact or the vulnerability and resilience of areas impacted. Likelihood can be expressed as the ability to predict and control the impact (Langer and Kolm, 2002). For example, environmental impacts that are limited to the site have a short duration, are of small impact, are easy to predict and are easy to control, are usually preferable to impacts that are far-reaching, severe, long-lasting, difficult to predict, and difficult to control. Similarly, long-lasting impacts are difficult to control, affect vulnerable areas, and commonly are unacceptable.

The *range of the impact* refers to the extent of the area that is affected by the aggregate operation, and can be expressed as restricted to the site, near the site or widespread. Changes in the use of the land are commonly restricted to the site. Noise and dust generated by mining are generally of limited extent. However, erosion, sedimentation, and changes to the visual scene may be widespread.

The *timing of the impact* refers to how soon the impact develops after initiation of mining site development takes place immediately but other effects may not be noticeable until many years later. An example would be lowering the water table.

The *duration of the impact* is expressed in terms of time. Impacts associated with noise last only as long as the equipment generating the noise is active. In contrast, land disturbance by the operation lasts until the operation is reclaimed, at which time another land use change will be initiated. Effects like erosion may last for an extended period of time beyond the life of aggregate extraction.

The *severity of the impact* relates to the vulnerability and resilience of areas involved. The harm the event creates is expressed in relative terms such as small to large, low to high, or minor to major. For example, noise may be a major issue near the source, but minor at some distance from the source. Habitat of rare or endangered species may be highly vulnerable.

The *ability to predict the impact* involves estimating the likelihood, range, timing, and duration of the event. This factor is expressed in relative terms such as easy or difficult. Predicting the range, timing, and duration that results from mine start-up is relatively easy; predicting for the extent of subsequent erosion is more difficult and requires expert analysis.

The *ability to control the impact* refers to how easily an impact could be avoided, minimized, or mitigated. It also is expressed in relative terms, such as very easy, moderate, difficult, or impossible. Dust generation, for example, commonly can be minimized by using modern production techniques and technology. Erosion may be as difficult to control as it is to predict. These impact characteristics often are interrelated. For example, an impact that starts a long time after the initiating event may be difficult to predict and control.

IDENTIFYING RISK CONTRIBUTORS AND OPPORTUNITIES FOR RISK REDUCTION

One of the most useful results of the environmental risk analysis process is to identify aspects of the systems that are most likely to contribute to environmental risk (Dryden and Beer, 1999). It is much easier to precisely target risk management measures by looking at individual parts of the system rather than at the whole system. The most sensitive variables can be identified from the logic trees by grouping risks with common consequences or by grouping risks with common initiating events. Grouping risks with common consequences can help control the seriousness of events. For example, grouping risks with common consequences, such as the creation of dust, can result in an integrated dust control plan. Grouping risks with common initiating events can help identify risk avoidance opportunities. For example, grouping potential problems that can stem from lowering the ground water table by quarry dewatering can help determine the relative value of dewatering and how to proceed to minimize risks. Once sensitive variables have been identified, the risks of environmental impacts can be reduced by modifying operational procedures, implementing different mining or processing technology, or by major changes such as relocation of the facility.

FEEDBACK AND SENSITIVITY ANALYSIS

Once aggregate extraction begins, analysis of the third dimension becomes possible. New information gained should be incorporated into the databases, and when necessary, new systems characterizations should be conducted.

The environmental analyses should also be subjected to sensitivity analyses by using the logic trees prepared as part of the environmental risk analysis. Events or outcomes at the tops of the logic trees happen less frequently than other events or outcomes. Points in the lower levels of the logic trees can be identified, and the predicted outcomes compared against actual operational experience. Periodically conducting this type of sensitivity analysis can also serve as an early warning indicator.

SUMMARY

Aggregate extraction involves development in three dimensions. Data is generally not available to completely characterize what is below the land surface or the hydrologic processes that are affected by mining. Furthermore, because the physical, biological, and cultural characteristics of the area impacted by an aggregate operation are constantly changing, the changes may interact with the impacts of mining. The complexity of natural systems, and the uncertainty associated with possible changes over time makes prediction of the type and extent of potential adverse impacts difficult.

Risk analysis is a formalized method of dealing with uncertainty that can be applied to the prediction and analysis of potential environmental impacts from aggregate mining. Environmental impact analysis allows operators to identify potential environmental impacts for a variety of aggregate mining approaches and to develop mitigation techniques. The risk assessment process systematically examines elements of the aggregate operation in the context of their natural systems. It breaks down the systems and their environmental risk attributes into their constituent elements by exploring, examining, and testing those elements, their linkages, and interactions. With the emphasis being so strong on environmental protection in today's society, it is essential to combine risk analysis with aggregate mining to head off environmental problems before they happen.

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	Consequence				
	Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood					
Almost certain	S	S	H	H	EX
Likely	M	S	S	H	EX
Moderate	L	M	S	H	H
Unlikely	L	L	M	S	H
Rare	L	L	M	S	S
Unknown	S	S	H	H	EX

- EX Extreme risk: Project not viable without major redesign
- H High risk: Effective control measurements, monitoring program, and hazard response program must be demonstrated
- S Significant risk: Effective control measurements and monitoring program must be demonstrated
- M Moderate risk: Program for reduction must be specified
- L Low risk: Manage by routine procedures

Figure 3. – Matrix characterizing environmental risk by combinations of consequences and likelihoods (Modified from Cross, 2000)

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CAN PROBABILISTIC NEURAL NETWORKS BE USED TO SUCCESSFULLY CLASSIFY CARBONATE AGGREGATE?

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Geologists, material engineers and others concerned about aggregate could benefit from using classifications resulting from probabilistic neural networks. Classification may be improved if both geology and geotechnical characteristics are considered together. Probabilistic neural networks are based on a combination of criteria that may lead to recognizing and delineating better quality aggregate sources.

Probabilistic neural networks belong to a class of techniques collectively called "artificial intelligence" where the program is structured in ways roughly patterned after the layout and network of biological neurons (Master, 1993). The computer program is taught to distinguish between groupings of items with the use of a training set. For probabilistic neural networks, assumptions about the distribution of random variables used in grouping are not required (Singer and Kouda, 1999.)

Aggregate, including that created by crushing carbonate rocks (for example, limestone, dolomite), is required to possess minimum geotechnical qualities before it can be used in asphalt and concrete construction. These geotechnical qualities are measures of the chemical and physical properties of aggregate samples as determined in the laboratory. The laboratory test results are believed to be reasonable approximations of how the aggregate is likely to behave during use. Specific gravity, absorption, resistance to disruption by mechanical breakdown by abrasion and impact (Los Angeles wear test), and freeze-thaw tests (Marek, 1991) are examples of some geotechnical variables that may be considered. Aggregate performance over the life of the structure in which it is used is vitally important because aggregate typically comprises well over 90 percent by volume of asphalt and concrete. The best aggregate is strong, chemically inert and readily adhered to by the bonding paste, be it asphalt or portland cement. Demands for better and longer-lived structures and roads have resulted in more stringent aggregate requirements. This translated into reduced usable aggregate resources.

Carbonate rocks have been one of the most important bedrock sources of crushed aggregate in the United States, accounting for about 70 percent of total aggregate production (Langer and Glanzman, 1993). Although numerous classification schemes have been developed for carbonate rocks, Mazzullo and others (1992) note that those of Folk (1959, 1962) and Dunham (1962) are the

most widely used by academia and the petroleum industry. Rock classification used by the aggregate industry is comparatively simple and too general for use in this study. To date, no classification has been developed that combines geotechnical with geological characteristics.

Detailed geologic information can be purely descriptive, giving observable characteristics of carbonate rocks including bed thickness and style, texture and grain size, nature and type of recrystallization and cementation, type and number of fossils, and the type and abundance of impurities such as chert. Chemical compositions of the carbonate rock and regional geologic setting can also be considered. The geologic setting may include depositional environment, for example, transgressive versus regressive, depth of burial, and tectonic setting. Carbonate rocks can be extensively modified when subjected to subareal weathering, cave development, and diagenesis.

Singer and Kouda (1997) developed an application of a probabilistic neural network to classify mineral deposits (based on mineralogy) into standardized mineral deposit types. When testing this classification, 98% of the deposits were correctly classified (Singer and Kouda, 1997).

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ENGINEERING GEOLOGY OF AGGREGATES BRITISH COLUMBIA

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ABSTRACT

Aggregates represent an often overlooked, but important portion of the mining industry in British Columbia. Engineering characteristics of aggregates are directly dependent on the geological composition and mode of origin of the sediments or rock being mined. A brief historical overview is provided for context, and then methods used for the engineering quality assessment of aggregates in British Columbia are presented, with examples of typical test data. Finally, a summary of problems and projected trends associated with engineering geology and quality in the British Columbia aggregate industry is provided.

INTRODUCTION

Historical Background

Historically, British Columbia has enjoyed a plentiful supply of economic, good quality aggregate, due to its geologic heritage and physiography. The combination of mountainous terrain composed of highly varied bedrock geology, and Pleistocene and Recent glaciofluvial activity produced numerous deposits of sand and gravel. Many deposits were located within or near the areas in which aggregates were required.

In fact, sand and gravel for use in construction was so plentiful, easy to find and develop, that little thought was given to quality testing, demand forecasting or inventory development, as has been done in areas where aggregates are less plentiful. Fortunately, many of the deposits produced materials of high quality.

British Columbia's heavily-populated south coast region consumes at least half the total aggregate produced in the province. Areas which are now heavily populated and extensively developed were once dotted with aggregate pits and a few quarries. Later, growth in the Greater Vancouver region population led to mining of larger deposits in areas such as south Surrey, Langley, Mary Hill (Port Coquitlam) and Coquitlam River valley in Coquitlam. These deposits differed from the smaller, local pits which provided the earlier supplies of aggregate in that they represented thicker, more extensive deposits where the economy of scale can be exploited.

Quality Testing of Aggregates

As the demand for aggregate increased, consideration of the quality requirements became more important. The combined effects of rapid population growth, environmental awareness, the stream-proximal

location of most aggregate deposits, and depletion of older pits resulted in steadily-mounting pressure upon the aggregate industry. As well, owners and engineers are demanding higher quality for all materials they use, including aggregates. Troublesome and expensive problems can sometimes be attributed to certain components of aggregates, so owners and specifiers have adjusted their specifications to ensure that only tested and proven materials are used on their projects.

Unlike other regions, where aggregate quality testing protocols can be at a considerably higher level, those in British Columbia are generally less stringent. This can be attributed in part to the overall natural high quality of many British Columbia aggregate sources, many of which have had a history of successful performance.

For road construction and asphalt paving, *Superpave* and other recently-developed standards have raised quality requirements relative to those previously used. Factors such as increased crush counts, and the use of angular rather than naturally-abraded (rounded) aggregates, have resulted in either the need to use crushed oversize aggregate or to blend in crushed quarried stone to meet the necessary quality standards. British Columbia roadways, with their constant heavy wheel loads, high traffic volumes, and low rehabilitation budget allowances, are at risk. Applying the new standards can avoid problems like deeply rutted wheel paths, heavy alligator cracking and premature pavement deterioration.

Ramping up of quality requirements in Standards such as CSA and *Superpave*, modified practice for new construction projects, and the need to meet requirements set for foreign markets where British Columbia aggregates are now being shipped is forcing aggregate producers to undertake higher aggregate testing protocols.

In contrast with eastern and central Canada, where quality control costs are estimated to be as much as

\$0.65/tonne of the cost of certain aggregate products, those in British Columbia are generally far lower. Typical costs for quality control testing in British Columbia range from \$0.0/tonne to \$0.10/tonne.

TEST STANDARDS

The test standards used in British Columbia generally were developed in eastern and central Canada, for example Canadian Standard Association (CSA), or in the United States, for example American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO). Their adoption, use and enforcement in British Columbia have been uneven, often lagging behind that in other regions. Occasionally, the use of British Standards, such as BS 812, is seen, reflecting the authority accorded those test standards.

Some test methods that are widely used and accepted in other regions of Canada are not as well known or as commonly used in western Canada. An example of this would be the Micro-Deval test (CSA A23.2-23A, -29A), which has been widely accepted and applied in Ontario, but only used in a few laboratories in British Columbia, including two Ministry of Highways facilities. Results from this test are promising, and it may be included in the next revision of the British Columbia Highways Standards.

The British Columbia *Master Municipal Specification* document generally references test methods from CSA, ASTM, and British Columbia Highways.

Canadian Standards Association (CSA)

Many of the test methods provided in CSA A23.1/A23.2, "Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete", assess quality of *concrete* aggregates. In practice though, these test methods are also used in British Columbia to assess aggregate used in other applications, including road base aggregate, paving aggregate, railroad ballast, and shoreline and coastal works materials.

Most of the CSA tests have equivalents in other standards. Typical CSA tests used in British Columbia include Sieve Analysis, Organic Impurities, Sulphate Soundness, Los Angeles Abrasion, Concrete Prism, Relative Density (i.e., "Specific Gravity") & Absorption, Flat & Elongated Particles, and Accelerated Mortar Bar tests.

In addition to these tests, CSA A23.2-00 also provides two Standard Practices that provide analytical tools for assessing the degree to which new concrete

construction may be affected by Alkali-Aggregate Reaction in concrete.

British Columbia Ministry of Transportation (BCMOT)

The Provincial Ministry of Transportation has developed test standards that are given in Standard Specifications for Highway Construction. Some of the test methods given in this standard have been adopted and modified from other existing test standards to reflect experience with British Columbia aggregates. Test methods specified in the British Columbia Standard Specifications are taken from BCH test procedures standards, and from CSA A23.2.

Aggregates to be used for highways construction are required to meet applicable BCH specifications.

American Society for Testing and Materials (ASTM)

The Testing Standards given in ASTM documents are voluminous and wide-ranging. Tests which evaluate aggregates are found in "Concrete and Aggregates", as well as in "Soil and Rock" volumes, and involve dozens of individual test methods. Some of the more commonly-used tests include Bulk Density, Sulfate Soundness (Sodium or Magnesium Sulfate), Specific Gravity & Absorption, Los Angeles Abrasion, Sieve Analysis, Petrographic Examination of Aggregate, Accelerated Mortar Bar Test, Concrete Prism Test, and Durability Index.

American Association of State Highway and Transportation Officials (AASHTO)

This intergovernmental body, of which the British Columbia Ministry of Transportation & Highways is an associate member, has developed a number of test procedures and specifications that are based upon similar requirements for road and highway construction. The focus of these tests is to evaluate and qualify aggregates specifically for road transportation. Hence, the emphasis is on tests of characteristics of aggregates that affect durability of pavements (asphalt and concrete), bridge decks and other bridge components, road bases, and road surfacing.

AASHTO thus provides tests that parallel those given in CSA or ASTM, but also provides a number of tests which are unique. In British Columbia, the Ministry of Transportation standards apply versions of some AASHTO tests.

California Department of Transportation (CalTrans)

CalTrans also has developed a number of its own tests, and some variants differ from those in similar ASTM or CSA standards. Their tests include Sand Equivalent, Los Angeles Rattler, Cleanness Value, and others.

The California market is a current as well as potential market for British Columbia aggregate suppliers located at or near the ocean; so many aggregate suppliers have elected to test their products using CalTrans test standards.

GEOLOGY OF AGGREGATES IN BRITISH COLUMBIA

In British Columbia, the proportion of aggregate derived from natural sands and gravels far exceeds that produced from crushing quarried rock. Research by Levelton (1996) found that only 14% of aggregate supplied to the Lower Mainland region of the province was derived from quarried materials. Although the proportion may be slightly higher now for the South Coast, on a provincial basis, the proportion is lower.

The surficial deposits which comprise most of the aggregate supplies in British Columbia are of fluvial or glaciofluvial origin. Many are Pleistocene or Recent in age, and the geological composition of most reflects the regional geology of the area where the deposit is located, although particles that have been transported from sources a great distance away from the deposit are common. Some typical far-traveled components include sandstones and quartzites in lower Fraser Valley deposits whose sources are formations in the Rocky Mountains. Indicated travel distance for these clasts would be on the order of 1500 to 2000 kilometres.

By contrast, some sand and gravel operations have been established in deposits which are of local provenance, for example, alluvial or colluvial deposits. In these cases, transport of sediments may have been only a few hundred meters. These deposits tend to be uniform in composition, and poorly-sorted, with angular particle shapes. Although some are suitable material for aggregates, others are of poor quality.

The most desirable aggregate resources tend to be in deposits that are of fluvial or glaciofluvial nature. Sediments in these deposits generally have favourable physical qualities, due in part, to “natural processing” by fluvial and/or glacial transport. Transport by glacial ice and/or stream water erodes weaker material, removes unwanted silt and clay fines, and sorts the material hydraulically to produce sand and gravel deposits of good to excellent quality aggregate.

Deposits with more complex settings, such as those consisting of materials from drainages with varied bedrock geology and glacially transported material are mixed, have highly varied clast compositions.

Partly due to local bedrock geology, some regions lack construction-quality aggregate resources. For example, sand and gravel deposits in some portions of the Rocky Mountains contain high proportions of weak or otherwise undesirable rocks, such as mudstone, claystone, ironstone, siltstone, shale, coal, or poorly indurated sandstone. Where transport distances have been short, these weaker materials survive and can be major components of the deposited aggregate material. This can result in aggregate of marginal quality, and in some cases, precludes the use of certain pits for aggregate uses where premium quality is required. Use of these types of aggregates can affect the durability and service life of constructed works made with them; road bases may deteriorate, and asphalt pavements may undergo stripping, rutting and popouts, and development of alligator cracking and potholes.

For some Rocky Mountain communities and regions, the identification and development of aggregate sources of acceptable engineering quality is an ongoing challenge. With the continuing drive for increasing quality in infrastructure construction, and the ‘spotty’ nature of sand and gravel deposits in mountain regions, exploration for and testing of these resources is hard-pressed to keep pace. In some areas, development of quarried rock aggregate sources may provide a reasonable alternative to traditional sand and gravel aggregate resources. This is particularly true for regions where annual flooding occurs. In these areas, the need to provide large-size armourstone and rip-rap material to protect against flooding has escalated in recent years. Quarried rock sources will likely become more common for rip-rap as well as aggregate production here.

ENGINEERING QUALITY OF AGGREGATES

Overall, natural sand and gravel aggregates in the western part of the province are of higher quality than those in the east and northeast parts. This resulted from a combination of regional geology, glacial history, and physiography.

Igneous and metamorphic crystalline rocks that underlie central and western British Columbia tend to be of high strength and durability (Table 1). A notable exception is the low quality of aggregates found in the Prince Rupert region, where local bedrock consists of metamorphic rocks of low strength, like phyllites, schists, and gneisses. As a result, Prince Rupert imports aggregate materials periodically to meet requirements for certain engineering projects.

Eastern and northeastern British Columbia is underlain mainly by sedimentary rocks, including formations of weaker, fine-grained sediments, claystone, mudstone, poorly-indurated sandstone, and coal. Where transport distances have been short, these weak components persist and may be important components of aggregate deposits in these areas. In contrast, where transport distances of materials which comprise many sand and gravel deposits are greater, weak components break down and are removed so the resulting aggregates are of better quality.

TEST METHODS – GENERAL TRENDS

The following engineering tests, when run singly or in combination, have been found to be very effective indicators of overall physical quality of British Columbia aggregates. Among these tests are:

Petrographic Examination – used to identify weak geologic components and highlight specific rock types known to be linked with poor performance, both in the field and in laboratory testing. This test procedure is an excellent tool for quickly assessing the quality of either a production aggregate or of a proposed (unprocessed), “pit-run” source of material, in coarse or fine fractions. It can help to set direction for subsequent phases of investigation of new sources by highlighting problem components which will require further attention, either by additional testing, or through specialized processing to remove unwanted components. In addition, the Petrographic Examination can be used to detect changes in production aggregates that may require fine-tuning of the processing methods or to indicate that quality has changed.

Petrographic Number (PN) – the PN is a numeric index of a coarse aggregate’s overall physical-mechanical quality and is based on a method developed in Ontario in the 1950s. It uses information generated in the Petrographic Examination, but focuses on the classification of the aggregate sample on the basis of its relative quality groupings. Typical quality classifications are “Good”, “Fair”, “Poor” and “Deleterious”. When the sample has been classified, the relative percentages of each quality class are multiplied by a “Petrographic Quality Factor”. In common usage, factors used are “1” for Good, “3” for Fair, “6” for Poor and “10” for Deleterious. Higher PN numbers indicate lower aggregate quality. Typical ranges for the PN number are: 100 to 140 for “Good”, 140 to 160 for “Fair”, 160 to 200 for “Poor”, and more than 200 for “Unsuitable”.

While this method can be used as a Quality Control test for production aggregates, its application also extends to evaluation of new aggregate sources, and

assessment of specific aggregate problems by comparison of “before” and “after” conditions.

Specific Gravity (“Relative Density”) & Absorption – provides a measure of the porosity of the material, and its heft. These characteristics can be correlated with other performance criteria, to evaluate the material’s ability to absorb moisture, resist deterioration under freezing and thawing conditions, and so on. Intergranular porosity if high often indicates poor quality aggregate.

Magnesium Sulphate Soundness – like the absorption value, $MgSO_4$ loss % can identify materials with a tendency to breakdown under repeated cycles of wetting and drying and/or freezing and thawing.

Micro-Deval Abrasion – this index has been found to be a good predictor of the overall competence of the material, as well as its resistance to breakdown under abrasive and other stress-inducing conditions.

In field performance, aggregate breakdown caused by various mechanisms can range from negligible to serious. Factors that influence resistance are the rock type, the exposure conditions, and the specific forces acting on the aggregate. The most frequently observed causes of aggregate deterioration and failure in British Columbia are the effects of running water, wave action, abrasion, loading stresses, freezing and thawing, and chemical attack. Selecting tests to accurately predict aggregate susceptibility to these forces can be a daunting task.

NEW APPLICATIONS OF EXISTING TESTS

Occasionally, these above described tests are used to assess the quality of materials for which they were not initially designed. For example, some rip-rap and armourstone specifications call for the use of concrete aggregate tests, such as Sulphate Soundness (CSA A23.2-9A, ASTM C-88). While this test provides an index of physical quality of the material under test, there is some confusion about the correct interpretation of the test data obtained from the small-size aggregate tests. Losses on larger pieces of stone (such as rip-rap) tend to be far lower due to the effects of lower surface area-to-mass ratios for the larger samples.

Another example is the Los Angeles Abrasion test, which is frequently specified in the quality testing regime for rip-rap. In preparing large samples for testing in the Los Angeles Abrasion machine, large pieces several inches across need to be manually reduced to appropriate gradings (typically 2” minus). This often involves breaking with a sledge hammer, and then reduction in a small laboratory jaw crusher. This latter method often produces highly angular, “flaky” pieces, which perform, poorly in the Los Angeles test.

TABLE 1: TEST DATA FOR SELECTED BRITISH COLUMBIA SAND & GRAVEL AGGREGATES

PARAMETER	AGGREGATE SOURCE					
	Vancouver Island	Sechelt Peninsula	Coquitlam Valley	Fraser Valley	Kamloops	Southeast B.C.
SG	2.88	2.656	2.72	2.75	2.73	2.64
Absorption	0.72	0.85	0.71	0.74	0.56	1.24
Petrographic Number	107 - 120	108 - 121	104 - 119	106 - 125	112 - 128	118 - 155
Petrographic Composition	Mafic volcanics, some sandstone & granitic.	Granitic, volcanic, minor metamorphic	Granite-diorite, volcanic, minor metamorphic	Mafic-felsic volcanics, quartzite, chert, metamorphic, sandstone.	Mafic- intermed. volcanics, quartzite, chert, granitic	Sandstone, quartzite, siltstone, limestone, shale
MgSO ₄ loss %	Sand: 2.9 Stone: 0.74	Sand:4.7 Stone: 0.87	Sand: 2.97 Stone: 0.56	Sand: 4.8 Stone: 0.4-1.4	Sand: 7 - 16 Stone: 0.6 - 5	Sand: 12 - 17 Stone: 5.8 - 8.5
Micro-Deval loss %	7	6.3	4.5	4.6	5.0 - 12.0	8.0 – 15.0
AAR Expansion %	AMBT: 0.07 - 0.32 CPT: 0.01 - 0.013	AMBT: 0.06 - 0.23 CPT: 0 - 0.02	AMBT: 0.32 CPT: 0.011 - 0.04%	AMBT: 0.19 - 0.52 CPT: 0.01 - 0.15	AMBT: 0.20 - 0.40 CPT: 0.013	AMBT: 0.10 - 0.36 CPT: 0.06
LA Abrasion Loss %	18.7	24.3	14 - 22	23.5	7 - 12	19 - 26

KEY: AMBT: Accelerated Mortar Bar Test (CSA A23.2-25A or ASTM C-1260) percent expansion at 14 days.

CPT: Concrete Prism Test (CSA A23.2-14A or ASTM C-1293) percent expansion at 1 year.

Losses near or in excess of 35% are not uncommon, when such preparation is used. Some specifications for construction materials set the Los Angeles loss limits at 35%, while some specifiers limit the loss to a maximum of 20%.

TEST METHODS – TYPICAL RESULTS

As noted earlier, high quality aggregate materials are more common in central and western British Columbia, while the quality of aggregates in the east is generally lower. Table 1 provides an overview of typical test data for aggregates from a variety of locations within British Columbia.

QUARRIED AGGREGATE

As noted earlier, there are comparatively few aggregate quarries in British Columbia. Historically, a few quarries in Vancouver and Victoria were operated to produce aggregate. Most notably, these included the basalt quarry in the present-day Queen Elizabeth Park in central Vancouver, as well as the present site of Butchart

Gardens in Victoria, where limestone was quarried for the production of Portland cement.

Today, British Columbia quarries that produce aggregate include Blubber Bay quarry on Texada Island; Texada Quarrying also on Texada Island; Producer’s Pitt near Victoria; Pitt River Quarries in Pitt Meadows; Mainland Sand & Gravel’s Cox Station quarry near Abbotsford; and Sumas Quarry near Abbotsford.

Current aggregate production from British Columbia quarries is estimated to be 5 million tonnes per year. However, recent efforts to market and distribute not only sand and gravel but also quarried aggregates to Washington, Oregon and California (ENR, Dec. 14, 2000) may push future production levels well beyond those of today.

Test data for some quarried aggregates are given in Table 2.

Some sand and gravel pits have bedrock cropping out within their property boundaries. This provides an opportunity for the blending of crushed high-quality bedrock with natural sand and gravel. One potential benefit is that blended production could extend the production life of the property.

CHALLENGES IN ENGINEERING QUALITY FOR BRITISH COLUMBIA AGGREGATES

British Columbia aggregate producers face a number of aggregate engineering quality problems. Among them are:

1. **Regional Poor Quality** – Aggregates of low quality occur in certain regions, as a result of local bedrock conditions and regional surficial geology. These include the Prince Rupert (north coast) area, where metamorphic schists and gneisses contribute gravel of low durability, and poor strength; and northeastern and southeastern British Columbia, where softer and weaker sedimentary rocks that occur in local gravels can downgrade the quality to a significant extent. As a result, exploration for high-quality gravel for use as construction aggregate during the development of coal resource areas at Elkford, Sparwood in the southeast, and Tumbler Ridge in the northeast was challenging.

2. **High Fines** - If there is a significant amount of silt and clay-sized material in the natural deposits it can add tremendously to the operating costs of a pit. Costs are incurred because of the need to wash and classify the sand, and to handle and eventually dispose of the fines. Impacts on mining parameters and environmental considerations help to further increase costs of mining.

This type of problem is illustrated in the aggregate pits of the Coquitlam Valley, east of Vancouver, where glaciofluvial deposits adjacent the Coquitlam River have been mined for many years. Estimates indicate that there are gravel reserves to support mining for forty more years, and the quality of the aggregates tends to be ‘good

to excellent’. The glaciofluvial sediments being mined are interlayered silty sands and silts with abundant gravels and sands and gravels. Thicknesses of the deposits range up to 100 metres or more. However, washing to remove silt is necessary to produce high quality aggregates to meet the required specifications. Subsequently, this places pressure on the producers to manage and dispose of the silt.

3. **Rounded and Smooth Aggregate** – Although it is not generally a problem, a high proportion of rounded aggregate particles with smooth surfaces can lead to lower-than-expected strengths for cementitious or asphaltic mixtures. The cementing agent cannot form strong bonds with very smooth aggregate particles. Aggregates with particles which have been water-transported for long distances are most susceptible to this problem. The typical solution has been to blend in crushed oversize aggregate or crushed rock to increase the proportion of particles with rougher surfaces.

4. **Reactivity in Concrete** – Many aggregates in British Columbia have some potential for “Alkali-Aggregate Reaction” (AAR) in concrete. AAR is a chemical reaction within hardened concrete, which causes it to expand over time. The reaction can continue indefinitely if sufficient alkalis are available to sustain the reaction. The hydroxyl ions of the concrete pore solution, which is highly basic, react with the alkaline and other unstable mineral phases in the concrete coarse and fine aggregate. Resulting expansion causes cracking in the cement paste and aggregates which adversely affects the strength and durability of the material. In severe cases, AAR leads to early weakening or disintegration of concrete, requiring either replacement or costly repairs.

TABLE 2: TEST DATA FOR SELECTED BRITISH COLUMBIA QUARRIED AGGREGATES

PARAMETER	QUARRY LOCATION				
	Vanc. Island 1	Strait of Georgia 2	South Coast 1	South Coast 2	Southeast 1
SG	2.96	2.715	2.72	2.74	2.677
Absorption %	0.46	0.22	0.51	0.43	0.89
Petrographic Number	103	109 - 144	104	108	108
Petrographic Composition	Basalt	Limestone	Granodiorite	Volcanic	Sandstone
MgSO ₄ loss %	0.5 - 1.8	0.6 - 5.5	0.5 - 2.8	1.8	1.16
Durability Index	--	72	85	--	--
AAR Expansion %	AMBT: 0.05	CPT: 0.006	AMBT: 0.09	AMBT: 0.09 CPT: 0.01	AMBT: 0.19 CPT: 0.06
LA Abrasion Loss %	7.5	22.4	25.0	13.7	26.1

Fortunately, this phenomenon is not as common in British Columbia (Shrimer, 2000) as in other regions of Canada and the United States because of the use of generally low alkali cement. Despite this, there are at least a hundred sites in British Columbia where concrete has been affected by AAR. Examples include Alexandra Bridge, at Boston Bar; Brockton Point, Stanley Park, Vancouver; Daisy Lake Dam, Squamish; Massey Tunnel walls, Richmond-Delta; and the Marine Way-Capilano River Bridge, Northwest Vancouver.

While this phenomenon is not as serious as that reported in other provinces, owners and technical professionals should be aware of and test to avoid using aggregates that have potential for AAR. Methods given in CSA, particularly A23.2-27A, can be used to evaluate whether AAR potential in aggregates might produce a deleterious reaction in concrete, and can also serve as a basis for avoiding or determining appropriate preventive measures to use with an aggregate where AAR is a high risk.

Currently, test data indicates that approximately 80% of British Columbia aggregates exceed the CSA limits for expansion in the Accelerated Mortar Bar test, while roughly 40% of the aggregates tested in the Concrete Prism Test exceed the CSA limit.

5. **Quality Testing Protocol** –testing of aggregate in British Columbia has not generally been carried out to the levels seen in other regions of Canada or the United States. In the future, in-province and exterior markets will demand testing to demonstrate that aggregates supplied meet specification requirements for the specific market, and for the intended applications. Aggregate producers will need to factor in higher costs for quality control to meet these demands and maintain their markets.

CSA A23.1 stipulates that testing of concrete aggregates should be done annually “as a minimum”.

The British Columbia Ministry of Transportation & Highways generally requires that testing results be furnished in advance of specific projects. In contrast, the Department of Transportation in neighbouring

Washington State requires suppliers of aggregates and/or concrete to submit their aggregates for testing in order to qualify for inclusion on the “Aggregate Sources Approval” list. Once an aggregate supplier is on Washington’s list of approved sources, the qualification is good for up to five years.

CONCLUSION

Aggregates in British Columbia have been developed close to their markets, and British Columbia has enjoyed the benefits of inexpensive, plentiful and generally high-quality aggregate supplies. The natural occurrence of high quality aggregate in the province has been fortuitous, and resulted in low emphasis on engineering quality testing. However, changing markets; rapid depletion of aggregate resources; increased economic and environmental pressures; and increased awareness of potential engineering and liability problems stemming from the use of under-tested aggregates must be considered. Today, to maintain existing and attract new markets, rigorous testing to demonstrate the engineering quality of aggregates is necessary and will become normal practice in British Columbia.

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GEOLOGY AND AGGREGATE PRODUCTION OF THE COLWOOD DELTA

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ABSTRACT

Industrial minerals from the Colwood Delta, which is arguably Victoria's most significant geological feature, have played an important role in the development not only of Victoria, but also Vancouver and Seattle. Since the turn of the century the Colwood Delta, which lies immediately west of Victoria on Vancouver Island, has been one of Canada's largest aggregate producing regions. The Metchosin gravel pit, operated by Construction Aggregates Limited, is the largest aggregate mine in the area. It is part of a large, raised, post-glacial delta that occupies 611 acres, and is easily visible from the City of Victoria. The operation uses conveyor belts to transport aggregate material from the pit to the processing plant. Up to 19 different types of aggregate are produced there and cheaply shipped to markets. The dominant material types are interbedded delta foreset sands and pebble to cobble gravels. When mining of this pit is completed, plans call for the reclaimed pit to be converted into a community development.

INTRODUCTION

The Colwood Delta (Figure 1) is a large, raised glaciofluvial delta located west of Victoria. It is one of the more dominant physical features in the Greater Victoria area, it is visible from the city, and throughout the last century has been a major supplier of aggregate materials for southwest British Columbia and the city of Seattle. Over the years numerous sand and gravel producers have

operated on the delta; at its peak, one of these was one of Canada's largest aggregate suppliers. Mining began on the delta as early as the 1890s, and has continued to the present. The delta, which was mapped by Monahan and Levson (2000), covers an area of 16.7 square kilometres; it is up to 10 kilometres long and 5 kilometres wide. Housing developments have expanded over most of the delta and the area available for aggregate extraction has rapidly diminished in recent years.

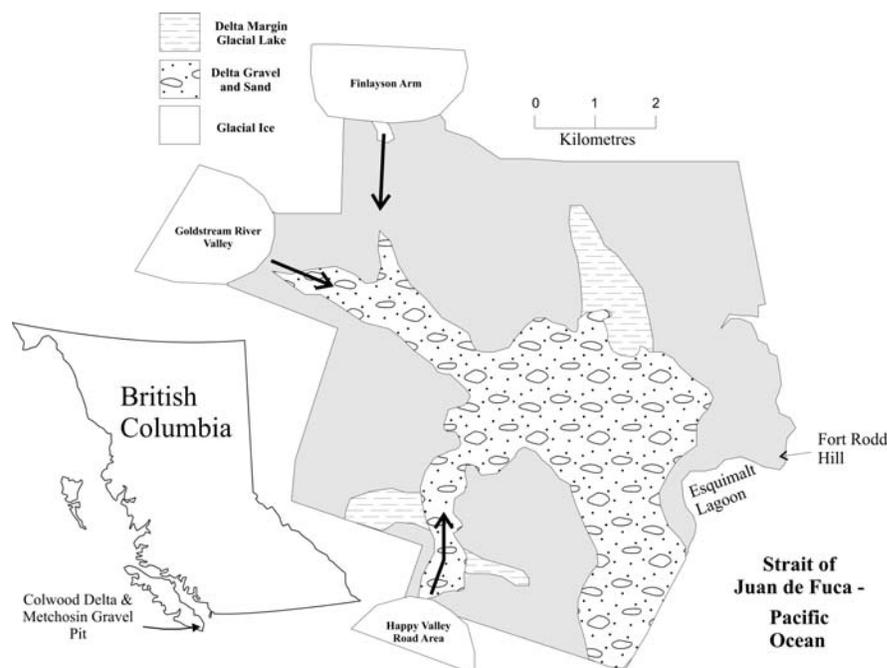


Figure 1. Location and aerial extent of the Colwood delta (modified from Monahan and Levson, 2000). This delta was fed by sediment laden glacial meltwater from Finlayson Arm, the Goldstream River valley, and the Happy Valley road area.

GEOLOGY

The Colwood delta formed near the limit of the late-glacial marine transgression at the end of the last, or Late Wisconsinan, glaciation. At that time the area was isostatically depressed and relative sea level was approximately 75 metres higher than present. The main source of meltwater feeding the delta was glacial ice in the mountains west of Victoria. Feeder channels issued from glacial ice occupying the upper Goldstream River valley and Finlayson Arm at the west side of the delta (Figure 1). A secondary channel in the Happy Valley Road area may

have also fed the delta from the south. Drainage was dammed in other valleys adjacent to the delta system, such as the Millstream Valley to the north, resulting in formation of small glaciolacustrine basins. A number of kettle holes occur in various locations across the entire length of the delta indicating that deposition occurred in contact with isolated blocks of ice. The absence of deltaic sediments north of Esquimalt Lagoon suggests that glacial ice still occupied that area when the delta was forming. As sea level dropped, a well-developed meltwater channel system was incised into the delta just prior to its abandonment.

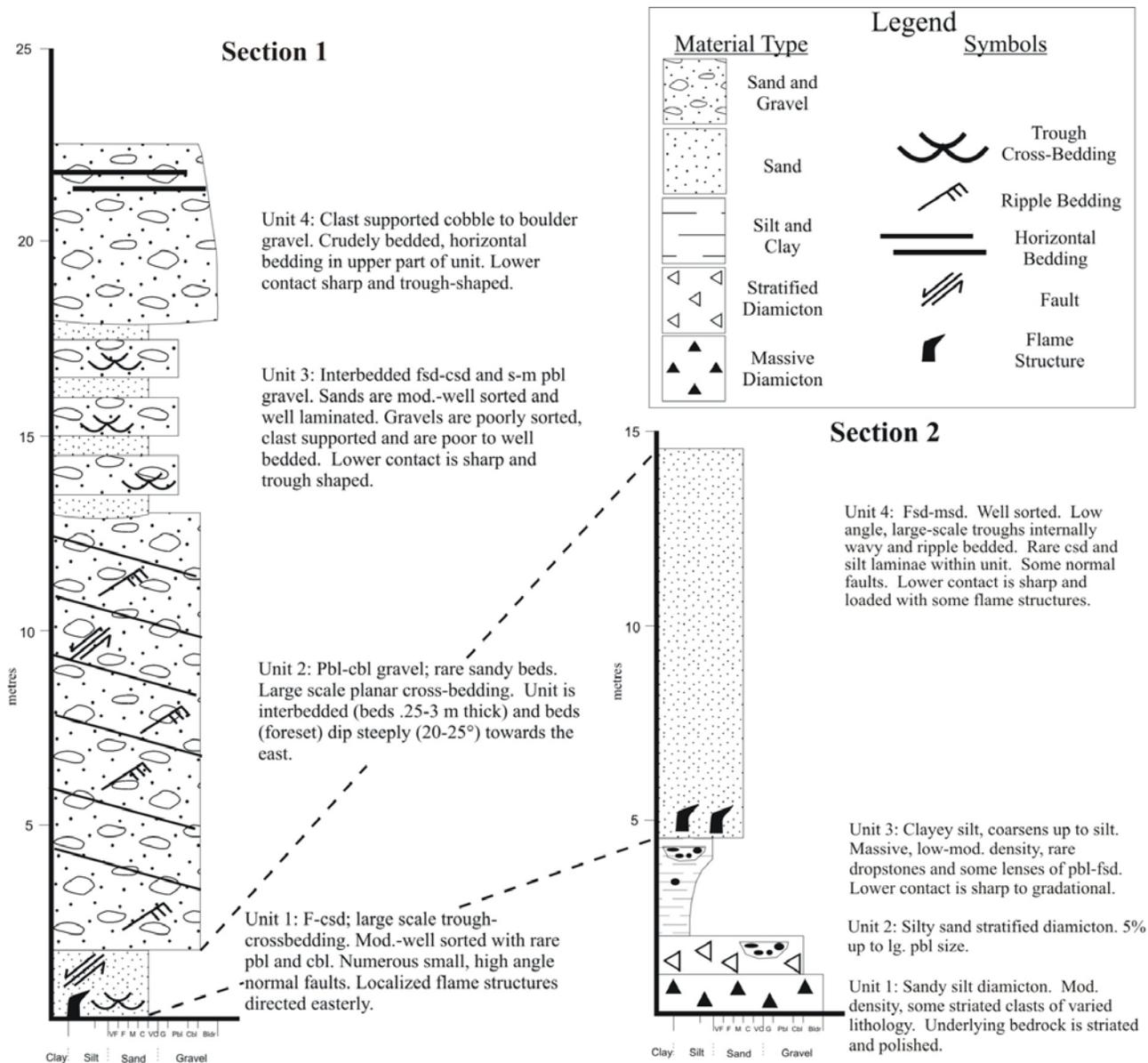


Figure 2. Sections illustrating the stratigraphy of the Metchosin gravel pit, Colwood Delta.

Five different stratigraphic units have been identified in the Metchosin gravel pit (Figure 2). The predominant unit consists of interbedded medium to coarse sands and pebble to cobble gravels (Blyth and Levson, 1993). These sands and gravels show large-scale planar and trough cross bedding and are interpreted to be prograding delta foreset beds (Figure 3a). In exposures at the southwest corner of the delta, beds dip up to 25° to the south-southwest and show well developed grading, a typical feature of subaqueous sediment gravity-flow deposits in river-dominated, delta foreset sequences. The unit coarsens upward, and the maximum thickness of gravel beds increases from about 0.3 metres at the base of the unit to 2 metres at the top. This reflects a facies change from distal, lower-slope deposits to more proximal upper-slope deposits. The gravel beds are mostly clast-supported and matrix-filled, but some coarse beds have an open framework. Clasts are well-rounded and are of mixed provenance. A petrographic analysis of sand and gravel from the Colwood Delta shows less than 30% siliceous minerals and pebble lithologies dominated by granitoid and finely porphyritic volcanic rocks. (British Columbia Research Council, 1967).

The foreset beds are locally underlain by a thin (2.5 metre) basal unit of gently dipping, finely laminated silts and clays interpreted to be bottomset beds (unit 3, section 2, Figure 2). The foreset gravels are erosionally overlain by about four metres of horizontally bedded sands and gravels that are inferred to be topset channel deposits (Figure 3b; unit 4, section 1, Figure 2). The lower contact of this unit is scoured and marked by numerous large clasts that are up to 50 centimetres in diameter. The unit fines upwards, indicating gradual channel abandonment.

The delta sands and gravels are stratigraphically underlain by a few metres of silty diamicton interpreted to be basal till (Figure 3c; unit 1, section 2, Figure 2) and retreat-phase debris flow sediments (unit 2, section 2, Figure 2). Pebble fabric analyses reveal a strong preferred orientation of the a-axes of elongated clasts to the southwest, typical of basal till deposits. The till locally overlies basaltic bedrock that is commonly well striated and glacially fluted. Glacially molded stoss and lee features and striae on the bedrock surface indicate a southwesterly (about 200°) ice flow direction. The diamicton is matrix-supported with 25% clasts, and the matrix is a moderately indurated, silty, fine sand. Clasts are mostly rounded to subrounded and up to about 30 centimeters in diameter. They consist of about 50% basaltic volcanics (including about 20% plagioclase porphyry), 20% diorite, 10 to 15% siltstone, 5 to 10% gneiss, 5 to 10% felsic intrusives and minor chert. These diverse lithologies and the presence of distally derived erratics are consistent with a glacial origin for this diamicton (Blyth and Levson, 1993). Older Pleistocene sediments locally underlie the till, and in one borehole in the pit they extend to a depth of 40 metres below sea level (Howes and Nasmith, 1983).

AGGREGATE PRODUCTION

The largest operation on the delta is the Metchosin gravel pit or Producers Pit, which is presently owned and operated by Construction Aggregates Limited (Figure 4). The quality of aggregate from the pit is excellent because the sands and gravels are well-graded and contain few fines. As well, gravel clasts from this deposit are hard, do

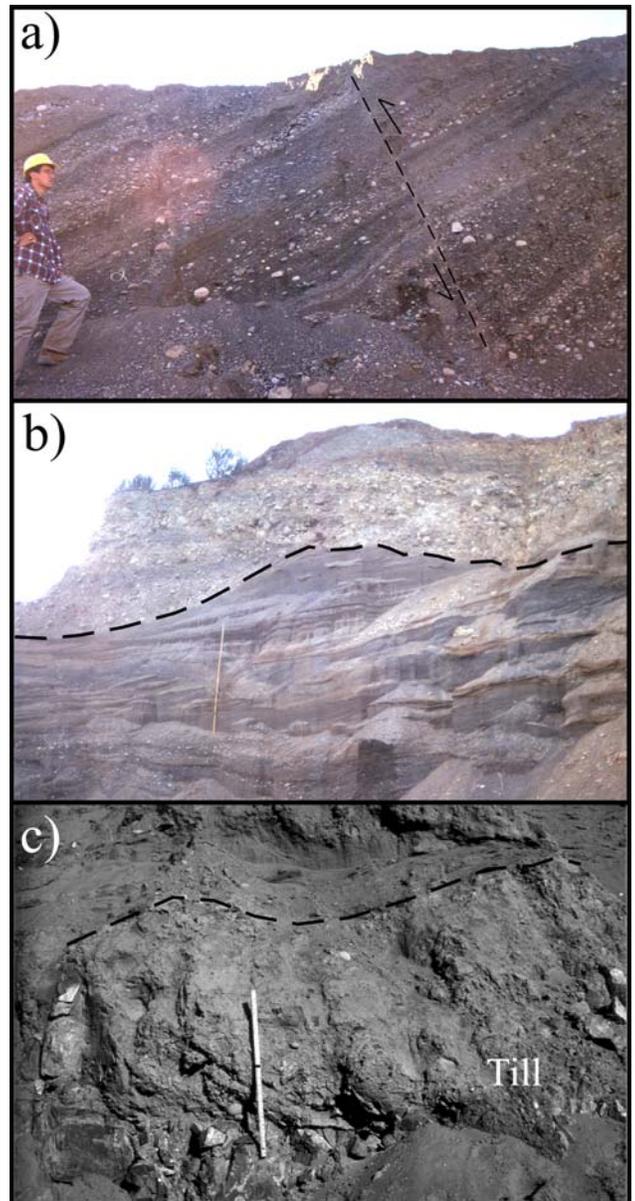


Figure 3. a) Photo of interbedded, medium to coarse sand, and pebble to cobble gravels (delta foreset beds). High-angle reverse and normal faults occur within this sediment. b) Clast supported cobble to boulder delta topset gravel deposit overlying trough cross-bedded fine to coarse sand and small to medium pebble gravels. c) Silty diamicton (basal till) underlying late-glacial sand and gravel in Producers Pit. In places, till is overlain by finely laminated silt and clay (delta bottomset beds).



Figure 4. Aerial extent of the Metchosin gravel pit (aerial photograph PIM-C-90013 #156, scale 1:5000). 1) barge loading facility, 2) washing and screening plant, 3) aggregate stockpile area, 4) water recycling tank, 5) tailing ponds and 6) field conveyor belt system.

not absorb much moisture, and have a high specific gravity. In addition, this gravel pit occurs near the ocean allowing for economic transport by barge. The deposit is approximately half sand and half gravel. This balanced grain size distribution is important because it allows a wider variety of aggregate material to be produced. In total, the Metchosin gravel pit produces aggregate that is sorted into as many as 19 different size fractions. Products include concrete sand and natural stone for buildings and roads; crushed rock for landscaping, road bases, asphalt, gravel driveways and parking lots; and specialty sands such as those used for sandblasting or masonry sand for mortar and stucco.

The earliest recorded gravel extraction on the delta began in the 1890s and a processing plant was operating by 1910. The pit, which is approximately 611 acres, is one of Canada's largest with a peak production of more than 20 000 tonnes/day or 4 million tonnes/year. Current output is about half this, and the pit is nearing the end of its operation. About 60 million tonnes of aggregates have been shipped from the Colwood Delta since 1919. Average cost per tonne of aggregate leaving the pit is \$11.50, of which approximately \$1.00 is profit.

A large processing plant was built in 1975 at a cost of more than \$11 million. It has a barge loading capacity of 3000 tonnes per hour (Figure 5a). Before 1993, 40% of the aggregate from the Metchosin gravel pit was used in greater Victoria with the remainder going mostly to the

Lower Mainland. Since then, 50% of the production has gone to Seattle, 40% to Victoria and 10% to the Lower Mainland. Development of the large Sechelt aggregate mine is believed to be responsible for the shift in markets. Sand and gravel from Metchosin has also been shipped as far away as Guam, the Alaskan panhandle and Hawaii.

EXTRACTION AND PROCESSING

Before the 1970s, sand and gravel were extracted from the Metchosin pit by repeatedly scraping a large bucket on a slack-line across pit faces. Material dislodged from the face fell to the pit floor in piles that contained a relatively even grain-size distribution. Material from these piles was then loaded onto conveyor belts and transported to the crushing and screening plant.

Since Construction Aggregates Limited took ownership of the pit during the 1970s, they have used front-end loaders to excavate the gravel from pit faces, and then dump aggregate material into a feed hopper. The hopper provides a steady feed mechanism that allows large volumes of aggregate to be fed onto conveyor belts (Figure 6). To ensure that materials loaded into the hopper have an acceptable blend of grain sizes, loaders excavate material from a series of locations along the pit face. Aggregate material is conveyed to a primary field jaw crusher and then to the main plant (Figure 4, # 2) where it is screened, crushed, and washed. There are 3.5 kilometres of conveyor belts between the field mining

system and the plant at this gravel operation (Figure 4, # 6).

In the mill, coarse (greater than 7/8 inch) rock is crushed and finer material is fed to a washing and screening plant. Concrete sand, which is blended automatically from coarse sand fractions and fine sand is produced and sent to a variety of stockpiles (Figure 4, # 3). Round stone is conveyed away for further washing and screening.



Figure 5. A) Photo showing how barges are loaded at Construction Aggregates Limited Producers Pit. B) Construction Aggregates Limited barge loading facility.

The thousands of litres of water used in the washing process are recycled in a large (36 metres in diameter) thickener tank (Figure 4, #4). Lime and flocculating agents are added to the water to help remove silt and clay. Treated water is reused in the washing plant while the fines are pumped into a tailings pond (Figure 4, # 5).

A 270 metre conveyor belt in a tunnel under the finished product stockpiles automatically withdraws and transports material to the barge loading facility (Figure 5b; Figure 4, # 1). Material can be blended in any quantity from a variety of different piles to produce a wide range of finished products (Construction Aggregates Ltd., 1975). The barge loading facility is capable of loading 3000 tonnes per hour and can fill barges with up

to 9000 tonnes capacity (Rimes 1975). In the 1890s and early 1900s, before conveyor belts were used at the barge loading facility, workers loaded barges with wheelbarrows. Most of the aggregate produced at this pit is transported by barge.



Figure 6. Front-end loader extracting gravel and dumping it into a feed hopper. This aggregate is run through a primary field crusher. Crushed aggregate is then conveyed to the processing plant for final screening.

A hard rock quarry was opened in the Producers Pit in 1993 to help extend diminishing sand and gravel reserves. This rock quarry has about 28 million tonnes of reserves. The quarried rock is dark grey Metchosin basalt. It is durable and has excellent characteristics for asphalt pavements, ready-mix concrete, road stone and erosion control applications (Consedine, 1995).

LAND USE RECLAMATION ISSUES

Land use matters have always been an issue on the Colwood Delta, especially when the Metchosin gravel pit is involved. Some controversial issues with the local community have been road relocation, PCB storage, and the possibility of a landfill. All these issues have been resolved, and plans call for a community development in the area of the Metchosin gravel pit once it is shut down.

CONCLUSION

The Colwood Delta, which is arguably Victoria's most significant geological feature, has played an important role in the development not only of Victoria, but also Vancouver and Seattle. Aggregate material from the Metchosin gravel pit has been used in building a large number of homes and buildings in these cities. Late glacial, sediment-rich meltwater issuing from retreating ice lobes in Finlayson Arm, the Goldstream River valley, and the Happy Valley road area built the delta. During the

early Holocene isostatic rebound raised the delta above ocean level. It is approximately 75 metres above the present day coastline.

The largest mine on the Colwood Delta is the Metchosin gravel pit. Interbedded sands and pebble to cobble gravel from delta foreset beds, are the most common material and comprise the major aggregate resource within the pit. Aggregate has been mined here since the 1890's. Poor land use planning allowed residential and community development to build on other potential aggregate producing regions of the delta and urban development is crowding in on the existing Metchosin pit. This pit is slowly being phased out and after mining is completed the pit area will be reclaimed as a community development.

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AGGREGATE POTENTIAL MAPPING ON THE SEA-TO-SKY HIGHWAY, BRITISH COLUMBIA

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INTRODUCTION

Aggregate is defined as naturally occurring hard construction material, such as sand, gravel, crushed stone or slag, which can be mixed with cementing material to form concrete and asphalt or can be used alone in road building, railroad ballast or other construction or manufacturing activities (Edwards *et al.*, 1985). Aggregate is an essential commodity in urban and suburban areas and despite its relatively low unit value; it has become a major contributor to the economy of most communities.

Globally, the aggregate sector has experienced ever-increasing pressure to manage this resource properly in response to accelerated urbanization, which is marked by increased consumption. Municipal expansion, alternate land uses, land sterilization, and public concern are just some of the factors that have impacted the availability of many traditional aggregate sources. Factors like this, and the cost added by increased transportation distances, has created concern about the ability of the aggregate industry to meet future demand. The Aggregate Advisory Panel held in 2001 evidences this concern in the province of British Columbia, where initiatives like the Sea-to-Sky Aggregate Potential Map Project provide the first step toward ensuring sustainable development of aggregate resources in British Columbia. The methodology used in this study provides a means for planners to efficiently manage land areas with aggregate resources that may be vital to the development and maintenance of municipalities and their infrastructure.

Natural aggregate, such as sand and gravel, is the product of unique geological processes (Langer and Glanzman, 1993), thus potential aggregate deposits are generally restricted to areas where specific environments of deposition exist or once existed (Edwards, 1998). Understanding gained about the geological processes and environments has enabled aggregate geologists to predict qualitatively which landforms are most likely to contain aggregate (for example, Gartner *et al.*, 1981). To improve estimates, statistical modeling can be used with landform data to provide quantitative predictions of aggregate volume and area (Bobrowsky and Manson, 1998). Unfortunately, we have not reached a stage where

quantitative predictions of location, volume and quality of aggregate resources are possible.

The Sea-to-Sky region, north of Vancouver, is faced with competing land use options that range from development of scarce but economically important aggregate resources, to complete conservation and preservation of the natural resources. However, with continued growth of communities, such as the villages of Whistler and Pemberton and the city of Squamish, coupled with the successful bid for the 2010 Winter Olympics, pressure on the known local aggregate reserves will eventually reach a critical stage. To address these concerns, the Ministry of Energy and Mines, with funding assistance from the Corporate Resource Inventory Initiative (CRII), British Columbia Assets and Lands (BCAL), and Ministry of Transportation and Highways (MoTH), initiated a joint project to assess, at a reconnaissance level, the aggregate potential of the Sea-to-Sky corridor.

LOCATION

The study area is located in southwestern British Columbia, north of the city of Vancouver. The area is best described as a 10-kilometre wide corridor along the major transportation routes, delimited in the south by Daisy Lake and in the north by the head of the Lillooet River Valley near Salal Creek. In more detail, the first part of the corridor extends from Daisy Lake north to the Village of Pemberton, and includes Callaghan and Rutherford Creeks; at Pemberton the corridor divides to encompass the Upper Lillooet River Valley, as well as Birkenhead Lake and D'Arcy on the southern end of Anderson Lake. In total, the corridor covers portions of NTS 1:50,000 map sheets 92J/2, 92J/3, 92J/6, 92J/7, 92J/8, 92J/9, 92J/10, 92J/11, and 92J/12 (Figure 1). The communities of Whistler, Pemberton, Mt. Currie, and D'Arcy all fall within the study boundaries.

PHYSIOGRAPHY AND GLACIAL HISTORY

The study area is centred on the west coast of British Columbia some 40 kilometres north of Squamish (at the head of Howe Sound). This is part of the "Coast

¹ Current Location: Alberta Geological Survey, Edmonton, Alberta

Mountain” morphogeological belt (summarized in Gabrielse *et al.*, 1991). Terrain is typified by high, rugged mountains and deep glaciated valleys. It includes the Coastal Western Hemlock, the Mountain Hemlock, and the Alpine Tundra biogeoclimatic zones, each differentiated by elevation (Meidinger and Pojar, 1991).

Most unconsolidated deposits in British Columbia owe their existence to the processes of glaciation and deglaciation. During the past few million years, the entire

province has experienced a number of glacial and non-glacial cycles, and the most recent event, the Wisconsinian ca. 25 000 to 10 000 years before present (BP), had the greatest impact on aggregate accumulation and distribution.

As climate began to deteriorate some 25 000 years ago, ice that was previously restricted to high alpine regions gradually expanded. Valley glaciers advanced, eventually over-topping inter-valley ridges and coalescing

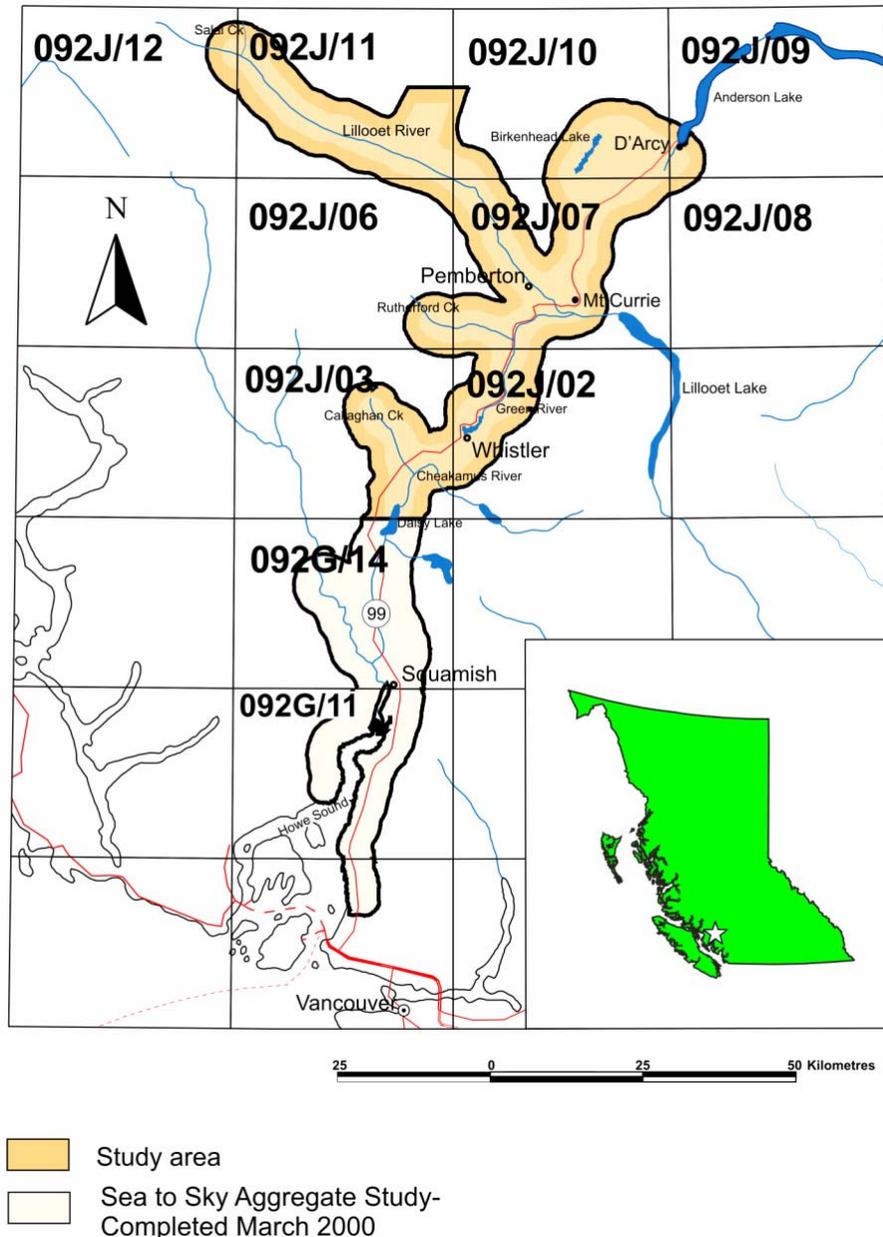


Figure 1. The Sea-to-Sky Aggregate Potential Map Project is located directly north of the City of Vancouver and includes the communities of Whistler, Pemberton, D’Arcy, and Mt. Currie. to form small mountain ice sheets (Davis and Mathews, 1944). Subsequently, glaciers spread across the interior plateaus and coastal lowlands, covering most of the province and parts of the continental shelf, finally producing the Cordilleran Ice Sheet (Clague, 1986). Minimal effort has been directed toward resolving the chronology of Quaternary events in the study area, but deglaciation history can be inferred from work completed

nearby at the head of Howe Sound and the Mamquam River Valley (Friele and Clague, personal communication, 2000). Apparently, by about 14 000 years BP glaciers had retreated from the Mamquam River Valley leaving it ice-free and forested. Deformed glaciolacustrine and diamicton deposits overlying unmodified glaciolacustrine sediments provide evidence for a glacial re-advance about 13 500 years BP. A dated submerged end moraine at Porteau Cove marks the maximum extent of the re-advance and also indicates that ice began to recede shortly after 12 800 years BP. By 11 800 years BP, ice had retreated up the Squamish River Valley as far as the confluence of the Cheakamus River. It is likely that the main trunk glaciers in the Cheakamus, Pemberton, and Birkenhead Valleys continued to decay throughout the Holocene into the high alpine, where remnant ice bodies persist today.

OBJECTIVES

The Sea-to-Sky Aggregate Potential Map Project has four main objectives:

- Locate, compile and review all existing and readily available geological and geotechnical information housed within government, academia, and industry.
- Through fieldwork, identify and accurately record (using GPS and UTM grid references) the location of both currently and previously active sand, gravel, and crushed stone aggregate extraction operations.
- Generate a Level III Aggregate Potential Map at a scale of 1:50 000 using surficial landform polygons as a base-map in accordance with a methodology that most closely approximates provincial standards for this procedure (Bobrowsky *et al.*, 1996).
- Create a multi-layered comprehensive digital map and interactive database in a GIS format (ARCVIEW) that is readily accessible by means of the Internet to government, industry, and the public.

METHODOLOGY

This study follows procedures and provincial standards established and detailed elsewhere (Bobrowsky *et al.*, 1996). The process consists of data acquisition and compilation, fieldwork, and polygon ranking. Data from a number of sources was first identified, located, compiled and evaluated as part of producing an integrated interpretive map product. Geotechnical reports, surficial and bedrock geology maps and reports, water-well logs, drill reports, and consulting reports, were used to evaluate the surficial geology landform data (illustrated in polygon style). Sources of this information included various levels of government, crown corporations, municipalities, and industry.

The following layers of data were compiled for the Sea-To-Sky study:

- surficial materials (primary and secondary components of landform polygons in map form; 1:50,000 scale)
- texture of surficial materials (primary and secondary modifiers of landform polygon labels in map form; 1:50,000 scale)
- landform expression (primary and secondary modifiers of landform polygon labels in map form; 1:50,000 scale)
- quality (qualitative) and thickness (quantitative) of identified aggregate resources
- surficial unit polygon area (map form; 1:50,000 scale)
- bedrock geology (map form; 1:50,000 scale)
- presence/absence of aggregate operations
- overburden thickness (quantitative)

The base map used to classify aggregate potential relies on polygon data denoting surficial geology/terrain/landform information plotted in accordance with British Columbia provincial Resource Inventory Committee (RIC) standards. For the purposes of this study, a 1:50,000-scale terrain map was prepared from air photo interpretation of surficial landforms, materials, and textures following the mapping methodology of Howes and Kenk (1997) and RIC (1996). This information was then digitized according to RIC (1997) digital standards. Finally, all the polygonal data was analyzed on a polygon-by-polygon basis for aggregate potential. Individual parameters were scored from 0 (low importance) to 5 (high importance) for data within each polygon. Final ranking for individual polygons was achieved in a 3-step process. First, undesirable polygons, such as those containing water and ice, were eliminated from the final polygon rankings. The second step was to generate a weighted algorithm, which includes at varying levels of importance, all the individual parameters for each polygon. Because some parameters are considered more important with regards to aggregate potential than others, these are given a weighting factor that increases their influence in the final value scored by the polygon. The following algorithm was used to evaluate polygons in this study:

Total Polygon Value = 3(Primary Surficial Material Rank) + 3(Secondary Surficial Material Rank) + 2(Quality A Rank) + 2(Primary Texture Rank) + 2(Overburden Rank) + (Secondary Texture Rank) + (Primary Landform Expression Rank) + (Secondary Landform Expression Rank) + (Minimum Thickness Rank) + (Maximum Polygon Rank) + (Thickness Rank) + (Quality B Rank) + (Quality C Rank) + (Area Rank) + (Bedrock Rank).

For a definition of the algorithm terms, weighting logic and details of the calculations, see Hickin *et al.* (2001). In addition, polygons that host current or historic extraction operations (that is, pits) were further evaluated. Pits were assessed to show their potential for further

aggregate production, which generated another layer of data that designated a production potential rank to the host polygon. A rank of 1 indicates a high potential, 2 a moderate potential, and 3 a low potential. High potential was assigned to any active commercial pit with additional reserves. A moderate potential was applied to smaller commercial operations, operations producing less desirable material, and/or operations with moderate reserves. Lastly, a low potential was assigned to inactive, non-commercial, borrow, and/or pits with limited or no reserves. A polygon with more than one operation would receive the highest pit rank to represent the potential of the polygon.

RESULTS

The study area consisted of 2289 polygons. From this total 111 represented water and ice and were removed from the algorithm. The remaining 2178 polygons generated final score values that range from 8 to 82. High values indicate high potential. Table 1 summarizes the classification and distribution of the ranked polygons. Figure 2 shows a portion of the final product, including primary, secondary, and tertiary polygons with drill holes, pits and pit potential. pits, and pit potential.

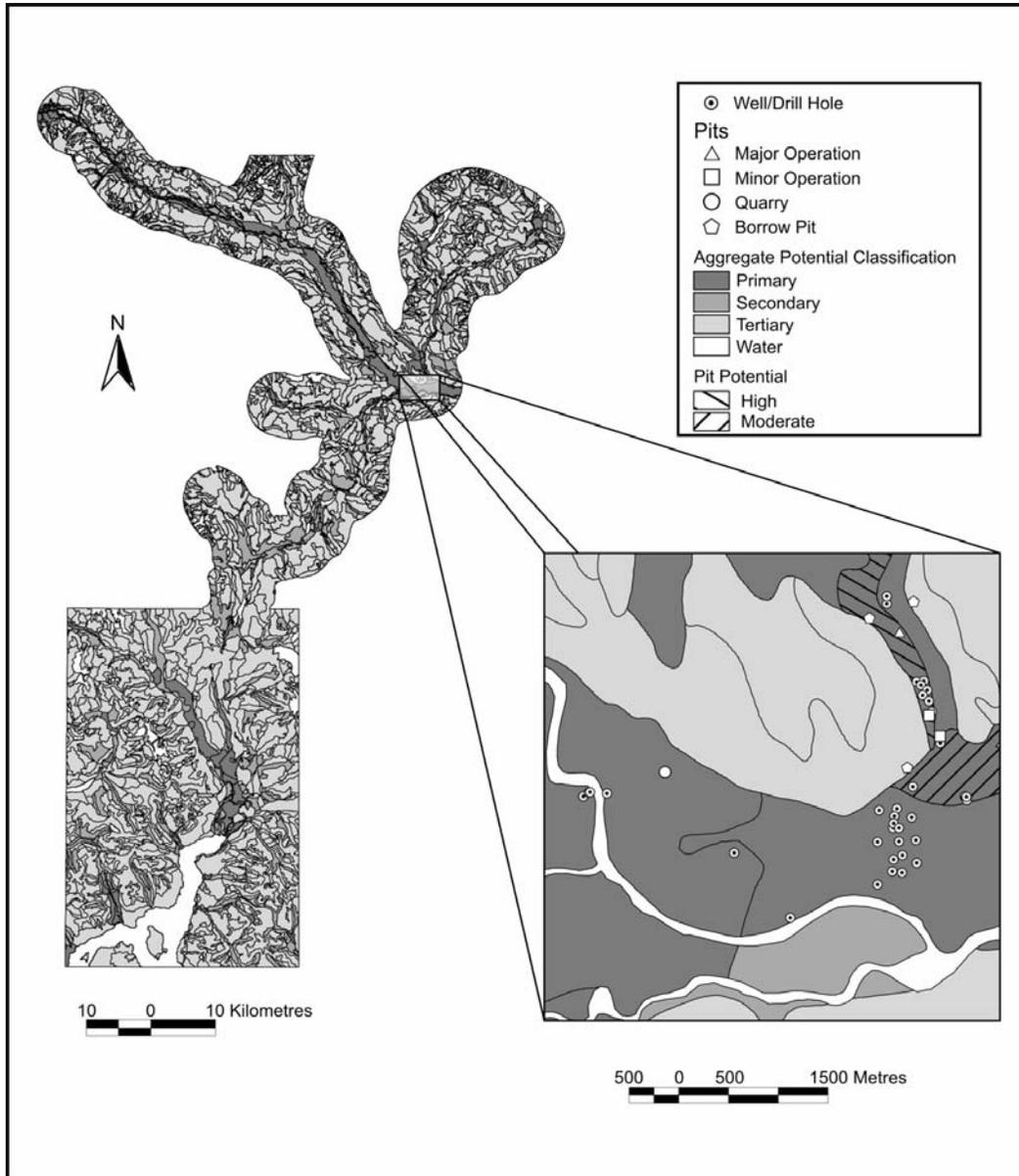


Figure 2. The final Sea-to-Sky Aggregate Potential map displays the distribution of the three polygon classes (primary, secondary, and tertiary). The insert is a magnified portion of the study area showing the additional information included in this project (Lillooet River, east of Pemberton). This information consists of drill hole and pit locations, as well as the pit potential for polygons hosting historic or active aggregate operations.

TABLE 1. SUMMARY OF THE DISTRIBUTION OF POLYGON CLASSES FOR THE SEA-TO-SKY AGGREGATE POTENTIAL MAP. CLASS WAS DETERMINED BASED ON THE AREAL DISTRIBUTION OF RANKED POLYGONS.

Class	Final Values	% of Polygons*	% of Map Area
Primary	≥50	7.0	5.8
Secondary	≥ 31 - <50	23.8	13.2
Tertiary	<31	69.9	75.2

*% of Polygons does not include polygons of ice or water.

CONCLUSIONS

Aggregate is often restricted to unique geologic settings which favour the deposition of sand and gravel. This is clearly evident by the distribution of primary aggregate potential polygons in this study. Almost without exception the most sought after material is located in the major valleys, particularly the upper Lillooet River, Birkenhead River, Squamish River and Pemberton, Valleys. This material is generally within glaciofluvial and fluvial deposits varying from moderately poor to well-sorted sand to boulder gravel. Current commercial operations are generally mining glaciofluvial and modern fluvial terraces along Highway 99 between Whistler and D'Arcy. Outside this corridor, land sterilization (agricultural land reserves) and hauling distance has restricted development. The present study exemplifies a global trend, which relies on GIS, multi-parameter data and fieldwork to generate maps of use to a wide range of user groups (see Kelly and Bobrowsky, 2001 for a review).

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A CENTURY OF SAND AND GRAVEL GEOLOGY AND USE IN ALBERTA: 1950 TO 2050

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Sand and gravel is the primary source of mineral aggregate in Alberta and an essential component in provincial growth. Trends in population growth, road infrastructure development, and sand and gravel production in Alberta over the last half-century are relevant to aggregate usage. Examination of these trends, together with resource management examples and a historical review of the Alberta Geological Survey (AGS) sand and gravel resource mapping, provides a basis for predictions about aggregate resource use and a context for proposed renewed mineral aggregate resource mapping at the AGS.

SAND AND GRAVEL PRODUCTION

The Alberta aggregates industry, which employs 10 000 people, has total annual revenues of about \$500 million. Aggregates are produced from 5962 pits with a total surface disturbance of 260 square kilometres (Walls, 2001). Federal statistics on sand and gravel production over the last 50 years in Alberta show an eight-fold increase from about 5 million tonnes in 1950 to approximately 40 million tonnes in 1999 (Hanes, 1956; Vagt, 1999). If provincial aggregate production continues to increase as it has in the last 25 years, it will reach nearly 70 million tonnes annually by 2050. To achieve this, 2.75 billion tonnes of sand and gravel will be required over the next 50 years.

POPULATION AND DEMOGRAPHICS

Alberta's population distribution has changed radically in the last 50 years. Rural population exceeded urban population in 1950 but has remained static since, as populations in Edmonton and Calgary increased by 3.5 times and are now 60% of the provincial population. Other cities and towns grew six-fold and now represent about 30% of the provincial population (Statistics Canada, 2000; City of Edmonton, 2000; and Alberta Department of Highways, 1968).

Annual aggregate consumption grew from 5.5 tonnes per capita in 1951 to 14.3 tonnes per capita in 1999. Provincial aggregate demand based on population can be divided into three regional components: Edmonton and Calgary (11.0 tonnes per capita in 1991), agricultural

regions containing other cities and towns and well-developed infrastructure (about 25 tonnes per capita in 1991), and rural and remote regions with under-developed, highly variable infrastructures (Edwards, 1995).

Per capita demand in Edmonton and Calgary is slowly decreasing as a result of recycling and in-place infrastructure. However, their large populations make these cities 'black holes', drawing in aggregate from an ever-expanding area. If we assume that Edmonton and Calgary combined will grow to 3 million in the next 50 years, and that annual per capita consumption will decrease to 8 tonnes, the combined aggregate requirements will be 920 million tonnes over this period. The secondary urban areas will require higher per capita consumption to develop and to expand their infrastructure. At an average annual per capita demand of 25 tonnes, other urban areas will require an estimated 1.8 billion tonnes to service a population that is projected to increase to 2 million by 2050. A relatively constant rural population of about half a million will consume about 400 million tonnes over 50 years at a per capita annual consumption of 16 tonnes. These population-based estimates indicate the need for about 3.2 billion tonnes of aggregate over the next 50 years.

ROAD INFRASTRUCTURE

Construction and maintenance of Alberta's 185 000 kilometres of roads accounts for two-thirds of provincial aggregate use (Edwards *et al.*, 1985). Alberta Infrastructure (AI) maintains 29 964 kilometres of primary and secondary roads and these will require about 122 million tonnes of aggregate over the next 25 years to be maintained. Aggregate reserves currently available to AI are about 550 million tonnes from more than 2200 pits. Although the resource is apparently adequate, in practice aggregate supplies are considered deficient for 42% of Alberta's public road system due to excessive hauling distances. AI considers a haul distance greater than 25 kilometres unduly expensive and beyond 55 kilometres impractical. Walls (2001) noted that if all gravel extraction were moved ten kilometres further from market (and that is happening today) the total cost increase would be \$40 to \$50 million annually.

Municipalities service the 154 640 kilometre secondary road system. Over the next 25 years the demand for aggregate by municipalities is expected to exceed 1.2 billion tonnes. Large regions in northern Alberta are crossed by a single primary highway surrounded by a very sparse network of public roads and an extensive network of private, graveled resource roads. Resource roads are used by energy and forestry companies, and maintained privately from Crown gravel sources that will ultimately be required for public roads. Resource roads are not counted in the projected maintenance demands of the public system identified previously.

Aggregate requirements to maintain the existing road infrastructure for the next 50 years will be in excess of 2.7 billion tonnes. This does not account for new public and resource road development in northern Alberta, maintenance of resource roads, or significant upgrading of the existing public road system.

RESOURCE MANAGEMENT

Aggregate-related land use issues provide insights into future aggregate development and the role that AGS information can play. Examples from the Edmonton and Calgary regions are examined.

During the 1950s, deposits in Edmonton's river valley supplied gravel to support rapid urban growth. Residential subdivisions enveloped these deposits during the 1960s and 1970s and development of any remaining aggregate resource was prevented through land use changes and haul restrictions. Massive gravel deposits at Villeneuve, fifty-kilometres northwest of Edmonton and in an adjoining county, were developed in the late 1960s to service the Edmonton market. In 1970, the Alberta government commissioned a major study on gravel extraction in this area. The resulting comprehensive report identified problems that would result from lowering the elevation of such a large area by 10 to 15 metres and recommended prohibition of residential development to ensure that proper management and reclamation took place. Development proceeded anyways and residents are now challenging gravel extraction in this area. An Environmental Impact Assessment costing more than \$500 000 will be required before operations can continue by extending pits that have been in existence for 30 years (Walls, 2001).

Information from the Alberta Research Council and the AGS in the 1970s helped identify and confirm the Villeneuve area as the premier source of aggregate for the Edmonton region. This information was used to formulate the initial regional resource planning and management plan that protected the resource. The current review resulted from the juxtaposition of residential development and mining, which is similar in some ways to the situation

that excluded Edmonton valley deposits from exploitation about 30 years ago. The new review is not using regional resource information.

Between 1976 and 1981, the AGS provided sand and gravel resource information to identify extractive zones for both Eastern Slopes (Bow Valley) and Calgary regional planning. In northwest Calgary, pits were established in a large, upland deposit. In approximately 1992, a gravel operation was proposed across the road from these long-established pits, in the Municipal District of Rockyview, that would exploit the same large deposit. Local residents opposed development. Approval for development was obtained in 1996 after a contentious public hearing, consulting costs of about \$1 million, and imposition of more restrictive operating regulations than applied to the competitors across the road (Walls, 2001; Edwards, 1995). The Calgary hearing also resulted from the juxtaposition of residential development and mining; it did not consider the regional implications of supply or examine AGS information.

The Edmonton and Calgary examples demonstrate the usefulness of geological information produced by the AGS in development of initial regional land use plans before there is close contact between residential development and mining. Zones where mining becomes constrained extend outward as centres of population expand. When urbanization engulfs aggregate resources, it engenders debate that does not make use of or require the kind of basic geological and resource information generated by the AGS.

Edmonton and Calgary, each with metropolitan populations of about a million, have the largest areas where resource extraction is restricted. In the Edmonton region, road haul of aggregate materials is as long as 85 kilometres, and gravel resource development is likely to be challenged anywhere within 50 kilometres of the city. In the Calgary region, gravel resources mined for Calgary have been challenged as far away as 85 kilometres from the city proper and Edwards (1995) reported haul distances of 140 kilometres.

SAND AND GRAVEL RESOURCE MAPPING AND SUPPLY

Between 1976 and 1983, the AGS mapped 18% of Alberta at a map scale of 1:50 000 at a cost of \$2.9 million. Between 1984 and 1990, the AGS mapped another 35% of the province at a scale of 1:250 000; this cost of \$0.8 million. Extrapolating the information to cover the entire province suggests that there are about 7650 sand and gravel deposits with a total surface area of 26 000 square kilometres, and some 50 billion tonnes of granular material. The gravel component overall is about 22% and less than 80% of the gravel occurs in concentrations sufficient for exploitation (deposits where

the gravel component exceeds 40%) (Edwards *et al.*, 1985). An estimated 10% of the total resource occurs in river valley deposits (Edwards, 1998). These deposits contain a high percentage of gravel and comprised about 45% of 1981 production, but the setting makes future exploitation unlikely. Taking these factors into account, the exploitable gravel supply reduces to 8 billion tonnes. This figure will be further reduced due to sterilization of deposits through zoning or land use planning.

The AGS anticipated increased demands in the growing Edmonton and Calgary regions and compiled information in these regions first. This information was used in formulation of land use plans for these regions in the late 1970s and early 1980s. Information from the reconnaissance mapping program was applied in broad integrated resource management exercises conducted during the late 1980s and 1990s, in which large areas for wildlife preserves and parks were proposed.

SUMMARY, PREDICTIONS AND RECOMMENDATIONS

Trends based on sand and gravel production, population and road infrastructure requirements all indicate that about 3 billion tonnes of mineral aggregate will be required in Alberta over the next 50 years. About 30% of this total will be required for Edmonton and Calgary with satellite cities and the dense road network that joins these two centres consuming another 20%. Most of the remaining demand will be from other cities and towns scattered about the province, and from a rapidly expanding infrastructure in northern Alberta. Major oil sands development in northern Alberta is also likely, and other resource developments such as diamond mining are a possibility. These will require additional large (0.5 billion tonnes?) amounts of aggregate.

Estimates of provincial resources at close to 50 billion tonnes (Edwards, 1998) fail to express the resource that is actually exploitable. These are probably less than 8 billion tonnes. The distribution of deposits is uneven, as demonstrated by the fact that 42% of Alberta's public road system is considered deficient in aggregate supply. Gravel operators note that reserves are being rapidly depleted and quality is declining. Walls (2001) concluded that reserves near Calgary would be essentially exhausted in 25 years.

AGS resource information is effective for planning and management in regions before they become densely populated. Industry representatives suggest that identification of sand and gravel deposits should be included in province-wide planning, making it possible to identify the existence of resources in areas where alternate zoning has been requested; provide authorities with information to honor the comprehensive plans; and ensure permitting of reserves (Walls, 2001).

Mapping in current regions where resource access is restricted was completed 20 years ago; existing mapping covers 17 of the 19 cities including Edmonton and Calgary, thus information was in place to aid resource management planning in areas of greatest urban growth and infrastructure development. There are no plans to upgrade mapping in these areas.

The greatest need for information is in unmapped areas beyond current urban centres. The remaining 47% of Alberta that has not been mapped for sand and gravel resources includes 40 of 63 towns and much of northern Alberta. Large sand and gravel reserves must be identified to maintain resource roads, to develop the public road infrastructure in northern Alberta, and to preserve deposits during land use planning. This is where AGS resource information is most useful in developing land use plans. The AGS intends to map the remainder of the province by 2011.

The budget for this work is much lower than previous mapping budgets, and the results will be of a reconnaissance nature. Although detailed resource information is more credible than reconnaissance information, land use planning will proceed with or without aggregate resources information. It is extremely important to get any scale of information into the process as early as possible.

Mapping sand and gravel resources is not enough. The predicted shortfall of sand and gravel for aggregate use makes it essential to identify potential bedrock aggregate sources as well. Walls (2001) predicted that within 25 years crushed stone from large deposits adjacent to the eastern slopes would likely be railed into the major urban markets. Bedrock with aggregate potential occurs in the foothills, the mountains and rocks of the exposed Shield.

Eastern slopes mapping is especially urgent, because industrial development in this area is already restricted, and information must be available for any new or revised planning initiatives.

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WEB-ENABLED GIS: AGGREGATE APPLICATIONS

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In the United States Geological Survey-National Stone Association collaboration, maps of national-scale sand, gravel, and crushed stone aggregate resources have been entered into a digital database (map server) in the public domain. Other data layers residing on the server are light aggregate resources, industrial mineral resources; geologic, hydrologic and physical attributes; infrastructure, and demographic data; and 1999 aggregate production. These data are accessible and can be browsed, queried, and analyzed via the Internet.

The data exist in the form of geo-referenced raster and vector files. Associated tabular data that are served over the Internet can be displayed in map form. Large geo-datasets such as complex raster images are compressed and tiled, and large complex vector files have been generalized to specified degrees to deal with data transmission speed. Data layers are thematically combined and arranged in customized, updateable map window environments. This project currently consists of four map windows: aggregate availability and suitability by physical division sections (after Witczak, 1972); national scale sand and gravel aggregate resources; national scale stone aggregate resources; and 1999 crushed stone, sand and gravel, and total production.

Multiple users can perform simple geographic analyses and tasks such as "buffering" and querying spatial elements on the remote map server. Users employ a free, downloadable program from AutoDesk's MapGuide group (www.autodesk.com) called "MapServer". All the data residing on this map server are updateable and can be periodically, continuously, or remotely updated using a manual or automatic login subscription system.

Links to current, available data and metadata used in this cooperative effort are provided for those researchers interested in acquiring and modifying data for their own use.

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NATIONAL INDIAN AGGREGATES PROGRAM

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INTRODUCTION

The United States produces approximately 1.9 billion tonnes annually of natural aggregate in the form of crushed stone and sand and gravel. These materials are primarily used for aggregate in the construction industry, especially in portland cement concrete for residential and commercial buildings, bridges, highways, and airports. They are also used in bituminous mixes for road construction, and parking lots, or as road base, railroad ballast, erosion control, landscaping and road surfacing. Aggregate production accounts for about half of the nonfuel-mining volume in the United States. Income to Tribal governments from sales of natural aggregates far exceeds income from any other mining activity. Potential income from new development of natural aggregate resources near the area of use is very significant as growth and infrastructure replacement are causing increasing demand for aggregate. However, no comprehensive source of information on this subject exists for all Tribal lands.

The Colorado School of Mines and the Bureau of Indian Affairs is conducting an inventory of aggregate resources for Tribal lands in the western United States. The inventory consists of a compilation of published information on surficial and bedrock deposits, and an assessment of the potential for mining these deposits for aggregates, either as crushed stone or as sand and gravel. The compiled information is available on the Division of Energy and Mineral Resources, Bureau of Indian Affairs website located at <http://snake1.cr.usgs.gov>.

The purpose of the project is to make information on aggregate resources located on Indian lands in the western United States readily available to the Tribes and the general public. Information from these studies should be a useful first step for planning the development or preservation of aggregate resources on each property.

METHOD

The study is being conducted by compiling geologic information from previously published studies, although most were not focused on aggregate resources. These reports may be found at

http://snake1.cr.usgs.gov/demr/niemr/phase1/PhaseI_Intro.htm.

The descriptions of geologic formations are evaluated with respect to whether geologic properties are favourable for producing crushed rock or sand and gravel aggregate resources. The formations are then classified on the basis of the potential (high to low) for use as aggregate.

A summary of findings for each Tribal land is being written, tables are being compiled for each state, and general geologic maps are included where available. The summary includes location of the land, size, ownership, access, road type and condition, descriptions of bedrock and surficial deposits, history of past aggregate mining, classification of potential of geologic units for use as aggregates, and a reference list of geologic information for the site. Tables include the name of the reservation, location and size of the reservation, areal extent and thickness of the deposits, whether or not there is current mining of aggregate on the reservation, the quality of information on potential deposits, general aggregate information, and aggregate potential based on the geology of the deposit.

Alaska, Arizona, California, Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming have been completed as of December 2000. Plans for the upcoming year include adding all of the aggregate assessments, geologic maps, and tables for Michigan, Minnesota, Nebraska, New Mexico, North Dakota, South Dakota, and Wisconsin. The web page can be found at <http://snake1.cr.usgs.gov/demr/niemr/aggregate/aggregate.htm>.

AGGREGATE SUMMARIES

On the website, the user may either click on the state on the map, or select the state from the list at the bottom of the page. Clicking on the list will allow the user to select all the reservations or individual reservations within the selected state. If the user chooses all the reservations within a state, the selected state's aggregate page appears. The user can then view the reservations by county from an alphabetical list of the reservations, or view the reservations spatially on a state map. Clicking on the county listing selects a table that provides the name, location and size of the reservation, areal extent and

thickness of the deposits, status of mining, quality of the information and aggregate potential. Clicking on the reservation name on either the alphabetical list or the state map accesses individual reservations. The summary page for an individual reservation includes location, size, ownership, access, road type and condition, description of geology, past mining activities, aggregate potential, and a reference list of geologic information.

TRANSPORTATION EQUITY ACT FOR THE 21ST CENTURY (TEA-21)

The Transportation Equity Act for the 21st Century was enacted June 9, 1998 as Public Law 105-178. TEA-21 authorizes the Federal surface transportation programs for highways, highway safety, and transit for the 6-year period 1998-2003. TEA-21 authorizes over \$217 billion of federal funds over a period of six years. This represents an increase of 43 percent over the prior bill, which was also a six-year program. While future events related to this bill and their impact on the Aggregate Industry remains uncertain, American Indian Tribes are well poised to participate in the growth in infrastructure spending as a result of the passage of the TEA-21.

Significant features of TEA-21 include the assurance of a guaranteed level of Federal funds for surface transportation through FY 2003. The annual floor for highway funding is keyed to receipts of the Highway Account of the Highway Trust Fund (HTF). Transit funding is guaranteed at a selected fixed amount, and all highway user taxes are extended at the same rates as when the legislation was enacted.

TEA-21 also provides for an extension of the Disadvantaged Business Enterprises (DBE) program. This program provides a flexible national 10 percent goal for the participation of disadvantaged business enterprises, including small firms owned and controlled by women and minorities, such as the American Indian Tribes, in highway and transit contracting undertaken with Federal funding. Additional information and program description can be found at TEA-21's web site, <http://www.fhwa.dot.gov/tea21>.

Tribes have an additional advantage with the Indian Employment Tax Credit. This credit is calculated on

wages (including employee health insurance costs) up to \$20 000 for each employee. This credit provides business with an incentive to hire and retain individuals who are enrolled members of an Indian Tribe who live on or near an Indian reservation. Detailed information on this tax credit can be found at <http://ftp.fedworld.gov/pub/irs-pdf/f8845.pdf>.

CONCLUSION

The Bureau of Indian Affairs Division of Energy and Mineral Resources, by providing technical support to the American Indian Tribes hopes to set a standard of technical service other agencies can imitate. Most Tribes do not need or cannot afford full time geologists and engineers to support their programs. By taking responsibility for making such scientific expertise available to the Tribal governments, the DEMR, in conducting an assessment of the reservation's mineral resource potential, hopes to aid the Tribes in managing their mineral resources. The Bureau of Indian Affairs supports and assists American Indian Tribes and individual Indians to enter mineral leases or agreements for development of their trust and restricted lands. The intent is to obtain maximum economic recovery and reasonable compensation for the development of their resources. Indian Tribes may negotiate directly with mining companies under the authority of the Indian Mineral Development Act (IMDA) of 1982, and enter a joint venture, operating, production sharing, service, managerial, lease or other agreement.

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BALD RIDGE, ANNETTE ISLANDS RESERVE, AK

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INTRODUCTION

The Tribal Council of the Metlakatla Indian Community (MIC), Annette Islands Reserve, Alaska, and the Bureau of Indian Affairs Division of Energy and Mineral Resources (DEMR) located a potential crushed rock quarry site on the southern portion of the island (Figure 1). The Bald Ridge Aggregate Project's (BRAP) northern extent is placed at the MIC hydroelectric plant and pipeline, and the western boundary is Tamgas Harbor (Figure 1). The southern and eastern extents of the deposit have yet to be determined.

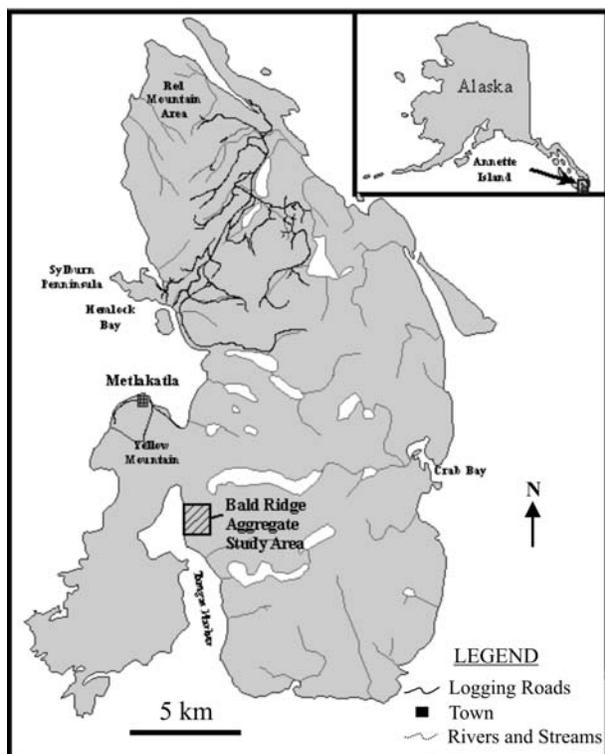


Figure 1 Location map of the Annette Islands Reserve and the Bald Ridge Aggregate Study Area

BEDROCK GEOLOGY

Bedrock units in Southeast Alaska have been divided into fault-bounded stratigraphic terranes. Bedrock underlying the Annette Islands Reserve is within the Annette subterrane of the Alexander terrane. Two thirds of the island is dominated by granitic rock of the Silurian: the Annette Pluton. The pluton, which is moderately to

strongly deformed, was intruded into greenschist to amphibolite grade metamorphic rocks. The Annette Pluton ranges in composition from granite to leucotondhjemite to quartz diorite. Host rocks to this pluton include meta-diorite, marble, quartzite, pelite, and greenstone. The Annette Pluton is overlain by metamorphosed Devonian and Silurian marine rocks including meta-conglomerate, marble, meta-pelite, greenstone, and meta-volcaniclastic rocks.

Rocks of the Annette pluton comprise the bedrock of the area within the Bald Ridge Area. In the BRAP area, the pluton is predominately quartz diorite with minor occurrences of mafic dikes and quartz veins.

GEOLOGICAL AND ENGINEERING STUDIES

In 1999, the DEMR collected surface samples and tested them using the Los Angeles degradation and sulfate soundness tests, along with whole rock analyses carried out using inductively coupled plasma (ICP) techniques. The purpose of this initial sampling was to determine areas that were favorable for potential aggregate production.

Structural data from detailed field mapping has been used to determine areas with potential for producing riprap, armor stone, and jetty stone. Field data was collected from existing quarries along Fish Hatchery Road as well as from outcrops along the hillside east of Fish Hatchery Road. Although several faults and a shear zone were mapped within the BRAP study area, these geological features do not appear to affect the quality of the rock with regard to the LA degradation and the sulfate soundness tests.

The MIC had thirteen holes drilled along Fish Hatchery Road (Figure 2) during the winter of 2000. DEMR geologists then logged and photographed the recovered core. Based on very favorable testing results additional drilling was conducted east of Fish Hatchery Road (Figure 2) during the summer of 2000. Approximately 5 985 feet of core has been recovered from 27 drill holes in the BRAP area.

The MIC has completed a topographic survey of the BRAP area using global positioning systems (GPS) surveying equipment. The survey has produced a more detailed topographic terrain model, which will be used during the creation of a mine model, and also to locate all the drill sites.

TABLE 1. SUMMARY OF THE DRILL HOLE DATA

TOTAL PROJECT AVERAGES			
Percent Loss at 500 Revolution	Uniform Hardness Ratio	Sodium Sulphate Soundness	Density
26.40%	0.229	1.81%	2.647

PETROLOGIC ANALYSIS

A petrologic analysis (ASTM C 295-90) on the recovered drill core was conducted to determine the overall mineral composition and chemistry of the rock. One purpose was to determine if there are any potentially detrimental minerals or element as it pertains to the production of aggregate. Thin section analysis, geochemical analysis and calculation of CIPW Norms were undertaken.

Thin sections were used to determine the mineralogy of each sample, the percentages of each mineral, and the overall rock type. Other features of possible importance that were noted include micro-fractures, alteration, and presence of sulphide minerals. Whole rock analyses and determination of 32 trace elements by means of the inductively coupled plasma (ICP) technique were carried out.

Using the whole rock analysis data obtained from the geochemical analysis, a CIPW Norm calculation was performed. This calculation uses the mole percentages of oxides present in the rock to calculate the minerals that would have formed if the initial magma had cooled slowly.

This calculation does not take into effect later alteration or secondary crystallization. The CIPW Norm calculation is used in conjunction with a thin section analysis to compare differences in lithology due to alteration or later mineralization. Preliminary results for the petrologic analysis indicate that the rock at Bald Ridge is primarily a quartz diorite, local areas are diorite, granite, and quartz monzodiorite. The primary constituents of this rock are plagioclase, quartz, and alkali-feldspar. Secondary minerals that are present include: titanite, hornblende, chlorite, calcite, pyrite, and various clay minerals. A mafic dike is also present in the study area, but makes up less than 5% of the total rock mass volume.

ENGINEERING TESTS

Los Angeles degradation tests (ASTM C 133), sulfate soundness tests (ASTM C 88), specific gravity determinations (ASTM D 5779), and whole rock analyses described in the previous section were performed on the drill core samples. These data sets may be found at: <http://snake1.cr.usgs.gov/demr/niemr/geochem/tables/annetlst.htm>.

Data gathered from lab testing of samples is used to determine both suitability of the rock for aggregate use, and any impacts that may occur from further operations. Testing of the drill core received from the initial phase of drilling has yielded acceptable results for construction materials (Table 1).



Figure 2. Aerial photo of the Bald Ridge Aggregate area showing drill roads and drillhole sites

Uniaxial Compressive Strength Test

Uniaxial compressive strength Test (UCS) (ASTM D 2938) was conducted on 55 samples to determine the unconfined compressive strength and the elastic constants of the rock. The unconfined compressive strength is often used as design criteria when constructing erosion control structures and can be an important indicator in determining the overall strength of the rock. This test is

TABLE 2. SUMMARY DATA FOR UCS TESTS

Project total	Peak Load (lbf)	Comp. Strength (psi)
Average	52,550.66	10,891.24
Max	122,061.70	25,066.33
Min	11,733.61	2,386.53
Std Dev	30,348.76	6,283.73
Median	43,163.27	8,856.80
Quartz Diorite		
Average	51,238.99	10,649.21
Max	113,066.00	24,510.48
Min	11,733.61	2,386.53
Std Dev	28,112.19	5,866.97
Median	42,563.11	8,650.11
Mafic Dike		
Average	58,453.17	11,980.35
Max	122,061.70	25,066.33
Min	17,700.83	3,591.60
Std Dev	39,888.62	8,126.82
Median	46,122.74	9,359.94

particularly important in determining the rock's suitability for use as riprap, gabion fill, or armor stone.

Summary values for the UCS test data are presented in Table 2. This table shows the maximum load and maximum compressive strength of each sample. This data set may be found at:

<http://snake1.cr.usgs.gov/demr/niemr/geochem/tables/annetlst.htm>. Test results for the UCS test varied greatly. Due to the many factors that can influence a rock's compressive strength, peak compressive stress varied from over 25 ksi to approximately 2.3 ksi. The mafic dike yielded slightly higher compressive strength than the quartz diorite.

The primary failure experiences were due to structural controls. On several samples, shear and columnar failure occurred. Failure of the rock is frequently linked to and caused by structures in the rock, such as joint planes. Thus the rock's compressive strength is primarily controlled by these structural discontinuities.

GEOLOGICAL AND MINE MODELING

The BRAP is being modeled in three dimensions. LA abrasion, sulfate soundness, and density are being modeled using inverse distance squared. The block size used is 30 x 30 x 12 metres (100 x 100 x 40 feet). Data collected by the drill holes is being composited to 12 metres (40 feet) to match potential mine bench height. The data used in the model creation include:

- a topographic model derived from United States Geological Survey Digital Elevation Model (DEM) files,
- GPS data points to supplement the topographic map,
- sounding data from Tamgas Bay,
- geologic field mapping including preliminary fault identification and lineament plots,
- access roads and drill roads,
- drill hole information and assays,
- location of streams,
- environmentally sensitive areas, such as eagles nests, and
- an air photo of project area

INDIAN MINERAL AGREEMENTS

The Metlakatla Indian Community may negotiate directly with mining companies under the authority of the Indian Mineral Development Act (IMDA) of 1982 and may enter a joint venture, operating, production sharing, service, managerial, lease or other agreement. Three objectives will influence the Metlakatla Indian Community in the development of their mineral resources: (1) orderly and timely resource development, (2) environmental protection, and (3) minimal cultural impacts associated with their development. The MIC has completed four Environmental Assessments: Walden Point Road was completed in 1997, Tamgas Bay was completed in 1999, Bald Ridge Drilling project was completed in 1999, and the Forestry Management Plan will be completed in 2001. In a recent meeting

with the approving Federal government agencies, it was decided that information in these reports may be applied to other Island areas, and may be used as environmental studies for the Bald Ridge Area.

LABOUR AVAILABILITY

Due to the recent closure of the Annette Hemlock Mill, coupled with the decline in the timber and fishing industries, which were the two primary sources of employment, a large labour driven workforce is available to the BRAP Project.

TRAINING

A grant to provide education and employment has been applied for cooperatively by the MIC and the University of Alaska-Southeast Ketchikan Campus to the United States Department of Labor Employment and Training Administration. The grant will provide pre-employment basic skills development, surface mining safety training, blasting and drilling courses, heavy equipment operation training, office skills, and accounting courses. The training will be a cooperative effort with several agencies including the University of Alaska, the Southeast Regional Resources Center, and the Mining and Petroleum Institute.

ENERGY REQUIREMENTS

The Metlakatla Power and Light Company (MPLC) is owned and operated by the MIC. It is a stand-alone utility with two hydro generator plants, a diesel generator and an emergency battery standby system. The total capability of the MPLC is 10 107 KW per hour. The two hydro generators are capable of producing 4942 KW per hour, the diesel generator 3300 KW per hour, and the emergency standby diesel generator 1865 KW per hour. MPLC has one of the lowest costs per KWH in Alaska.

The Purple Lake hydro generator plant is conveniently located at the base of Bald Ridge, and there is a surplus of energy to fulfill the BRAP needs.

TAXES AND TAX BENEFITS

The Mission of the MIC is to promote the planned, orderly growth and development of the Annette Islands Reserve, utilizing the following strategies:

- Promote a stable, reliable economic environment in which business can prosper and strive to eliminate factors which unreasonably increase the cost and complexity of doing business on the Island.

- Promote development and implementation of a long-term fiscal plan that addresses the diverse needs of the Community
- Advocate a strong education system to insure a fully qualified Metlakatla workforce

To this end the tax structure on Annette Island is:

Federal	35% *
Corporate	none
Property	none
Mining	none
Sale	none

* If the MIC is the major partner in a Joint Venture, the deal may be structured so that no Federal taxes are paid on the production and selling of the rock.

In January 1999, the MIC was designated as an Enterprise Community; therefore it receives the following benefits to encourage business on the Reservation:

(a) Indian Employment Tax Credit

The credit is calculated on wages (including employee health insurance costs) up to \$20 000 for each employee. This provides business with an incentive to hire and retain individuals who are enrolled members of an Indian Tribe who live on or near an Indian reservation.

(b) Welfare to Work (WtW) Credit

Provides a two-year credit against Federal tax liability for a business that hires long-term welfare recipients. Credits up to \$3 500 for the first year, and \$5 000 for the second year for each new hire.

(c) Work Opportunity Tax Credit (WOTC)

Provides a credit up to \$2 400 against Federal taxes for businesses for each new hire from groups that have high unemployment rates or other special employment needs, for example, youth ages 18 to 24, welfare recipients, ex-felons, and 16 to 17 year old EZ resident summer hires.

(d) Depreciation of Property Used on Indian Reservations

Special accelerated depreciation rules apply to qualified property placed in service on an Indian reservation after 1993 and before 2004.

For a more detailed discussion visit <http://www.ezec.gov>. Internal Revenue Service (IRS) Publication 954, "Tax Incentives for Empowerment Zones and Other Distressed Communities" and Form 8845 "Indian Employment Credit", contains a detailed description of the tax benefits, tax forms to use, and other information. The IRS web site at <http://www.irs.gov> contains detailed information on these tax incentives.

CONCLUSION

Calculation of the geological reserves in the BRAP area indicates that there is potential for over 200 million tons of crushed rock. Bald Ridge could become the first large crushed granitic rock quarry in the northern West Coast. Rock can be crushed at the quarry and loaded directly into either tug & tandem barges or self loading Panamax class bulk ships for transport to the West Coast and other Pacific Rim construction sites. The Metlakatla Indian Community believes that with proper planning and oversight, mineral resource production from their lands can provide financial benefits to both the community and a company without creating detrimental side effects.

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THE UNITED STATES AGGREGATES INDUSTRY - AN OVERVIEW

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The unprecedented growth in the United States aggregates industry that started in the early 1990s continues. For nine consecutive years, United States production of natural aggregates - crushed stone and sand and gravel - has increased; starting with 1994, output established a new record high level every year. Increased demand for natural aggregates is due to a continued high level of activity in commercial, public and private construction work.

As demand for natural aggregates increased, consolidation took place in the industry, with major aggregates producing companies making most of the acquisitions. As a result of this trend, the market share of

the large producing companies, at the national and state level, continued to increase.

In response to a growing interest in information about this industry, Minerals Information Team of the United States Geological Survey produced an enhanced database of commercial aggregates producers. The database was included in the United States Geological Survey National Atlas and is presented as a series of maps showing the locations of individual aggregates operations. The maps, as well as information about individual operations, are available on the United States Geological Survey National Atlas website (<http://www.nationalatlas.gov>).

EVALUATION OF POTENTIAL DIMENSION STONE DEPOSITS

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There are many criteria to consider when evaluating a dimension stone deposit for its development potential, including the geological characteristics, extraction methods, production requirements, organizational structure, the current demands and future trends in the market place, and the costs of capital, development, fabrication, transportation, and sales. Political and environmental issues related to permitting are also factors that must be integrated to determine development feasibility for a particular dimension stone deposit.

Demand for dimension and decorative stone for residential, commercial, and institutional buildings, as well as, for the restoration and expansion of existing structures, has grown. This increase has fostered development of new stone sources, and led to re-activation of previously idle quarries worldwide. High level market demand and improvements in quarry equipment and techniques have reduced extraction costs. These factors have facilitated the development of stone deposits that, based exclusively on geologic conditions, would otherwise have been marginal. Geological evaluation criteria become less important in defining a commercially viable dimension stone deposit when market conditions are favourable.

As with other industrial mineral commodities, the most successful recent developments have been brought on-line by groups having previous experience with the specific commodity (dimension stone). These groups typically have a vertically integrated organization for quarrying, fabrication, and marketing of the finished product. A second successful group includes organizations that are producing raw materials in the form of readily marketable blocks. These are sold to producers with access to fabrication facilities directly from the quarry. As with other industrial mineral ventures, adding value to the finished product is often the key to making a profit, and access to start-up capital to construct a fabrication facility is a critical factor.

In many cases, local and regional government support programs are critical factors in raising capital and affect the outcome of feasibility studies. In a number of jurisdictions, government support is available to facilitate construction or improvement of the regional infrastructure required to sustain the dimension stone industry.

The North American dimension stone industry thrived at the beginning of the 20th Century. This was due in part to the governmental and institutional building boom that resulted from the expansion of cities in the

United States. Now, at the beginning of the 21st Century, the current global economy has created a similar demand for dimension stone. Through globalization of the industry, blocks are now quarried at such diverse locations as Vermont, Atlantic Canada, and Brazil. The raw materials are shipped overseas in block form to Italy for fabrication, then finished products are shipped to consumers in North America, the Far East, and worldwide. Global market conditions and competition are major considerations when preparing a business plan with realistic cost and profit projections for a dimension stone project. The development of a viable dimension stone deposit is based, in part, on favourable political and economic conditions, not just the geological characteristics of the deposit. Successful development of new stone sources and re-activation of existing quarries is often based on the availability of supporting industry infrastructure and the presence of an established market for the stone commodity. Ultimately, the development feasibility of a dimension stone deposit must be based on a thorough evaluation of geologic, economic, and geopolitical conditions. Each criterion must be satisfied to establish a sound foundation for a quarry business plan.

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CARVING OUT A NICHE IN THE SCULPTURE STONE MARKET

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Stone carving dates back to the time of primitive man. Stone has been used not only in buildings, utensils, tools and weapons, but also artistic objects much like what is produced by stone sculptors to this day. The works of the Egyptians, both small and monumental, as well as the classical structures and statues of the Greeks and the Romans are well known. However, many other cultures less known for their works have carved stone throughout their histories, including cultural groups in parts of the Far and Middle East, Africa, Central and South America, to mention a few.



Figure 1. "Eye of the Storm" by Deborah Wilson
Made in British Columbia marble

Contemporary Stone carving in North America has been and still is highly influenced by the Europeans, but that is changing. The European influence is due not only to their long history of stone sculpture, but also as

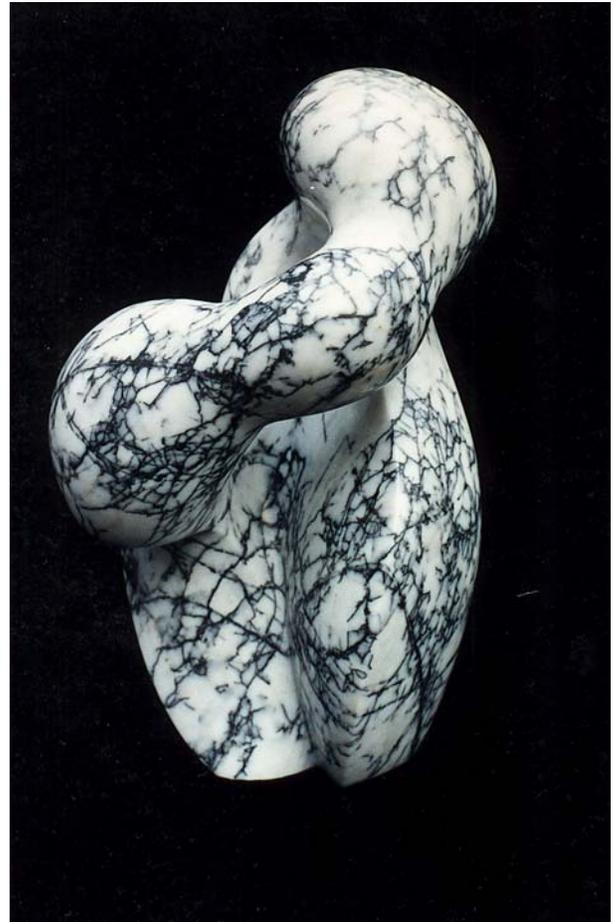


Figure 2. "Baise" by Deborah Wilson
Made with British Columbia marble

a result of many contemporary North American sculptors traveling there to learn from the masters.

Further, large amounts of stone and many tools are still imported from this region. However, as marble, limestone, granite, gypsum, talc and other mines developed in North America, an eager group of sculptors looked to use this local stone in their work. Locally produced stone appeals to both sculptors and their customers and is avidly sought when available. In addition, entrepreneurs have begun to exploit smaller and less commercially viable mineral deposits purely for sculptural and lapidary purposes.

Traditionally most of the artists in North America sculpted in stone of moderate hardness, such as marble (Figure 1), limestone and alabaster, using simple techniques and tools that have not changed much in



Figure 3. "Rapture" by Denis Kleine. Made from British Columbia Black Chlorite.

centuries. The colour of choice for the stone also tended to be pure and simple and was often selected to match a shape that was either figurative or required a higher measure of detail in the design. Beginners prefer to work stones that are softer, and then progress to harder

stones as their experience grows. However, in recent years, abstract designs have become increasingly popular (Figure 2). As well, air and electric tools have become affordable and efficient. Consequently, more people have been willing not only to explore stone sculpture as an art medium, but also to try a wider variety of non-traditional, more colourful, and harder stones.

The traditional definition of what constitutes a suitable sculpture stone has continued to expand beyond the basic qualities of having high purity, lacking fractures and taking a pleasing finish. The new definition for many now includes having an interesting natural pattern or design within the stone, beautiful or unique colours, interesting natural shapes or unique effects caused by nature such as weathering and oxidation. Traditionally, the sculptor often came to the stone with an idea, and then imposed their desired form on the stone. Now, with the greater variety of unique stones available, many sculptors are willing to let much of the natural beauty in the shape of the stone speak for itself (Figure 3).

In North America, a few established quarries that have been supplying stone to artists for years, yet many sculptors know little about the diverse variety of stone that can be found here. A small percentage of sculpture stone suppliers have put effort not only into collecting and quarrying stone but also into research and exploration in areas where interesting new stones might be found. Neolithic Stone Company was created by Randy Zieber, a sculptor in stone who originally began to search for new sources of stone for his own work. He soon realized that many others were interested in carving the stone that he found. As a result, he has spent a large amount of time and effort prospecting for deposits of new and unique carving stones, often stones that have never before been used for sculpture.

SOME CASE HISTORIES OF THE USE OF SANDSTONE AS BUILDING CLADDING IN WESTERN CANADA

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Around the turn of the last century many buildings and structures constructed on South Vancouver Island and the Lower Mainland were clad with sandstone quarried on the various Gulf Islands located in the Straits of Georgia. The performance of the various sandstone claddings has varied significantly, some had to be replaced but some are still performing well after approximately 100 years of service. This report presents several case histories of the performance of sandstone veneers on various buildings and structures. The physical performance of the sandstone is documented and, if available, the source of the sandstone is identified. Test data are presented to document the physical characteristics of each sandstone and recommendations are made about minimum criteria for compressive strength and water absorption for sandstones that will be exposed to the weather.

INTRODUCTION

The physical requirements of sandstone intended for use as building cladding is specified in the American Society for Testing and Materials document ASTM C616: "Standard Specification for Quartz-Based Dimension Stone". This standard provides the absorption, density and strength requirements for sandstone in three classifications that are related to rock type (Table 1). It is highly unlikely that minimum sandstone requirements were available for any of the buildings investigated in this study before they were constructed. Regardless, it is useful to compare these standards to the physical

characteristics measured for the cladding sandstones from various sources, and compare it to the actual performance of the cladding on different buildings and structures.

CASE HISTORIES

The Courtney Museum was constructed in 1925 using material from a quarry on Denman Island. The performance of the stone has been poor. It was used as lintel pieces over the main entrance and deterioration occurred in the form of peeling on the surface (Figure 1).



Figure 1. Courtney Museum (detail)



Figure 2. Young Building

The Young Building in Victoria (Figure 2) was constructed in 1911 using material from a quarry on Denman Island. The stone performance was poor. It was applied as cladding on the first floor level and on the clock tower. Deterioration is occurring as loss of material at the edges and corners, and also as exfoliation where the stones were laid with the bedding planes vertical.

The Naden Drydock (Figure 3) in Esquimalt was constructed in 1887 using material from a quarry on Newcastle Island. The performance of the stone has been good. It was used as cladding for the drydock walls and the seawall at the entrance to the drydock. The seawall part of the structure is subject to tidal fluctuations of salt water, freezing and thawing and erosion due to wave action, yet the stone is in excellent condition 113 years after construction.



Figure 3. Naden Drydock

TABLE 1: STANDARD SPECIFICATION FOR QUARTZ-BASED DIMENSION STONE.

PROPERTY	TEST REQUIREMENTS		CLASSIFICATIONS	TEST METHOD(S)
Absorption by weight, max %	8	I	Sandstone	C 97
	3	II	Quartzitic Sandstone	
	1	III	Quartzite	
Density, min, lb/ft ³ (kg/m ³)	125 (2003)	I	Sandstone	C 97
	150 (2400)	II	Quartzitic Sandstone	
	160 (2560)	III	Quartzite	
Compressive strength, min, psi (Mpa)	4000 (27.6)	I	Sandstone	C 170
	10000 (68.9)	II	Quartzitic Sandstone	
	20000 (137.9)	III	Quartzite	
Modulus of rupture min, psi (Mpa)	350 (2.4)	I	Sandstone	C 99
	1000 (6.9)	II	Quartzitic Sandstone	
	20000 (13.9)	III	Quartzite	
Abrasion resistance, min H _a ^{A,B,C}	2 ^D	I	Sandstone	C 241/C 1353
	8	II	Quartzitic Sandstone	
	8	III	Quartzite	

^A Pertains only to stone subject to foot traffic.

^B The supplier of the abrasive, Norton, has indicated that the formula for No. 60 Alundum abrasive (Norton Treatment 138S) has been changed. The new abrasive is currently more aggressive. Resulting in lower H_a values than when the standard was initially established. As such, care should be taken when interpreting H_a test results, both with regard to this standard and with regard to historical data from the same quarry source. Committee C-18 is actively studying alternatives to deal with this issue.

^C Abrasion Resistance Test Method C 1353 will eventually replace Test Method C 241 and it is not necessary to perform both tests. Availability of the proper equipment and materials by the testing laboratory may determine which test is performed.

^D Not recommended in areas subject to heavy foot traffic.

TABLE 2 TEST DATA FOR SANDSTONE FROM LOCAL BUILDINGS

Structure	Quarry	Water Absorption (% of dry weight)	Compressive Strength (Dry) (MPa)	Performance
Wesley Hall	Calgary	5.8	41.27	Very Poor
Courtney Museum	Denman	2.06	58.96	Poor
Young Building	Denman	2.06	58.96	Poor
Naden Drydock	Newcastle	1.34	102.38	Good
Customs Building	Gabriola	2.69	73.01	Fair
Craigdarroch Castle	Koksilah	1.49	102.8	Good / Fair



Figure 4. Craigdarroch Castle, Victoria

The Customs Building was constructed in 1898 using material from a quarry on Gabriola Island. Although some reports indicate that stone for this building may have come from the Saltspring Island quarry, stone performance has been fair. Significant peeling of the stone on the west building exposure is suggests that the stone was laid with the bedding planes oriented vertically.

It seems that the Gabriola sandstone had to be replaced due to deterioration within a few years of construction.

Craigdarroch Castle (Figure 4) was constructed in 1885 with material from the Koksilah quarry on Vancouver Island. In general the stone performance has been good but surface peeling is occurring in some areas, particularly those that face south and have the most weather exposure.

Wesley Hall was constructed in 1894 with material from a quarry in Calgary. Stone performance has been very poor, with severe deterioration at all areas where the stone is exposed to moisture. Considerable deterioration has occurred at rainwater leaders where they have become plugged (often due to freezing), and the water has leaked out and cascaded down the wall. Deterioration is also occurring at projections, such as cornices. Along the entire perimeter of the building, where rising damp has combined with freezing and thawing, the bottom 2 meters of wall above grade is damaged.

ANALYSIS AND DISCUSSION

The measured physical properties and stone performance for structures in this study are summarized in Table 2. We determined values for the Calgary and Koksilah quarries in the laboratory. Those for the Denman Island, Newcastle Island and Gabriola Island quarries were obtained from work by Parks (1916).

As shown in Table 2, the durability performance of the stone is directly related to the degree of water absorption and the compressive strength. The data suggests that the maximum water absorption should be of the order of 1.4% and the minimum compressive strength should be 100 MPa. Lower absorption and higher strength values would be desirable, because even at those values some deterioration is likely, for example, the deterioration seen at Craigdarroch Castle.

Considering requirements of ASTM C 616, for stone to perform well, only class III sandstone should be used in the coastal British Columbia climate. Class I and II sandstones permit unacceptable levels of water absorption, and are unlikely to perform well.

CONCLUSIONS

Sandstones that have been quarried on the various Gulf Islands are not very durable and not suitable for use as a building cladding in the British Columbia coastal climate. If local sandstone as a cladding must be

used for example in restoration work, then only stone with a compressive strength exceeding 100 MPa and water absorption of not more than 1.4% should be considered. If one is specifying the sandstone to meet the ASTM C 616 standard, then only class III material should be used in our climate.

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GOVERNMENT-INDUSTRY PARTNERSHIP EXPLORATION FOR DECORATIVE AND DIMENSIONAL STONE SITES IN SOUTHERN WYOMING

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The Industrial Minerals Section of the Wyoming State Geological Survey (WSGS) published two reports on the decorative and dimension stone resources of Wyoming in the early 1990s (Harris, 1991; Harris, 1994). Another key article was written on Wyoming's stone resources by Porter (1992). Wyoming's Precambrian geology includes most of the Wyoming Province, an extension of the Superior Province of the Canadian Shield, which all consist of a variety of granites, marbles, and other stones.

Granite decorative and dimension stone products of Minnesota and South Dakota are produced from the Superior Province. As the decorative and dimensional stone resources of Wyoming became more widely known, landowners and others interested in development began to take an active role in exploration and development. One of the largest private landowners in Wyoming is the Union Pacific Railroad. The railroad was granted surface and mineral ownership of every second square mile for 20 miles on either side of the original railroad right of way. This right of way and area of Union Pacific mineral ownership extends from the Nebraska border through the southern one-quarter of Wyoming to the Utah border on the west.

At the 1998 Wyoming Geological Association Annual Meeting, representatives of Union Pacific Land and Resources Corporation (UPLRC) met with the Industrial Minerals Geologist of the WSGS. The purpose of the meeting was to begin negotiating details of an agreement in which UPLRC would sponsor a grant to study decorative and dimensional stone resources on and near the Union Pacific land grant property in southern Wyoming. In order to assure that the study would not unfairly benefit any entity, the negotiations involved the Wyoming State Attorney General's Office, UPLRC, and the Wyoming State Geologist. An agreement reached in March 2000, and signed at the end of the month provided \$23 896 for field expenses, equipment, and publication costs over a three-year time period. At the end of that time, the WSGS will publish a report covering approximately sixty sites in Wyoming south of the 42nd parallel suitable for the production of decorative or dimensional stone. Although the offices of UPLRC were almost destroyed by a tornado that damaged several

buildings in downtown Fort Worth, Texas during the spring of 2000, this did not affect the beginning of the field study. Later in the summer, Anadarko Petroleum purchased UPLRC, and the offices were moved to Houston, Texas. Anadarko Petroleum maintained the industry commitment to this project.

This grant is a milestone in government-industry partnerships. Although the WSGS has previously received private industry funding for geologic studies, this is the largest award to date. Sites to be studied include those with potential to produce dimensional stone (quarriable for large blocks 1.5 metres by 1.5 metres by 3 metres), monument stone (smaller than 1.5 metres by 1.5 metres by 3 metres), decorative aggregate, and fieldstone (moss rock, landscape rock, boulders, and so on).

Fieldwork under this grant began in April 2000, and is currently three-quarters complete. Field studies included site mapping; joint and fracture density determination, sampling to prepare small polished samples; photography, property ownership determination, and site access reports. Heavy snow in southern Wyoming ended the field season on October 31, 2000. During the winter, reports and maps were prepared for 41 sites that were determined to have stone production potential. As these reports have been prepared, they have been posted on the internet. Mapping has been assisted by the use of Global Positioning System (GPS) technology.

HERMOSA GRANITE

The following is a preliminary report on the Hermosa granite site; one of the first sites examined during the course of this study.

This coarse-grained dark pink granite (Figure 1) crops out over a wide area with many choices of quarry sites available. Mahogany-colored coarse-grained granite in railroad cuts near west portal of the Hermosa Tunnel have the following attributes:

- Location: S 1/2 SE 1/4 Sec. 17, Sec. 16, Sec. 21, NE 1/2 Sec. 20, T.13N., R. 72W, Albany County, Wyoming
- Base map: Dale Creek Wyoming 7 1/2' Quadrangle



Figure 1. Westernmost outcrop of pink Hermosa Granite. Hermosa Road (Albany County Road 222) in left foreground. Photo by Ray Harris, September 2000.

- Land Status: Section 17 and the S. 1/2 21 are under Union Pacific surface and mineral ownership; the state has Section 16 surface and mineral ownership. The NE 1/4 Section 20 has Private Surface (Weaver) but Federal mineral ownership, as does the remainder of Section 20 (Private Surface - Kilpatrick). The N1/2 of Section 20 has private surface (A-X Ranches Inc.) ownership, but the minerals are owned by Union Pacific.
- Jointing and fracture spacing: Joints approximately 13 metres apart with some minor exfoliation jointing. Massive outcrops (Figure 2).



Figure 2. Close-up of pink Hermosa granite. Orange and yellow colors are lichen. Photo by Ray Harris, September 2000.

SUMMARY

Excellent quarry sites are present in this area. Although dark pink granite is the common variety, unusual mahogany-coloured granite is likely to be a highly popular product.

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DIMENSION STONE INDUSTRY PRODUCTION AND TRADE STATISTICS OF THE UNITED STATES—ISSUES AND TRENDS

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INTRODUCTION

The purpose of this report is to provide a general overview and history of dimension stone production in the United States during the 20th century. Production statistics are discussed along with the prevailing economic conditions and historical events. The report focuses primarily on domestic production of dimension stone in the United States, with a short discussion on foreign trade. Unless otherwise noted, the data used in this study include all dimension stone types. Dimension stone production data for the United States are currently derived by the United States Geological Survey (USGS) from a voluntary survey of United States dimension stone producers of rough and dressed dimension stone. Data generated by the USGS cover rough crude quarried, irregular-shaped and rectangular blocks, and also more highly processed stone. Production and trade data are in tonnes. Dimension slate was reported separately and added to the dimension stone figures for the years 1905 to 57. Data from 1900 to 1989 were converted from short tons to tonnes by multiplying short tons by 0.9072.

DESCRIPTION AND TERMINOLOGY

Dimension stone can be defined as natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length, and thickness) and shape (Currier, 1960). Specific colour, grain texture and pattern, and surface finish of the stone are normal requirements. Durability (essentially based on mineral composition, hardness and past performance), strength, and the ability for the stone to take a polish are other important selection criteria.

Although a variety of igneous, metamorphic, and sedimentary rocks are used as dimension stone, the principal rock types are granite, limestone, marble, sandstone, and slate. Other special minor types of dimension stone include alabaster (massive gypsum), soapstone (massive talc), and various products fashioned from natural stone. Rough stone blocks split or cut from a quarry face are transported to processing plants, frequently located at the quarry site, at least for preliminary sizing. Further dressing, including final sizing and finishing operations, such as polishing, edging, and decorating, also may be done at the quarry site.

There is significant overlap between scientific and commercial descriptions of various dimension stone types.

Scientific descriptions of dimension stone types focus primarily on the stone's origin and its mineralogical composition, whereas commercial descriptions focus mainly on the locality and color of the stone. Stone producers use various combinations of scientific and commercial descriptions to effectively market their stone products. The following descriptions were adapted from Barton (1968, pages 2 to 8) and Currier (1960, pages 1 to 10):

Granite—Commercial granites include all feldspathic crystalline rocks with interlocking textures and individual mineral grains visible to the naked eye. This category includes rock types such as gneiss, syenite, monzonite, granodiorite, anorthosite, and all other intermediate rock types. Primary colours of granites are white, grey, pink, and red, with green and brown being secondary colors. Black granites, which are not true granites mineralogically but rather mafic rocks such as diabases, diorites, gabbros, and similar rocks, are also included in this category and range in color from dark grey to black.

Limestone—Commercial limestones are rocks of sedimentary origin primarily composed of calcium carbonate with or without magnesium. Included in this category are calcitic limestone, dolomite, dolomitic limestone, and travertine (a rock that is chemically precipitated from hot springs).

Marble—Commercial marble includes metamorphosed limestones and serpentine rocks—all capable of taking a polish. An important member of this classification is serpentine marble, also known as *verde antique*, which is composed of green to black serpentine (a hydrous magnesium silicate mineral) crisscrossed by veins of lighter minerals such as calcite or dolomite.

Sandstone—Commercial sandstone is a lithified sand composed chiefly of quartz or quartz and feldspar of fragmental (clastic) texture. Sandstone contains interstitial cementing materials such as silica, iron oxides, calcite, or clay. Arkose, with abundant feldspar grains; greywacke, with abundant rock fragments, and conglomerates are included in this category. Other members of this category include: bluestone, which is a dense, hard, fine-grained feldspathic sandstone that splits easily along planes into thin, smooth slabs; brownstone, which is a feldspathic sandstone of brown to reddish-brown color, owing to abundant iron oxide; and flagstone, which is a sandstone or slate that splits into large, thin slabs.

Slate—Commercial slate is a microgranular metamorphic rock formed by the recrystallization of clay-

rich sediments like shale, siltstone, or claystone. It is characterized by excellent parallel cleavage, so slates are easily split into relatively thin slabs.

Greenstone—Commercial greenstones are metamorphosed basaltic rocks. Greenstone is so named because of the predominance of greenish minerals such as chlorite, epidote or actinolite.

Basalt and traprock—The commercial basalt and traprock category includes igneous rocks that are too fine grained to be termed black granite. The name traprock is derived from the term “trappa,” meaning stairway, in reference to the characteristic terraced or step-like appearance of certain basalt lava fields. This category includes both extrusive igneous rocks, such as basalt, andesite, or dacite, and intrusive igneous rocks, such as diabase, diorites, fine grained gabbros, pyroxenites, amphibolites, and peridotites.

Miscellaneous—This category includes types of dimension stone such as soapstone, talc, or steatite. These rocks contain various amounts of talc and do not easily fall into the other categories. Additional miscellaneous dimension stones are diatomite, mylonites, pumice, schist, tripoli, tuff, and porous and scoriaceous volcanic rocks.

HISTORICAL PERSPECTIVES ON UNITED STATES PRODUCTION OF DIMENSION STONE

Punctuated by labour strikes, and high costs and wages, the production of all types of dimension stone in the United States in 1900 amounted to 1.6 million tonnes (Mt). The top producing State, by value, was Pennsylvania (Table 1). In the early 20th century, reinforced concrete and structural steel superseded dimension stone as major structural components in buildings. As early as 1906, granite quarries in the United States expressed concern over the encroachment of substitute materials such as concrete and asphalt for road building. In 1931, when the Empire State Building was officially opened, it featured cladding of Indiana limestone, and helped create a new market for dimension stone as interior and exterior paneling. That same year, United States production of dimension stone rose to the highest level of the 20th century at more than 6 Mt. The lowest level of United States dimension stone production in the 20th century occurred in 1944 during World War II at 649 000 tonnes, owing to a lack of skilled labor, nonessential commodity status, and virtually no building construction.

In 2000, production of dimension stone in the United States amounted to about 1.3 million tonnes. The top producing State by value was Indiana. Also in that year, the United States imported more than \$1 billion worth of dimension stone. It was used extensively in home improvements, historic preservation, exterior and interior paneling for buildings, and construction applications. Most dimension stone was sold or used as rough blocks for

building and construction, flagstone, curbing and ashlar, as partially squared pieces, and as monumental and memorial stones.

In 2000, limestone was the most widely used dimension stone because of its uniform color and texture, and the ease with which it can be carved. Granite, the second most widely used stone, is used for buildings, monuments and bridges. Limestone was more extensively used prior to the early part of the 19th century, when Portland cement became widely available. Sandstone, obtained mostly from local sources, was commonly used in the northeastern United States before 1900, but only accounted for about 10% of consumption in 2000.

In the first quarter of the 20th century, the marble quarrying industry was much larger than it is today. Solid marble wall construction was virtually abandoned when steel-framed reinforced construction was introduced. Now ‘marble’ buildings feature only a thin marble veneer. In 2000, marble was one of the least used dimension stone types nationwide for new buildings, but was used extensively in buildings of historical significance (McGee, 1997).

Dimension stone production in the United States reached its highest production level in 1931, at 6 060 000 tonnes, and its lowest level in 1944, at 649 000 tonnes (Figure 1). In the following discussion, dimension stone production data for the 20th century are divided into three groups.

1900 to 1933—In the first ten years of the 20th century, relatively high wages and the cost of supplies, coupled with a lack of unskilled labour for quarries were detrimental to the industry. Industry concerns included the encroachment of substitute materials, the financial panic of 1907, which eroded consumer confidence, tight money supplies, and severe limitations on credit. The industry experienced a modest recovery between 1907 and World War I. When the United States entered World War I in 1917, dimension stone production was hampered by the lack of skilled labour, because dimension stone was declared a nonessential commodity, and because building construction came to a virtual standstill. In the years immediately following the War, the dimension stone industry again recovered.

As for the industry as a whole, production of block granite was static from 1904 until 1928; however, nearly mounting prices nearly doubled the value of annual production. Granite used for memorials showed a large increase in value with a small advance in production during the same period. Building granite increased in value slightly, and there was a decline in the use of granite paving blocks and rubble (Bowles and Hatmaker, 1931).

In the 1920s and early 1930s, the building granite industry was stagnant, in sharp contrast with increased production of many other building materials of mineral origin. The value and amount of limestone produced in

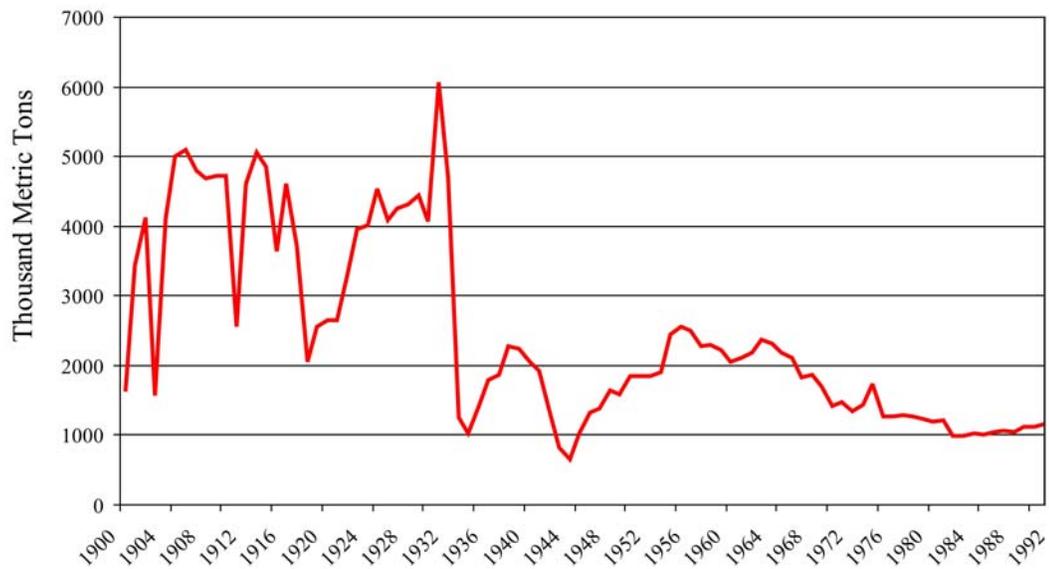


Figure 1. United States Dimension Stone Production in the 20th Century

Indiana, chiefly for construction purposes, increased greatly during this period. In 1921, the United States Congress passed the Federal Highway Act to coordinate and standardize road building. By the end of 1921, total surfaced road in the United States was 387 000 miles, nearly double the amount at the beginning of the century (Trager, 1992). Building marble sales dropped sharply during the industrial depression of the 1930s, and dropped again (along with virtually all dimension stone types) during World War II, owing to the fact that construction of buildings using marble came to a standstill (Bowles, 1958).

With the increasing use of the automobile, demand for aggregates for concrete and asphalt made the production of aggregate more attractive than dimension stone. Nationwide, cement, sand and gravel, crushed stone, and gypsum production continued to increase from 1904 until the early 1930s.

From 1923 to 1928, the dimension stone industry experienced steady growth with few labour problems. However, there was greater competition among operators, as well as from substitutes, such as Portland cement, increased (Bowles and Hatmaker, 1931). In 1929, Black Friday heralded the start of the Great Depression that lasted through 1932. The Depression had a profound effect on all aspects of the United States and global economies. In 1932, United States industrial production dropped to one-third of the 1929 total, with the Gross National Product falling to \$41 billion, barely 50% of the 1929 level. In 1931, the year of greatest production of dimension stone in the United States, New York City's Chrysler Building, which is mostly structural steel and concrete, and the Empire State Building, which has Indiana limestone cladding, were officially opened, and construction started on the Rockefeller Center. The new

skyscraper era introduced a new niche for dimension stone as both interior and exterior paneling for these buildings. In 1931, the introduction of the wire saw in two quarries in Indiana, greatly increased the speed of stone processing and diminished the volume of waste (Bowles, 1939). Another notable structure that used dimension stone and was completed between 1900 and 1933 was the Lincoln Memorial in Washington, D.C., which used Colorado Yule marble on its exterior. It was completed in 1916 and dedicated in 1922. Additionally, the Tomb of the Unknowns at Arlington National Cemetery, Virginia, which used the Colorado Yule marble, was completed in 1931 (McGee, 1999).

Unemployment in the United States was between 15 and 17 million by the end of 1932; 34 million Americans had no income. The average wage for those who worked was \$16 per week (Trager, 1992). The United States Government instituted several programs during the era of the New Deal to stimulate the sagging economy. Road and dam building associated with the creation of the Tennessee Valley Authority and the Civilian Conservation Corps in 1933 contributed to gradual increases in dimension stone production in the following years (Trager, 1992).

1934 to 1967—In 1934, the United States Government instituted the Works Progress Administration to stimulate employment. The focus was on building construction and infrastructure projects. This helped contribute to a gradual rise in dimension stone production in the years leading up to World War II (Trager, 1992). When the United States entered World War II in 1941, lack of skilled labour and the nonessential commodity status of dimension stone contributed to production declines that reached an industry



Figure 2. The United States Supreme Court Building

nadir in 1944. Sales of memorial marble remained at a high level during World War II and the immediate postwar years and then significantly declined; however, the postwar recovery of the entire marble industry was moderate (Bowles, 1958).

In 1944, a large-scale migration of Americans from rural to urban areas began, creating major problems in cities. Conversely, for veterans the G.I. Bill of Rights of 1944 provided home loans at 4% interest, and allowed purchase with no down payment. This subsidized a postwar building boom, and triggered an exodus of populations from major metropolitan areas (Trager, 1992).

After World War II, the populations of urban areas continued to decline into the 1950s and 1960s, with concomitant increases in building and engineering construction. Dimension stone production experienced moderate recovery during the post-War years, culminating in 1955. For example, in 1954 and 1955, 1800 shopping centers were built in the United States, considerably more than in prior years (Trager, 1992).

The United States Supreme Court Building in Washington, D.C., which was dedicated in 1935, featured Vermont white marble in its facing and structure (Figure 2). Georgia granite, Tennessee marble, and Indiana limestone were used in construction of the Jefferson

Memorial in Washington, D.C. (Figure 3), which was dedicated in 1943 (Withington, 1998).

1967 to 2000—Devaluation of the United States dollar in 1971 and 1972 resulted in products being more competitive in both domestic and foreign markets, and helped generate dimension stone production increases as well. The 1.7 Mt of dimension stone produced in 1974 was the highest since 1967 and 1968 and has not been matched since. The diamond wire saw was introduced to the United States dimension stone industry during the 1970s (Power, 1994). The new saw gradually replaced the older wire saws and became the standard technology used to cut dimension stone by the end of the 20th century. Companies closely guarded their own methods of using the diamond wire saws.

Economic recession in the United States continued from 1974 until 1983, attributed in part to higher global prices for oil. During the latter third of the century, dimension stone production levels were lowest in 1982 and 1983. This low correlated with severe global economic recession that led to declining international trade and caused United States unemployment levels to reach 10.8%, the highest since 1940. Economic recovery began in 1983 and unemployment dropped during the year (Trager, 1992). The economic boom of 1983 to 1990 contributed to slowly



Figure 3. The Jefferson Memorial Building

rising dimension stone production levels in the United States. With continued economic growth towards the end of the 20th century, the industry began to slowly exploit and diversify into the growing markets for home improvements, such as kitchen counter tops, home restoration, and historic preservation. Dimension stone offered consumers an alternative to substitute materials such as Formica and Corian.

Noteworthy projects that employed dimension stone in the United States during the latter third of the century include the Franklin Delano Roosevelt Memorial in Washington, D.C., which used granite from South Dakota and California, the new Denver airport, which used Colorado Yule marble on the interior, and restoration of the Washington Monument, which used Cockeysville marble (McGee, 1999).

UNITED STATES DIMENSION STONE TRADE AT THE BEGINNING AND END OF THE 20TH CENTURY

In 1900, the total value of United States dimension stone imports was slightly over \$1 million. Marble accounted for approximately 80% of the value, and Italy was

the primary source. Imported lime and limestone, valued at \$63 900, came almost entirely from Canada.

In 2000, preliminary data indicate that United States dimension stone imports exceeded \$924 million. Granite accounted for over \$700 million of this figure. Major sources by descending order of value were Italy, Brazil, India, Canada, and China. The United States imported more than \$105 million worth of dimension stone from Canada in 2000.

Preliminary data indicate that the United States also exported approximately \$60 million of dimension stone in 2000. Most was granite, and about half went to Canada. Following Canada in descending order by value, major export markets for United States dimension stone in 2000 were Mexico, China, the United Kingdom, and Japan. Dimension stone tonnages imported and exported in the 20th century are shown in Figure 4.

SUMMARY OF PROGRESS

The dimension stone industry of the United States has shown remarkable resilience during the 20th century, despite economic and political upheaval, which is the mark of a mature industry. It is interesting to review suggestions made

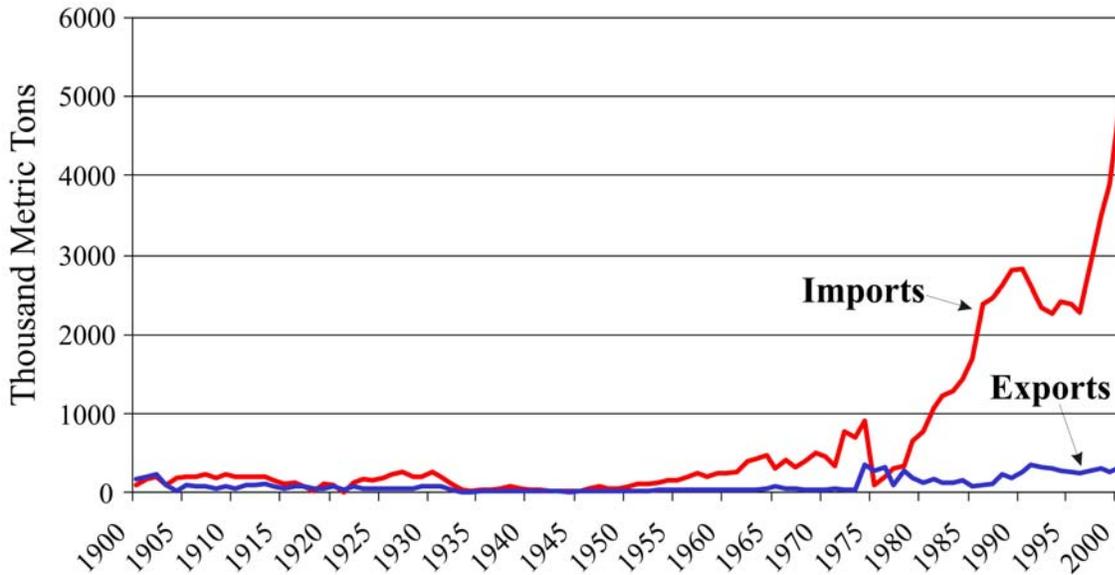


Figure 4. U.S. Dimension Stone Trade In the 20th Century

in the early part of the 20th century by Bowles and Hatmaker (1931) to improve the granite industry:

Suggestion 1. Wider diversification in products and, consequently, better utilization of waste materials.

This suggestion has materialized, as evidenced by the myriad of new downstream products offered by the dimension stone industry. Additionally, most major companies now use former waste materials from a quarry, for example, granite sold as crushed and/or pulverized rock.

Suggestion 2. Improvement in certain manufacturing methods.

The decreasing unit cost of dimension stone production is directly related to the increased mechanization of the quarrying and finishing of stone. This approach also requires less manpower and lowers costs relating to the manufacturing process. For example, electronically controlled lines for cutting blocks, fabrication and polishing, and the increasing use of computer-controlled machinery are now almost ubiquitous in the industry.

Suggestion 3. Greater sales effort in the marketing of building stone and paving blocks, as the field of use for these products is certainly large and appears to be well worth cultivating.

Although marketing of dimension stone products is now a major focus of producers, the current market for building stone and paving blocks is not as large as it was in the earlier part of the 20th century. In recent years, most dimension stone has been used in construction applications with the largest portions being sold or used as rough block for building and construction, flagstone, curbing, ashlars, partially squared pieces, monuments, and memorials.

Suggestion 4. Further progress in standardization of products.

Standardization of products has improved during the past century, however certain problems remain. Simpler guidelines for improved standardization of manufacture, design, and installation may be needed. For example, certain types of imported slate behave poorly when exposed to the United States climate, which can result in poor performance for both customers and installers.

If the global economy continues to be robust, demand will grow for dimension stone during the beginning of the 21st century. Improved technology, product variety, and the increased costs of alternative construction materials will be important factors. Additionally, use of dimension stone is expected to grow for residential and office building construction, in new prestige markets as well as in renovations to attract and keep tenants.

ACKNOWLEDGMENTS

Carl A. DiFrancesco and Donald Bleiwas of the United States Geological Survey (USGS) in Denver, Colorado, gathered and compiled most of the data. Their help was invaluable in the preparation of this report. The primary sources of data for dimension stone in this report are the mineral statistics publications of the United States Bureau of Mines (USBM) and the USGS—Minerals Yearbook (MYB) and its predecessor, Mineral Resources of the United States (MR), and Mineral Commodity Summaries (MCS), and its predecessor, Commodity Data Summaries (CDS). The United States Census Bureau is the source of trade data.

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DIMENSION STONE EVALUATION WITH SPECIAL REFERENCE TO GEO-RADAR INVESTIGATIONS

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INTRODUCTION

Dimension stone is a natural rock that fulfills specific quality requirements and is extracted and quarried into definite shapes and sizes. Rocks used as dimension stone include, granite, gneiss, gabbro, diabase, marble, limestone, sandstone, soapstone, and slate. Dimension stone is mainly used in the building, construction, monument and tombstone industries. The definition of dimension stone covers rough blocks and finished material, but excludes crushed or powdered stone consumed as an aggregate or reconstituted to form artificial stone (Allison, 1984; Niini, 1986).

Applied geological investigations of dimension stone deposits may have two goals: identification of a “new” deposit or development of an “old” deposit/quarry (Selonen *et al.*, 2000). Evaluation requires knowledge of the production properties of a prospect or a quarry. Generally, reserves of feasible stone for at least ten years of production should be identified, which emphasize the necessity of three-dimensional investigation of the deposits.

DIMENSION STONE IN FINLAND

The Precambrian bedrock of Finland is a part of the Fennoscandian Shield and consists of an Archean craton (3100 to 2500 Ma) in the eastern parts of the country and the Paleoproterozoic Svecofennian orogenic belt (1930 to 1800 Ma) in the southern parts. The Svecofennian belt is intruded by Paleo/Mesoproterozoic rapakivi granites (1650 to 1540 Ma) in southern Finland. The Proterozoic plutonic rocks, which are traditionally divided into four groups with respect to the Svecofennian orogeny, occupy over half of the bedrock area in southern Finland. Intrusions are: Synorogenic, Late-orogenic, Post-orogenic and Anorogenic (Nurmi and Haapala, 1986).

The Finnish terrain has been glaciated several times since the beginning of Quaternary age. Consequently, most of the Proterozoic sedimentary formations as well as the weathered surface of the older bedrock have been eroded to reveal sound bedrock.

For geological, historical and economic reasons, the extraction of dimension stone is confined mainly to Proterozoic plutonic rocks in southern Finland, close to the coast. The anorogenic rapakivi granites, which are the most significant types of dimension stone in Finland, are

quarried at some 20 sites in southwestern and southeastern Finland. *Balmoral Red* is the classic Finnish dimension stone quarried at several sites in the Vehmaa rapakivi granite batholith in southwest Finland. The Wiborg rapakivi granite batholith in southeast Finland is the source of brown dimension stone types such as *Baltic Brown* and *Monola Brown*. The red types include *Carmen Red*, *Karelian Red* and *Eagle Red*. Synorogenic Svecofennian granitoids are quarried mainly in central Finland with products like *Kuru Grey*, *Viitasaari Red* and *Viitasaari Pink*. *Kuru Black* and *PM Black* represent mafic components of the synorogenic rocks. Multicoloured *Lieto Red*, *Aurora*, and *Amadeus* are extracted from the late orogenic granite-migmatite zone in southern Finland.

In addition to the igneous rocks, soapstone is extracted in large quantities in Finland. It is processed mainly for ovens, fireplaces and liners. The production of Finnish dimension stone in 1999 was approximately 500 000 tonnes.

QUALITY CRITERIA AND EXPLORATION PROCEDURES FOR DIMENSION STONE

Strict quality criteria are used to determine whether a rock is suitable as dimension stone. The appearance of a stone is critical. In single-coloured stones the colour must be as homogeneous as possible across the whole deposit, whereas in multi-coloured stones a vivid variation of the colour is preferred.

The second critical criterion is soundness; the spacing of the fractures must be at least 2 to 3 metres to enable production of blocks for the international stone market. The third essential criterion is market demand for the stone. To be economic, the dimension stone deposit must have access to good transport facilities. It should not be located close to major landmarks, parks or environmentally sensitive areas. When used in the construction and building industry, stone must satisfy strict physical and mechanical requirements. These properties are measured in certified laboratories by standardized methods (DIN, ASTM, and CEN). For discussions of the quality demands of dimension stone, see Harben and Purdy (1991), Jefferson (1993), and Selonen *et al.* (2000).

Geology-based dimension stone exploration (Figure 1) is systematic and stepwise. It begins with compilation, then field mapping, more detailed examination, geo-radar surveys, core drilling, and additional studies (test production, test processing, and commercial testing). The exploration process is presented in more detail by Selonen *et al.* (2000).

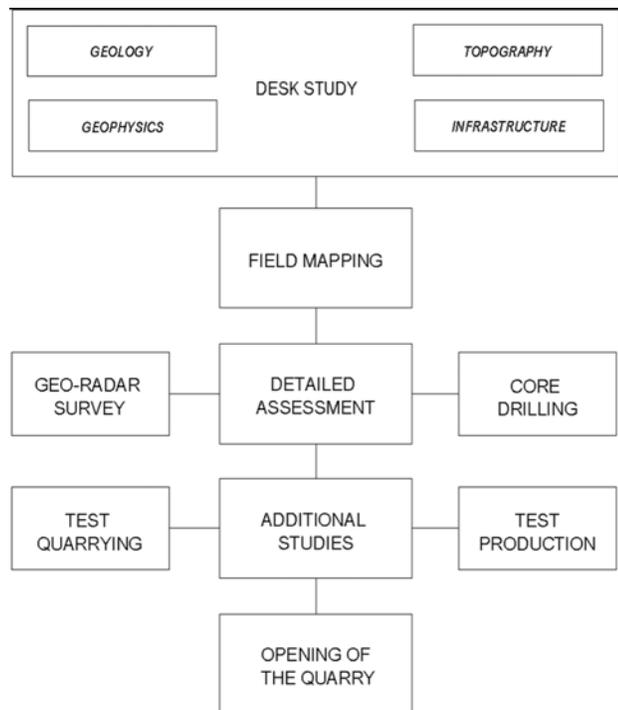


Figure 1. Process of geological dimension stone exploration (Selonen *et al.*, 2000).

USE OF GEO-RADAR IN DIMENSION STONE INVESTIGATIONS

Especially in granitic rocks, geo-radar is an effective exploration tool. It provides a useful, quick and inexpensive method both in prospect evaluation and in making regular measurements in a quarry to assist production planning (Luodes *et al.*, 2000; Luodes and Selonen, 2000).

Geo-radar or ground penetrating radar (GPR) is an electromagnetic sounding method, which uses radio frequencies. The measuring equipment has transmitting and receiving antennae, a control unit and a power supply. The computer based control unit is normally portable and it is used to adjust the measurements and store the data. The antenna equipment is moved over the measured medium at a constant speed. The transmitting antenna sends electromagnetic pulses into a medium, in this case rock. When the pulse reaches a layer or an object with deviant electronic properties, some of the energy will be

reflected back, while the rest will proceed. The amplitude of the reflected part and the time elapsed between the pulse and reflected wave and the moment of transmission are recorded at a rate of approximately 25 to 52 times per second. This produces a continuous cross-section of fluctuations in the electrical properties of the rock (Hänninen 1992). Direct contact between the antenna and the measured medium improves the quality of the results.

Propagation of the waves is dependent on the dielectric properties of the rock. The dielectric values of different rock types vary from 4 to 10. Wave propagation is attenuated at each reflective interface because some of the energy is reflected back. Physical and mineralogical properties of the rock can further increase attenuation. Large quantities of conductive minerals can restrict penetration of radar waves. Moisture, dissolved salts and some clay minerals can also seriously limit the effectiveness of the geo-radar. (Hänninen *et al.*, 1991).

The Geological Survey of Finland has adopted geo-radar as a standard method in evaluation of dimension stone prospects. During the “Exploration for new dimension stones in Eastern Finland” project (<http://stone.gsf.fi>) from 1996 to 1999, several new prospects were surveyed in order to get an overview of their soundness. Some examples of the benefits and pitfalls of geo-radar investigations are listed below. The problems encountered strongly emphasized the need to use several exploration methods when evaluating a prospect.

Use of Geo-radar in Rapakivi Granite

A rapakivi granite prospect was located in central southeast Finland by geological field mapping. The overburden was removed with an excavator to prepare for mapping traverses and also to enable contact between the geo-radar antenna and the rock surface. Although the prospect was considered promising because of its homogeneous appearance and sparse fracturing, strong weathering of the surface prevented a reliable confirmation of the soundness or colour variation. A limited core drilling program was conducted on the prospect to test the homogeneity and fracture frequency. Geo-radar measurements were made over a wide area to explore soundness. The geo-radar was tested with the most common antennae (100 MHz, 200 MHz and 300 MHz) to compare the results with the drill core data (Figure 2).

The radar measurements were consistent with the drilling results; the best and most usable data were with the 200 MHz antenna. Open fractures of the prospect were filled with water or moisture, which produced clear reflectances from rock/fracture interfaces.

The energy of the radar pulse weakens at a depth of 30 metres with the 100 MHz antenna, and at 20 metres with the 200 MHz antenna; only a few reflections are

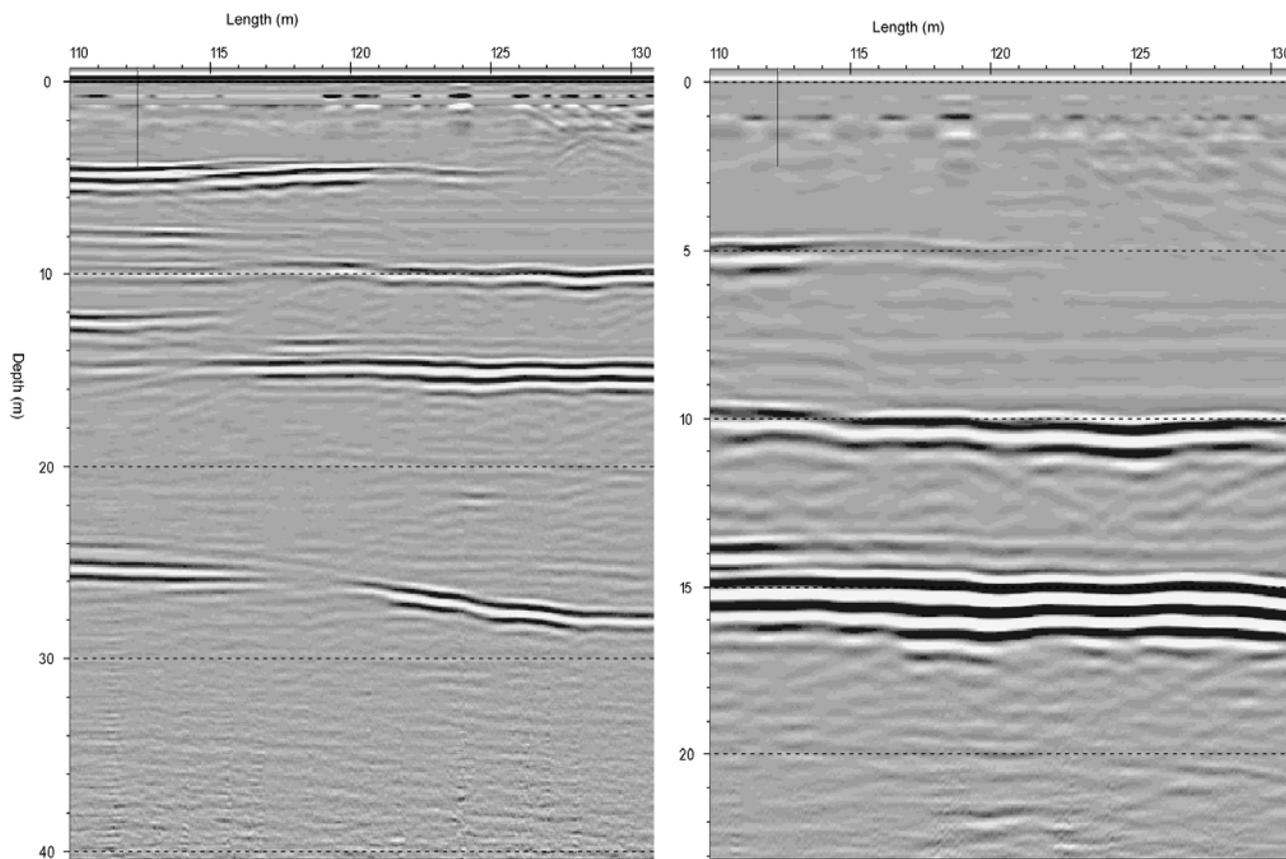


Figure 2. Depth penetration of geo-radar with 100 MHz (left) and 200 MHz (right) antennae.

returned below those depths (Figure 2). This could lead to false interpretations, indicating that the deeper layers are more sound than they really are. If there is a significant amount of surface fracturing, it can also reflect most of the pulse energy back, leading to rapid falloff of the radar signals, which gives even less information from the deeper sections. The identification ability of the antenna is dependent on the wavelength used, so closely spaced fractures might not be detectable from data produced by low frequency antennas.

Use of Geo-radar in Porphyritic Granite

Geo-radar measurements were performed on a homogeneous porphyritic granite with well developed horizontal fractures. The intention was to explore the nature of horizontal fracturing and to try to determine changes in fracture density with depth. The prospect was also drilled.

The geo-radar measurements and drilling gave quite different results, as shown in Figure 3. The discrepancy was caused by a weak contrast in electronic properties between the fractures and the rock. The fractures seen in drill cores were clear open fractures that should have been visible in the geo-radar log. However, a long period of

draught had preceded the survey, so the open fractures in the upper part of the prospect were dry. Consequently, geo-radar resolution was negatively affected.

The well-developed horizontal fracturing was observed during field mapping in a larger area prior to the geo-radar survey. Thus the results would have been suspect, but without the diamond core drilling, it would not have been possible to assess the prospect. This emphasizes the importance of integrating methods when assessing the soundness of a rock.

Use of Geo-radar in Migmatite

A garnet-cordierite gneiss prospect located in southern central Finland was identified during regional exploration. It was briefly evaluated by field mapping, which indicated that the general soundness and appearance of the stone was encouraging. To further evaluate the prospect, the subsurface fracturing was investigated along specially prepared traverses by geo-radar, using antennae of 100 MHz and 400 MHz. The depth penetration was 20 to 25 metres, and the total length of the geo-radar profiles was approximately 800 metres. Eleven core holes were drilled to study the soundness and composition variations in the stone. The core drilling revealed a 2 to 5-metre thick sub-

Length (m)

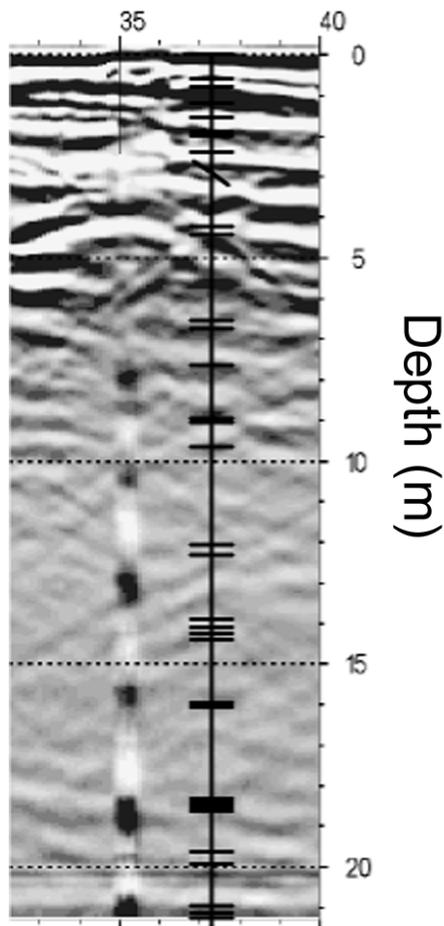


Figure 3. Comparison of geo-radar data and drill core interpretation. The drill hole and the observed fractures are marked.

horizontal lens of a younger, coarse-grained red granite located about 8 to 20 metres beneath the surface.

The geo-radar measurements revealed no large horizontal fracture systems, which agreed with the surface mapping results. Strong reflections interpreted as being due to surface weathering were observed in the uppermost part of the deposit. The weathered surface and occasional clusters of open fractures were saturated with water, giving good radar reflections, whereas the individual fractures seldom appeared in the profiles. Features, which could be interpreted as tilted large-scale fracture zones, were observed locally, but they could not be confirmed by core drilling.

No sign of the younger red granite could be found in the geo-radar profiles. The difference in dielectric properties between the gneiss and the granite were apparently too small to be detected by the geo-radar where the contact was sharp and unweathered.

The geo-radar measurements gave an overview of general soundness, but were not able to detect changes in rock type crucial in dimension stone evaluation.

CONCLUSIONS

Geo-radar has been used in dimension stone exploration for several years, and technical developments have made the equipment easy and quick to use. As well, interpretation of the radar signal has evolved to give clear and undisturbed pictures of the results. The nature of the geo-radar measurements puts limits on its usefulness. To accurately assess the results, one has to know the geological environment, tectonic nature and also the mineralogy of the deposit being surveyed. Geo-radar offers an easy way to examine the soundness of a deposit, but it must be used in conjunction with other methods to avoid undue risk in decision-making.

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RE-OPENING THE HARDY ISLAND GRANITE QUARRY, BRITISH COLUMBIA, CANADA

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The Hardy Island Granite Quarry (MINFILE No. 092F425) is about 20 kilometres southeast of Powell River. It is one of the historic Jervis Inlet Quarries, which are on Nelson Island, Kelly Island and Fox Island (White, 1986). These quarries provided stone for many of British Columbia's notable buildings in the early part of the last century, producing a classic grey, "salt and pepper" granite, which Parks (1917), in his survey of the Building Stones of Canada, referred to as "the best in BC". Products of the stone from the Hardy Island Quarry include the lions in front of the old Vancouver Courthouse, and the Ogden Point breakwater. The quarry was re-opened by Hardy Island Granite Quarries Ltd. in the summer of 1999. Since then, Hardy Island granite has been exported as far as Oregon to Alaska; some 5 500 tonnes of blocks were shipped by the end of 2000.

The stone at the Hardy Island quarry splits with unusual facility along both the rift and the grain (the primary and secondary splitting directions). This quality, together with the favourable joint orientation and spacing, allows the stone to be quarried easily. Blocks are freed either by drilling one hole halfway through the block on the rift, or two on the grain, followed by careful black

powder blasting. The gas pressure of the black powder is used to split the stone. This eliminates the need for a line of closely spaced holes. The large blocks produced by the method described above are then split to manageable sizes (usually about 10 tonnes) using plugs and feathers. Blocks are pulled apart with an excavator, moved to a storage area with a front end loader, and finally transported by barge to Vancouver. The stone is hydraulically split into 4-inch facing stone, pillar caps, coping, and other products at Bedrock Granite Sales in Coquitlam. Over half the stone produced by the quarry was exported to the United States, either as blocks or as split products.

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DIAMOND EXPLORATION IN CANADA

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ABSTRACT

Demand for both gem and industrial diamonds is very strong. Synthetic production supplies industrial uses, but synthetic gems remain inferior and expensive, so the gem market is largely supplied by mining. Several major mines have been depleted, and the market is receptive to new sources of high quality gems. Canada's Precambrian terrane, extending across the Canadian Shield and under the Phanerozoic cover of the Plains and Hudson Bay, has excellent potential for diamonds, but exploration conditions are difficult due to recent glaciation. Early world exploration, which relied on finding diamonds in alluvial sediments, was adequate to launch pre-1900 production from India, Brazil, and Africa. Exploration success in Canada as in Russia and other more recently discovered sources, however, had to await large investments in effort supported by advanced science and technology. Canadian exploration, in many ways, is similar to that in other regions, relying on analysis of tectonics, indicator minerals, geophysical surveys, and multiple stages of drilling and sampling. Canada differs from other regions in that recent glaciation has caused fresh indicator minerals to be transported hundreds of kilometres. Exploration accelerated in Canada after 1960, first in Ontario and the Arctic Islands, then in Saskatchewan in 1988, and especially after the Chuck Fipke-Stew Blusson discovery at Lac de Gras, Northwest Territories in 1991. Ekati Mine opened in 1998 and Diavik Mine of Rio Tinto and Aber will open in 2003. These mines will bring Canadian output to over 10% of world supply, and will position Canada with Botswana and Russia as world leaders in production of high quality gem diamonds. Other new mines, such as Snap Lake, are possible, as an array of companies, including De Beers, other majors, and several juniors explore sites across the Arctic and in the south from Alberta to Québec.

INTRODUCTION

World demand for diamond is strong. The annual US\$0.7 billion market for industrial diamond is now almost exclusively supplied by synthetic production of about 1000 million carats; 1 carat (ct) = 0.2 grams. Gem-quality synthetics remain inferior and expensive to produce, so the diamond jewelry trade is supplied by mining natural diamond, derived from kimberlites, lamproites, and placer deposits.

Recent gem diamonds sales have broken records, especially in the United States, where half of all gem diamonds are sold. Annual production of natural diamond, at a cost of about US\$2 billion, has exceeded 110 million carats per year, and this production sells for about US\$ 8 billion. Botswana, South Africa and Russia dominate the high-quality production market, which is handled mainly in Antwerp and Tel Aviv, while Australia and the Congo are leading suppliers of the low quality stones that are cut in India. The two-thirds of this annual supply of rough that is of gem quality is reduced to between 20 and 30 million carats of polished goods and sold in jewelry for about US\$55 billion. The one-third of all natural diamonds produced are used for industrial purposes but these fetch only about 1% of mining revenue.

De Beers, the world's leading producer, is attempting to re-position itself as supplier of choice rather than custodian of the industry. The company plans to reduce its stockpile, increase marketing, nurture brand recognition, work more cooperatively with clients, and withdraw from open market purchases. Rio Tinto Diamonds, handler of the large Australian output, has resisted a recent attempt by De Beers to buy Ashton and its minority share in Australia's Argyle mine.

A threat to the gem diamond market, comparable to that previously faced by the fur industry, is posed by the association of diamonds with conflict in Africa. This issue has been addressed by a certification scheme that began to be implemented in mid-2000.

In 1998, Canada joined the ranks of high-quality producers, and the new output compensated for production cutbacks due to the depletion of mines in South Africa and Russia.

CANADA'S GEOLOGY AND DIAMOND POTENTIAL

The majority of Canada's landmass has excellent potential for diamond-bearing kimberlites, which typically are small, cylindrical pipes about 0.1 to 1.0

kilometres across that represent high-pressure intrusions from deep within the earth. Pressures at the source depths are adequate for diamond to be formed from the lower-pressure crystal forms of carbon. The old, thick Archean rocks that form the core of the continent are the areas in which kimberlites, as well as lamproites, are most likely to occur, and these can transport fragments of diamond-bearing peridotite and eclogite from about 200 kilometres depth to the earth's surface. Together with the adjacent, somewhat less prospective, younger Precambrian terranes, these ancient rocks extend across the Canadian Shield and under the Phanerozoic cover of the Plains and Hudson Bay, which provides prospective terrane over most of the area from Calgary to Montreal and from the Great Lakes to the Arctic.

Development of this potential, however, has been made difficult by the effects of the Ice Age. Because glaciation of Canada occurred only 10 000 years ago, most of the country is blanketed by homogenized soil parent materials. Kimberlite pipes are recessive, and in almost all cases are hidden by this cover. Further, there has not been time for diamond and other more resistant minerals to concentrate in streams where they could form placer deposits that would reveal the diamond potential of an area.

CANADIAN DIAMOND EXPLORATION

Recognition of diamonds in alluvial sediments and upstream tracing of these diamonds supported the centuries-old trade in diamonds from India, and led to discovery of diamonds in Brazil in the 1700s and in Africa in the late 1860s. However, discovery of major diamond sources during the mid- to late-1900s, in Russia, then Australia, then Canada, required advanced science and technology as well as large investments.

Diamond exploration programs target favourable Archean terrane, focus the search by sampling sediments for kimberlite indicator minerals, use airborne geophysical surveys to identify drill targets, then carry out multiple stages of drilling and bulk sampling of kimberlite or an allied rock such as lamproite to define the resource. In Canada, diamond exploration was originally launched by discovery of a few diamonds in alluvial sediments and soils of the Great Lakes region in the late 1800s. Enthusiasm waned when there were no more promising discoveries of alluvial diamonds or *in situ* kimberlite. Exploration success awaited developments in science and technology. The tectonic criteria for priority setting and the array of the modern exploration approach begin with indicator mineral sampling. In Canada's recently glaciated surficial environment, a knowledge of glacial history and selection of appropriate sandy materials for sampling is required to interpret the distinctive sand-sized kimberlite indicator minerals that have been glacially transported hundreds of kilometres from source.

With the aid of investment, science, technology, and perseverance, progress in Canada accelerated after 1960. This was led by work by De Beers and others in Ontario and the Arctic Islands, as well as in 1998 in Saskatchewan. Most important, however, was work by Canadian prospectors Chuck Fipke and Stew Blusson, whose decade-long search culminated when their company, Dia Met, joined with BHP to make a kimberlite find at the center of the Slave Craton at Lac de Gras in the Northwest Territories in 1991. Since then, hundreds of kimberlites have been found on the Slave Craton, and additional finds have been made elsewhere in the north. In addition, exploration has been very active across the south, from Alberta to Labrador, including such areas as the Buffalo Head Hills of Alberta, the Attawapiskat area in Ontario, the buried kimberlite volcanoes of the Fort à la Corne camp of Saskatchewan, the Ungava Bay area of northern Quebec, and northeastern Manitoba. Canadian diamond exploration expenditures rose from a few million to a peak of over US\$100 million per year in the mid-1990s but have now leveled off at about US\$50 million per year. More than two-thirds of these funds are committed to exploration in the Northwest Territories.

CANADA'S DIAMOND INDUSTRY

Canada's Ekati Mine, built by BHP and Dia Met in the Lac de Gras area of the Northwest Territories, was completed in 1998 at a cost of about US\$1 billion; it employs about 600 people. Five kimberlites out of 125 on the property make up the current 78 Mt (million tonnes) resource. According to the mining plan, the mine is expected to produce about 4 million carats per year from ore with values of about US\$100/ct and 1 ct/t. Thus average revenue is expected to be about US\$0.5 billion dollars; early production figures have exceeded expectations. Just over one third of the Ekati production is being marketed by De Beers.

Rio Tinto Diamonds and Aber Diamond Corporation are currently constructing the Diavik Mine. It is similar in scale to Ekati, and expected to start producing in 2003 at the rate of 7 million carats per year with an estimated value of US\$ 70/ct, which represents a half billion dollars of revenue per year. The Diavik mining plan is based on a resource of nearly 40 Mt that occurs in 4 out of more than 50 kimberlites found on the property. Average grade is 4 ct/t. Aber has entered a marketing arrangement with Tiffany & Company.

There are several candidates for a third Canadian diamond mine. In mid-2000, De Beers acquired Winspear Diamonds Inc., co-owner with Aber of the Snap Lake property in the Northwest Territories, originally found by tracing glacial boulders. Snap Lake is a sheet-like dyke rather than a pipe, and has on the order of 40 Mt of kimberlite containing 1.7 ct/t of diamonds worth about US\$120/ct. A significant mine, smaller than Ekati, could

result. There are other promising projects as well, so Canada's output within a few years is expected to rise from the present level of about 5% of world supply to more than 10%. With income of more than US\$1 billion dollars per year, diamonds will make a significant contribution to Canada's total annual mineral production, which Natural Resources Canada currently lists as US\$12 billion in nonfuel materials. In addition to mining, the new Canadian diamond cutting industry is marketing stones under the Canadian banner.

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GEOLOGY AND EXPLORATION HIGHLIGHTS: DIAMONDIFEROUS KIMBERLITES OF SASKATCHEWAN

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The discovery of two rootless, ice-rafted blocks of kimberlite at Sturgeon Lake, Saskatchewan in 1988 led to an unprecedented staking rush and a high level of exploration activity for diamond. Exploration peaked in 1993 and 1994 when expenditures exceeded \$10 million per year; the late 1990s saw a decline in activity and rationalization of land positions. However, results since 1999 on the Star kimberlite and the Fort à la Corne joint venture have been encouraging and exploration expenditures, which rebounded to more than \$4 million in 2000, are forecast to exceed \$8 million in 2001.

The central Saskatchewan kimberlite field is comprised of more than 70 drill-tested bodies, many of which are macrodiamond-bearing. The kimberlites intruded through the so-called Sask Craton, a Proterozoic crustal element underplated by Archean crust, which is exposed in a tectonic window to the north of the kimberlite field (Figure 1).

Kimberlite volcanism was contemporaneous with mid-Cretaceous sedimentation along the shore of the Cretaceous seaway. Positive relief preserved on the upper surface of some of the kimberlite bodies is probably indicative of rapid sedimentation. In general, the kimberlites are flat-lying and covered by approximately 100 metres of overburden. The stratabound bodies are underlain by Cretaceous sedimentary rocks and overlain by either Cretaceous rocks or Pleistocene glacial drift (Figure 2).

The gross form of the kimberlites is often characterized as pancake-shaped to emphasize the contrast with the classic carrot shape of kimberlites exploited in other parts of the world. Petrographic study indicates that most of the kimberlites are well preserved crater-facies volcanoclastic rocks including lapilli tuff, olivine pyroclastic kimberlite, olivine/lapilli pyroclastic kimberlite, and various kinds of resedimented kimberlite. Diatreme-facies kimberlites typically found worldwide in the carrot-shaped volcanic pipes were not known to occur in Saskatchewan until late 2000, when Shore Gold intersected 539.4 metres of kimberlite in vertical corehole Star 020. The hole was terminated in kimberlite at 627 metres below surface. This is reported to be the thickest intersection of kimberlite in North America. The lower portions of the drill core contained kimberlite with textures that are consistent with diatreme emplacement and numerous large mantle-derived xenoliths.

The Fort à la Corne Joint Venture (De Beers Canada

Exploration Inc., 42.3%; Kensington Resources Ltd., 42.3%; and Cameco Corporation, 5.4% directly and 10 % through wholly-owned subsidiary UEM Inc.) area includes 69 drill-tested kimberlites located about 80 kilometres northeast of Prince Albert. The estimated sizes of the kimberlites range from 3 million to more than 600 million tonnes. The exploration program in 2001 focused on two bodies that were judged to be of high potential, based on previous work. Three large-diameter air-assisted reverse-circulation drill holes in kimberlite body 122 recovered 212 macrodiamonds (greater than 1 millimetre) with a total weight of 17.3 carats, including six stones larger than 0.5 carats each. The largest stone from this body weighed 0.760 carats. Two holes in body 141 yielded 278 macrodiamonds with a combined weight of 21.2 carats. Eight stones exceeding 0.5 carats were recovered, including stones of 0.86, 1.09 and 1.54 carats. Based on the 2000 work, the joint venture's grade estimate for body 122 was revised upward to 13 carats per hundred tonnes (cpht), and the grade for body 141 was revised upward to 19 cpht.

Shore Gold Inc. owns 100% of the Star Kimberlite, a composite body that probably represents multiple eruptions. Shore has completed 28 core holes to date, all have intersected kimberlite. Widths vary, but average in excess of 50 metres, even when the 539 metre intersection of hole 020 is excluded. Diamond grade for the sixteen year 2000 drill holes, for which results are available, averaged 28 cpht.

War Eagle Mining Co. Inc. owns 20% and Great Western Gold Corp. 80% of the Candle Lake joint venture. The partners have reported two kimberlites. Pipe 28 on the Candle Lake south block is reported as 6 million tonnes. Pipe 29/30, which is an apparent composite body on the northern of two claim blocks in the Candle Lake area, is reported as 60 million tonnes. The partners have had difficulty recovering a sufficient volume of sample to make accurate grade forecasts, but grades as high as 27 cpht have been reported from individual samples.

United Carina Resources Corp. (50%) and Consolidated Pine Channel Gold Corp. (50%) control a large ground position in the Fort à la Corne area. The holdings include the Smeaton kimberlite, which 1996 drilling showed to be 90 metres thick, but no diamonds have been reported. In recent drilling the partners reported intersecting up to several metres of fragmental and marine-worked kimberlite.

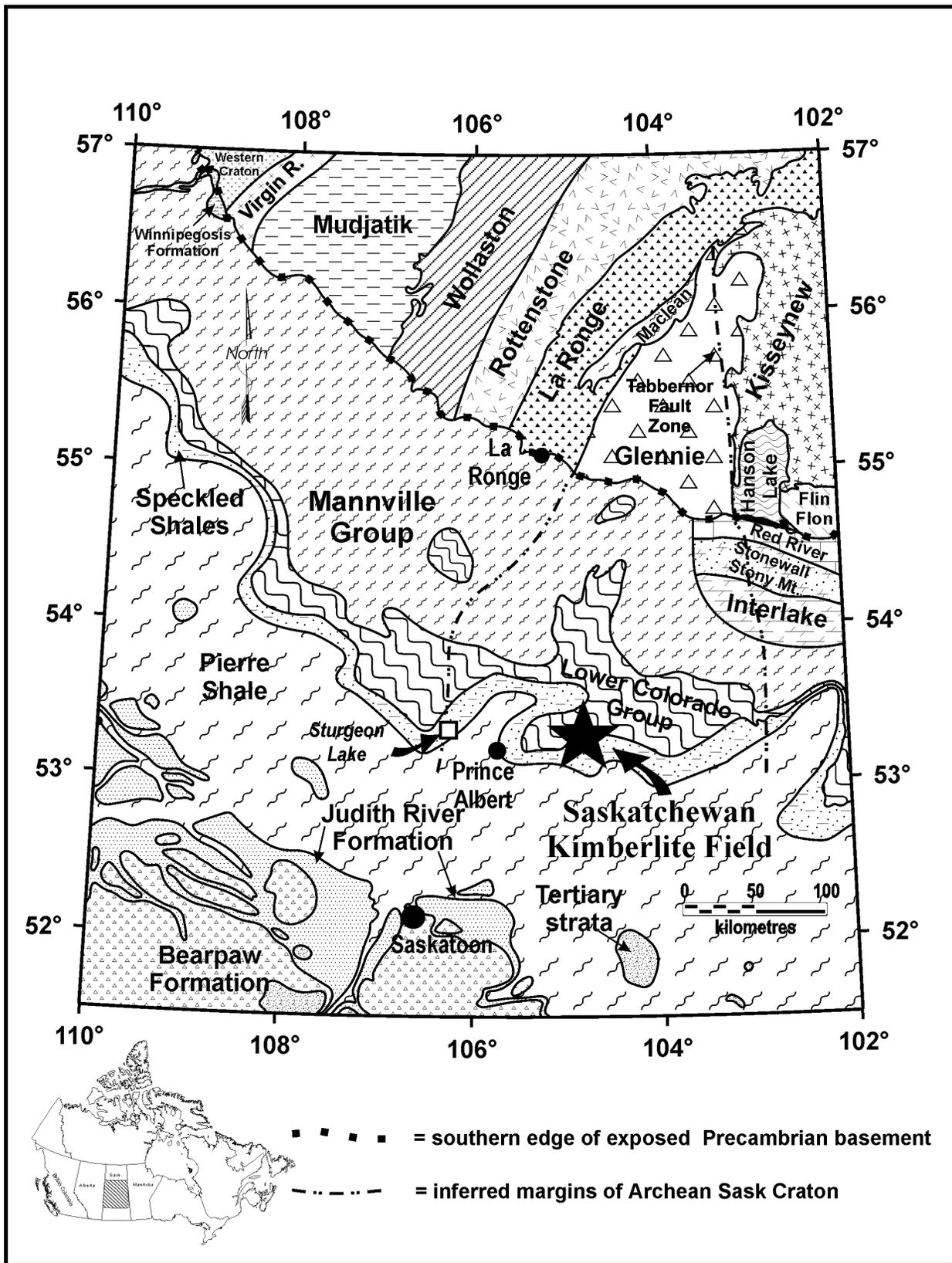


Figure 1. Geological map of central Saskatchewan, showing the general location of central Saskatchewan Kimberlite fields. (Modified from Macdonald and Slimmon, 1999).

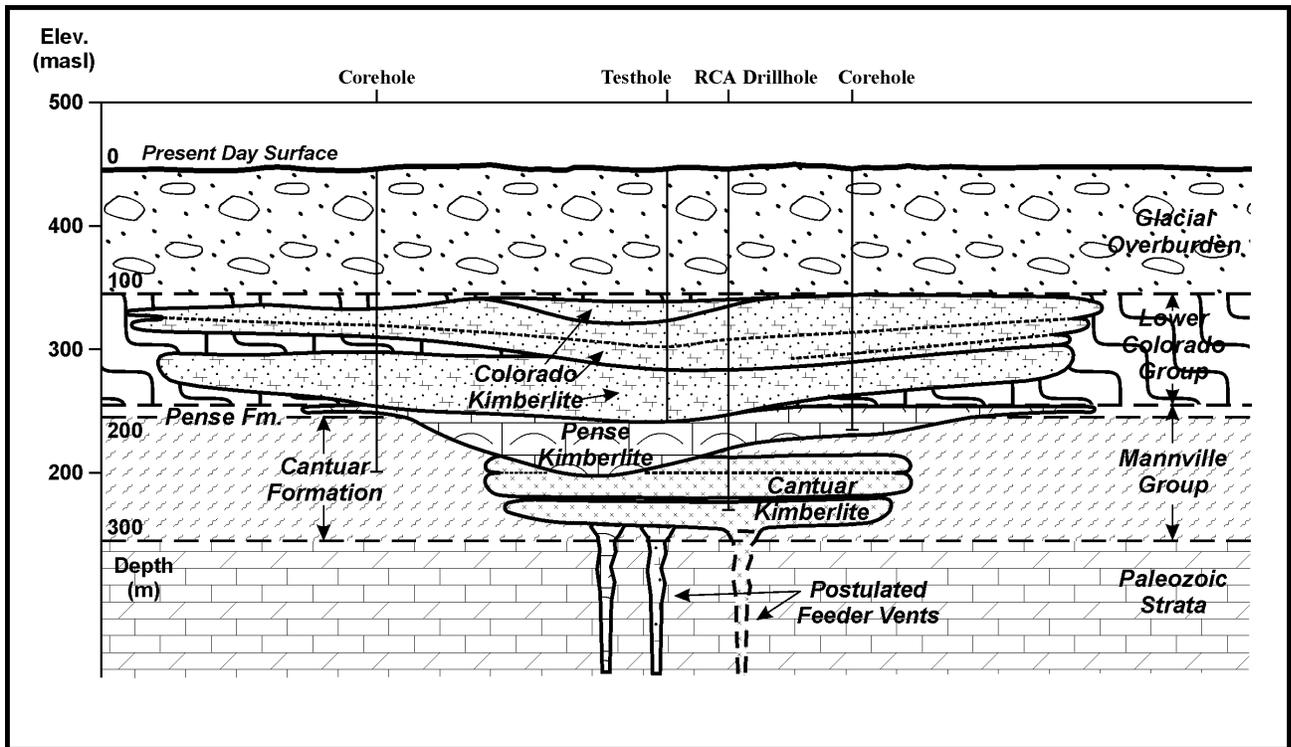


Figure 2. Schematic cross-section showing stacked, temporally diverse, multi-centered, multi-eruptive kimberlite bodies that are stratabound by Cretaceous sedimentary rocks. (Modified from Jellicoe *et al.*, 1998).

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THE BUFFALO HEAD HILLS DIAMONDIFEROUS KIMBERLITE PROVINCE, ALBERTA

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INTRODUCTION

The Buffalo Head Hills region is located approximately 350 kilometres northwest of the city of Edmonton in north-central Alberta (Figure 1). The Alberta diamond joint venture, consisting of Ashton Mining of Canada Inc., Alberta Energy Company Ltd and Pure Gold Minerals Inc., began exploring for kimberlites in the Buffalo Head Hills region in late 1996. At the time, the Mountain Lake diatreme, which lies 200 kilometres to the southwest, was the only reported kimberlitic rock in Alberta (Leckie *et al.*, 1997, Figure 1). Exploration efforts by the joint venture partners have identified a new diamondiferous kimberlite province in Canada.

REGIONAL GEOLOGY

The Buffalo Head Hills region is underlain by Precambrian basement rocks of the Buffalo Head terrane, and Phanerozoic sedimentary rocks of the Western Canadian Sedimentary Basin. The Buffalo Head terrane is defined primarily by geophysics and consists of rocks with crystallization ages of 2.0 to 2.3 billion years (Ross *et al.*, 1991 and Villeneuve *et al.*, 1993). Paleozoic and Mesozoic units that are up to 5000 metres thick overlie the basement. Cretaceous mudstones and sandstones at the surface range in age from 80 to 100 million years. The entire region was glaciated during the Laurentide ice advance and its retreat deposited a blanket of till, lake sediment and glaciofluvial sediment that is up to 200 metres thick. The Peace River Arch, an east-northeast-trending asymmetrical structure that extends from the British Columbia border on the west to northeastern Alberta on the east, is the dominant structure in the area (Figure 1).

EXPLORATION

Discovery of diamondiferous kimberlites during the initial drill program in 1997 prompted aggressive exploration that has included regional airborne geophysical surveys followed by ground geophysics, heavy mineral sampling, drilling and kimberlite mini-bulk and bulk sampling. In the initial drill program, 11 kimberlites were discovered, and 8 contained diamonds. The drilling of 74 targets in the Buffalo Head Hills region, resulted in the discovery of 36 kimberlites, and at

least 23 of these are diamondiferous (Figure 2). Diamond results are pending for the most recent kimberlite discovery, K281. The first 34 kimberlites were discovered by aeromagnetic surveying. These kimberlites display a marked magnetic susceptibility contrast to the sedimentary host rock. The thirty-fifth kimberlite discovered, K252, is virtually non-magnetic. It was located using electromagnetic techniques. The conductive, clay-rich bedrock in Alberta contrasts with the resistive kimberlitic rocks. Gravity and seismic surveys have also proven to be effective geophysical tools for locating kimberlite bodies beneath the glacial sediments.

KIMBERLITE GEOLOGY

Kimberlites outcrop in four locations, whereas those in other areas are under overburden that is up to 127 metres deep. Surface size estimates of the bodies are based on geophysical modeling and range from 1 to 47 hectares. All but one of the kimberlites are classified as crater facies; most can be described as volcanoclastic olivine-rich kimberlites with varying amounts of lapilli and xenoliths. A variety of indicator minerals are present; olivine is the dominant mineral followed by chromite, peridotitic and eclogitic pyrope garnets, and rare picroilmenite. Kimberlites in the southern part of the province contain rare subcalcic (G10) garnets. Subcalcic garnets are more abundant in kimberlites located in the central and northern regions of the province. Some of these garnets have exceptionally high chromium content, up to 17.8 wt% Cr₂O₃ (Carlson *et al.*, 1999).

DIAMOND CONTENT

At least one tonne was collected from each of the six kimberlites that showed the most potential from microdiamond tests. Samples weighing from 1 to 469 tonnes yielded estimated grades ranging from 3.5 to 66.2 carats per hundred tonnes (Table 1). A total of 1.28 tonnes of material from the K252 kimberlite that was tested in late 2000 yielded an estimated grade of 66.2 carats per hundred tonnes, the best estimated grade determined to date in the province. A second mini-bulk sample of approximately 20 tonnes was collected from the K252

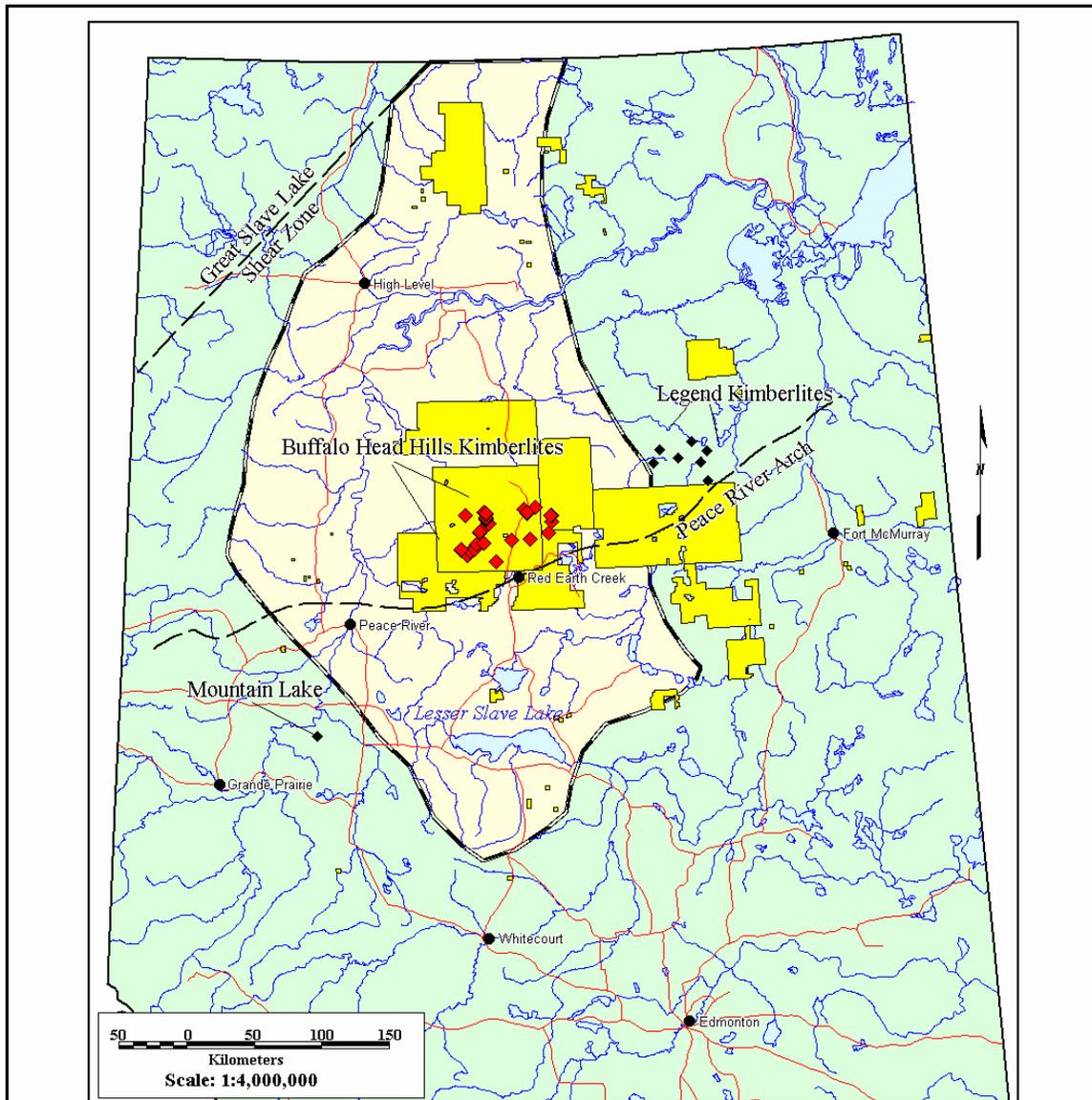


Figure 1. Location Map of the Buffalo Head Hills Kimberlite Province, Alberta.



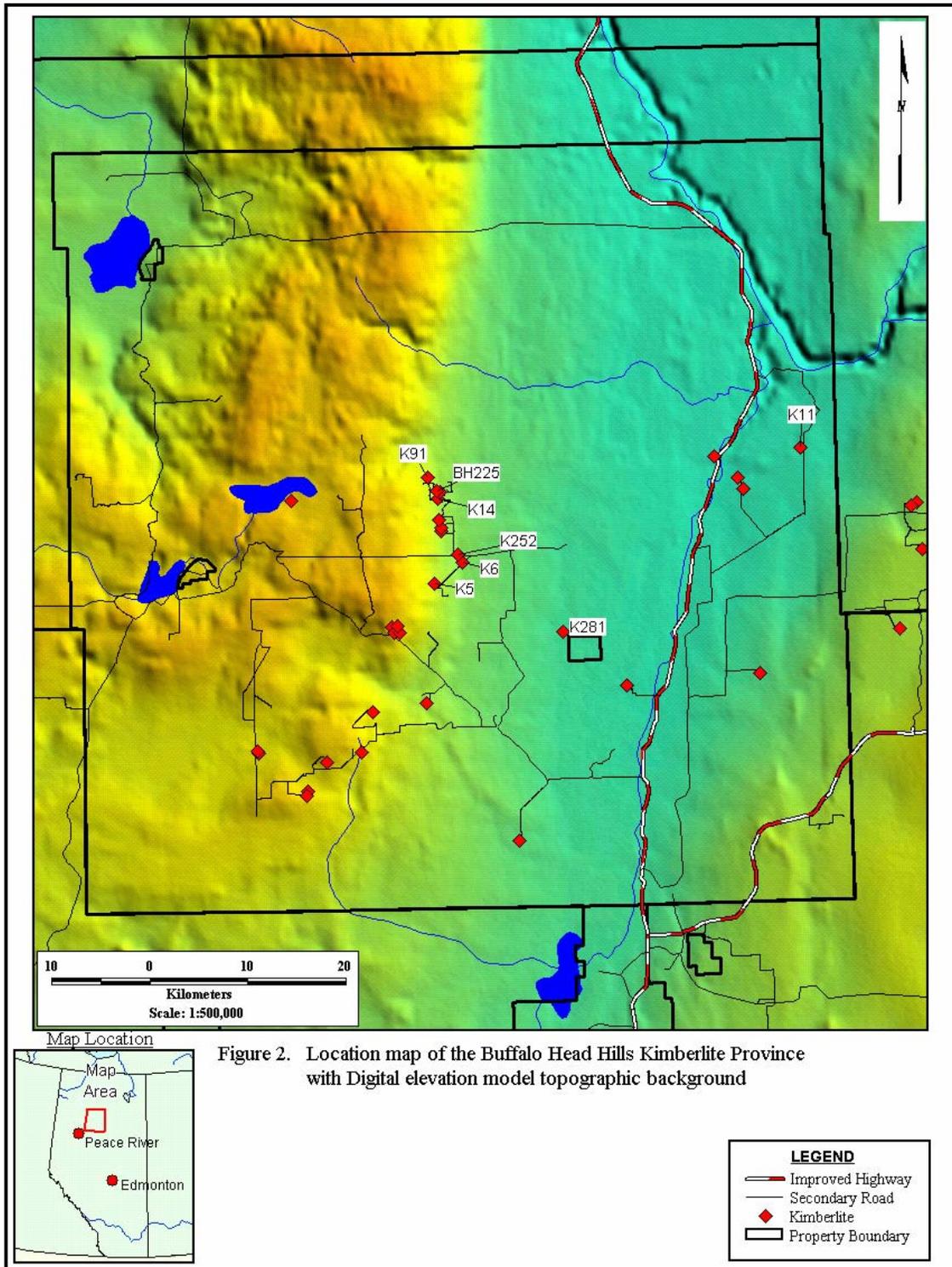


TABLE 1: ALBERTA MINI-BULK AND BULK SAMPLE RESULTS

	Mini-Bulk						Bulk
	K6	K11	K14	K91	BH225	K252	K14
Tonnes	13.95	21.85	44.87	35.87	1.0	1.28	479.0
Diamonds (ct)	0.88	0.96	7.79	4.56	0.03	0.85	56.45
Content (ct/100 tonnes)	5.6	4.4	17.0	12.7	3.5	66.2	11.7
Largest Stones (ct)	0.76	0.10 0.09	1.31 0.60	0.45 0.41	--	0.36	0.90 0.88

kimberlite in March 2001. The results are not available at the time of writing.

FUTURE WORK

At least six of the kimberlites in the Buffalo Head Hills kimberlite province have estimated grades greater than three carats per hundred tonnes, a value thought to be significant when evaluating the economic potential of a kimberlite province. Equally important is the presence of commercial-sized and high quality stones. The network of roads and facilities established by the oil and gas industry provides easier access and better infrastructure development than in other parts of Canada. Therefore, the economic threshold for diamond mining in Alberta may be lower than that in more remote regions of the country. The joint venture is encouraged by the region's potential to host an economic diamond deposit and will continue to explore its 2 922 000 hectares (7 219 000 acres) of mineral permits in northern Alberta. An integrated program involving geophysical techniques and heavy mineral sampling followed by drilling is being employed to continue discovering kimberlites in Alberta.

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EKATI DIAMOND MINE, 2001 UPDATE

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Figure 1. The EKATI Diamond Mine

The BHP Northwest Territories Diamonds Project became a reality in August 1990 when BHP signed an agreement with Dia Met Minerals and the geological team that had discovered kimberlite in the Lac de Gras area. In accordance with the joint venture agreement, BHP Minerals funded additional exploration in the region. This provided a mechanism for BHP to earn an equity share of the project based on funding and, ultimately led to the joint venture ownership as at 2001 – BHP Diamonds Inc. (51%), Dia Met Minerals Ltd. (29%), Charles E. Fipke (10%) and Dr. Stewart L. Blusson (10 %).

In late 1997, during the peak of construction activity at the site, the project was re-named the EKATI Diamond Mine. The first kimberlite was processed in September of 1998, and the mine officially opened on October 14, 1998. The mine is operated by BHP Billiton Diamonds Inc., a part of BHP Billiton. BHP Billiton Diamonds Inc. is an incorporated Canadian company with offices in Vancouver and Kelowna in British Columbia, and Yellowknife, in the Northwest Territories.

The project was completed on time and within budget; total capital investment was more than C\$700 million. In 2000, the mine produced about 2.8 million carats. BHP employs about 680 people, of which seventy-nine percent are residents of the Northwest Territories and forty percent are Aboriginals from the north. EKATI Diamond Mine (Figure 1) is located on a 10 960 hectare (ha) land lease area, 300 kilometres northeast of Yellowknife. Long-term exploration activity has identified 136 kimberlite pipes as of summer 2001 within the 344 000 ha claim block. Eight kimberlite pipes

have been identified as resources and are being considered for the long-term mine plan including Panda, Misery, Koala, Koala North, Fox, Sable, Beartooth and Pigeon.

The commercial pipes are typically crater facies kimberlite, which is characterized by interbedded coarse grained olivine-rich and fine grained mud-rich lithologies as well as kimberlitic mudstones, siltstones and sandstones. The Panda and Misery pipes appear to have been filled with a complex mixture of discontinuous units of resedimented volcanoclastic kimberlite that are not easily resolvable into distinct phases. In contrast, the Koala pipe appears to consist of a relatively well defined layered sequence of sub-horizontal primary and resedimented volcanoclastic units. The current geological model of the Fox kimberlite involves resedimented crater facies volcanoclastic material overlying what appears to be relatively uniform diatreme facies consisting of tuffisitic kimberlite and tuffisitic kimberlite breccia.

Diamond production in 2001 was solely from the Panda pipe. The Misery and Koala pipes are under development and future production will be a blend from several pipes. BHP learned a great deal about equipment specifications and usage during the development of the Panda pipe. Exposure of waste rock and kimberlite during on-going mining of Panda has also increased BHP geological and geo-technical understanding of this area. This data allowed us to improve our modeling for both our resources and mining reserves. Pipes are continually reviewed for economic viability based on this improving geological model, better geo-technical knowledge, and operating and marketing information.

THE DIAVIK DIAMONDS PROJECT – A 2001 UPDATE

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The Diavik Diamonds Project is an unincorporated joint venture between Diavik Diamond Mines Inc. (DDMI 60%) and Aber Diamond Mines Ltd. (40%). DDMI is a wholly owned subsidiary of Rio Tinto plc of London, England, and is headquartered in Yellowknife, Northwest Territories. Aber Diamond Mines Ltd. is a wholly owned subsidiary of Aber Diamond Corporation of Toronto, Ontario. DDMI is the project manager.

The Diavik Diamonds Project is located on a 20 square kilometre island in Lac de Gras, approximately 300 kilometres northeast of Yellowknife, Northwest Territories. Canada's first diamond producer, the BHP Ekati Diamond Mine, is located approximately 30 kilometres northwest of the Diavik site (Figure 1).

The Diavik Diamonds Project (Figure 2) involves the development of four economic kimberlite pipes: A154 South, A154 North, A418 and A21. Diamond production from A154 South is scheduled to commence during the first half of 2003, by means of open pit mining methods. Construction of mine infrastructure, including the processing plant, accommodations complex, power generation facility and maintenance shop is currently underway at the site (Figure 3), with planned completion in 2002. Construction of the first water retention dike around A154 South and A154 North is scheduled to begin mid-2001, to allow for dewatering and pre-stripping in the second half of 2002.

KIMBERLITE EVALUATION

The Diavik claim block encompasses 238 000 hectares, and fifty-six kimberlite occurrences have been discovered on the claim block from 1992 to the present. Exploration methods have included airborne and ground-based geophysical surveys, glacial till sampling and geological mapping.

The four kimberlites under development were discovered during 1994 and 1995. Subsequent years saw a series of drilling and sampling campaigns carried out to evaluate the deposits, and bring resource estimates to a feasibility study level. Following encouraging microdiamond results from the discovery holes, delineation drilling provided geologists with important information about the size and shape of the pipes, geological continuity, and a better indication of predicted grades. Mini-bulk sampling using a 6-inch coring rig was then undertaken, providing a large enough, representative kimberlite sample from each of the pipes to perform a valid grade estimate. To fully evaluate these deposits, a further bulk sample was extracted from A154 South and A418 via an

underground decline. This large kimberlite sample was required to recover enough diamonds (approximately 10 000 carats were recovered from each of the bulk samples) for a statistically valid estimate of predicted run of mine production value.

Resource modeling of the pipes was completed using Compass/MineSight®, an exploration and mine planning software package with 3-dimensional graphics. The grade data collected from the sampling programs was integrated into the geological models, and a resource estimate for each of the pipes was created using simple kriging interpolation.

Estimated resource and reserve classifications were based on the Australasian Joint Ore Reserves Committee (JORC) code. Diluted proven and probable reserves included in the mine plan are presented in Table 1. Indicated resources are estimated to be 12.7 million tonnes, at a grade of 2.5 carats per tonne, and are excluded from the feasibility study mine plan. The mine plan calls for a two-year ramp-up period, after which kimberlite production is expected to reach 1.5 million tonnes or approximately 6 million carats annually. Over the entire mine life, the Project plans to produce roughly 100 million carats at an average value of US\$63 per carat (based on 2000 valuation price estimates).

GEOLOGIC OVERVIEW

In the context of kimberlites worldwide, the Diavik Project kimberlites are considered unique. The pipes are small, with surface areas less than 2 hectares, compared to a world average of some 15 hectares, but their grade is three to four times higher than that of most other major producing diamond mines.

The Diavik Project kimberlites are Eocene (58 to 54 Ma) volcanic-intrusive complexes hosted by late Archean aged (2.8 to 2.5 Ga) granitoid and metasedimentary rocks of the cratonic Slave Structural Province. The Archean rocks are intruded by at least five Proterozoic (2.2 to 1.3 Ga) diabase dike swarms. The kimberlite diatremes cut both the Archean and Proterozoic rocks.

The kimberlites and their host rocks are covered by thick but variable, Quaternary glacially deposited till. These till deposits are associated with the retreat of the Laurentide ice sheet (14.0 to 8.4 Ka). The tills are locally capped by a thin veneer of glacial lake sediments, melt water channel deposits and esker



Figure 1. Project Location

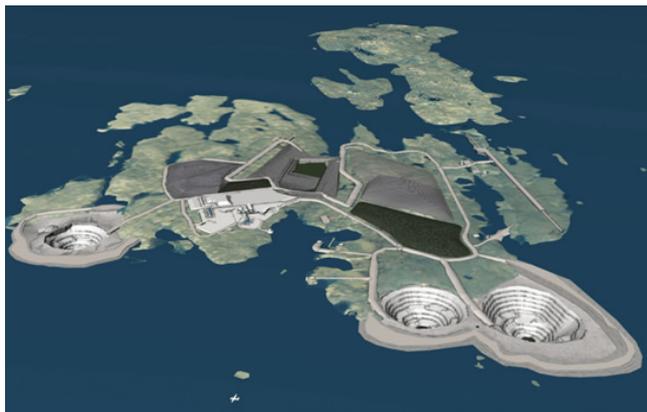


Figure 2. Digital Representation of the mine site at maximum development in 2018.

systems. The Diavik Project kimberlites are located just offshore of East Island, in Lac de Gras, and water depths in the vicinity of the kimberlite pipes range from 4 to 25 metres.

The Diavik Project kimberlites occur as steeply inclined to vertical cone-shaped intrusions, or “pipes” within granitoid host rocks. The pipe walls are inclined at angles between 78 and 84 degrees, and are assumed to be converging with depth. Irregularities in the smooth cone-shaped walls seen from delineation drilling are attributed to the effects of joint structures that have been observed in the host rock. The surface expressions of the pipes are roughly circular to elliptical.

During kimberlite emplacement, the granitoid country rocks were overlain by mid-Cretaceous to early Tertiary sedimentary rocks (135 to 55 Ma). The sedimentary cover rocks and upper portions of the kimberlite craters, have since been eroded, but evidence of their existence is seen in mudstone xenoliths at depth

TABLE 1. DILUTED PROVEN AND PROBABLE RESERVES.

Reserves	Tonnage (Mt)	Grade (cpt)
Proven	14.4	4.2
Probable	11.2	3.6
Proven & Probable	25.6	4.0*

*Average grade.

within the kimberlites. These regionally extensive cover rocks are thought to have been at least several tens of metres thick. Material within the kimberlite pipes comprises three broad classes:

Hypabyssal Kimberlite: material resulting from direct crystallization of kimberlite magma

Volcaniclastic and Epiclastic Kimberlite: material that has been explosively ejected during the formation of the pipe, to fall back into the crater directly from ash or ejecta “clouds”, or to return indirectly from slumping of the crater-rim deposits.

Xenolithic Materials: fragments including the surrounding basement rocks, and a number of mudstone and siltstone components derived from the Cretaceous to Tertiary sedimentary rocks that were extant in the area at the time of volcanism.

Volumetrically the kimberlite pipes are dominated by volcaniclastic and epiclastic material, often with a



Figure 3. Aerial photo of construction activity at Diavik site in April, 2001 (looking north). Bulk fuel tanks and 700-man construction camp in foreground.

significant xenolith component. The hypabyssal phases are volumetrically less significant, occurring as feeders to the pipes at deeper levels, and as contact intrusions along the pipe margins.

The common components of the volcaniclastic rocks include primary magmatic minerals and their altered equivalents; mantle xenoliths and xenocrysts (including diamond); and crustal xenoliths dominated by near surface granitoid rocks and Cretaceous-aged sedimentary rocks. Fossil tree fragments, twigs and leaves and microfossils occur in the Cretaceous clasts.

Primary volcaniclastic structures and textures developed at the time of kimberlite emplacement. They are mainly represented by bedding or banding and grain size variations that reflect the mechanisms by which material was introduced into the crater. Included are material deposited from an explosive ash cloud and material re-deposited into the crater due to collapse of unconsolidated material near the crater rim. There is also evidence that crater walls collapsed, or slumped to produce mixed mud or mud-kimberlite fragment deposits.

GEOCHEMICAL EXPLORATION FOR KIMBERLITES IN NORTHERN ALBERTA

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During the 1990s, ultramafic diatremes were discovered in three separate areas of northern Alberta. In 1990, Monopros Limited found the Mountain Lake diatreme, located northeast of Grande Prairie. In 1997, Ashton Mining of Canada Inc., in conjunction with Alberta Energy Company and Pure Gold Resources Ltd., discovered kimberlites on the southeastern flanks of the Buffalo Head Hills. To date, Ashton has located 36 pipes. In 1998, Kennecott Exploration Canada Inc. in conjunction with Montello Resources Ltd. discovered 7 kimberlites in the Birch Mountains of northeastern Alberta. In December 2000, New Blue Ribbon Resources Ltd. found an eighth kimberlite in the Birch Mountains.

The Alberta Geological Survey published several diamond-related reports (see bibliography), including preliminary soil and vegetation orientation surveys over the Mountain Lake diatreme (Eccles, 1998a,b). Additional surveys were carried out over the Mountain Lake and other ultramafic diatremes in northern Alberta in 2000.

The 2000 geochemical exploration program focused on defining surface geochemical techniques capable of detecting both exposed and buried kimberlite pipes in northern Alberta. The main objective of the program was to identify sample media and analytical techniques that could be used to explore for diamonds and other commodities on both regional and detailed scales. The long-term goal of the project is to produce a geochemical map of northern Alberta over the next 10 years.

A total of 806 samples were collected during detailed orientation surveys at (1) Mountain Lake (1 pipe), (2) Buffalo Head Hills (3 pipes), and (3) Birch Mountains (1 pipe). Samples collected over the pipes included aspen bark (n=23), willow twigs (n=23), spruce needles (n=102), A-horizon soil (n=212), B-horizon soil (n=202), C-horizon till (n=196), peat (n=24), and sub-peat sediments (n=24). The sample spacing varied from 25 to 50 metres over the pipes and from 50 to 100 metres in background areas. The pH of bog water was measured at 50-metre intervals near TQ155 in the Buffalo Head Hills. The A-horizon and vegetation samples were processed at the Geological Survey of Canada (GSC) and sent to Acme Laboratories for multi-element analysis using several processes: ICP-Mass Spectrometry after an *aqua regia* digestion (Group 1F), ICP-Emission Spectroscopy

after a LiBO₂ fusion for major oxides (Group 4A), and for trace elements supplemented by ICP-ES for base metals (Group 4B), LOI, pH, and conductivity. Peat, sub-peat sediments, B-horizon soil, and C-horizon till were processed at the Alberta Geological Survey (AGS) Laboratory and sent to Acme for Group 1F analysis, pH, and conductivity. Splits of the same B- and C-horizon samples were submitted to Activation Laboratories for Enhanced Enzyme Leach analysis.

A treetop orientation survey was conducted in the Buffalo Head Hills area to test for anomalies over kimberlite pipes using a lower sample density. A total of 205 spruce-top samples were collected at a density of 1 per 4 square kilometres over a 500 square kilometre area during a two-day period. At each site, a GPS coordinate is recorded and the samples are placed in pre-labeled cloth bags. Samples are collected at a rate of 1 every 2 minutes at this sample density, and the cost of such a survey works out to approximately \$25 per square kilometre. The rationale behind collecting spruce-top samples is that spruce will preferentially concentrate kimberlite indicator elements (e.g. P, Ni, Nb, Au, Rb) in the crowns of the tree.

The encouraging findings of the 2000 geochemical program are summarized as follows: Magnetic and gravity anomalies could be followed up with high density sampling (1 per 0.01 square kilometre) of spruce-top twigs, ground-level spruce needles, A- and B-horizon soils, or C-horizon till over prospective targets. Spruce-top twigs should be ashed and submitted for Group 1F analysis. Important pathfinder elements for the detection of kimberlite pipes are Au, P, Ni, Nb, and Rb. Spruce needles should be ashed and submitted for Group 1F analysis. Pathfinders that could be spatially correlated with kimberlite pipes are P, Ni, Nb, K, Rb, La, Mn, Fe, and Al. Soils and till should be disaggregated using a mortar and pestle, sieved to -63 µm, and submitted for Group 1F analysis. Important pathfinders in soils and till are Ni, Cr, Nb, Ti, Th, Al, Sc, and REE.

Peat-bog sampling is a viable method for the detection of buried kimberlites. Sub-peat sediments should be sieved to +63-250 µm, and submitted for Enhanced Enzyme Leach analysis. Important pathfinders to kimberlites are Ni, La, Th, Al, and Eu. Sieved peat samples (-63 µm) should be submitted for Group 1F

analysis. Significant pathfinders in peat include Ni, Nb, Zr, Y, Ce, and Eu. There may also be Hydrogen ion anomalies in bog water near buried pipes.

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EVENTS, TRENDS, AND ISSUES IN THE UNITED STATES AND WORLD DIAMOND INDUSTRY

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In 2000, United States and world diamond production reached record high levels. While the United States has only one commercial gem diamond mine, it is the world's largest market for unset gem diamonds, exceeding \$9 billion a year. The United States leads the world in production of synthetic diamond and is the world's largest market for industrial diamond, consuming an estimated 480 million carats. Most of the industrial diamond use is in the stone cutting and highway building industry sectors. More than 90% of the industrial diamond market is now satisfied by synthetic

industrial diamonds, whose quality can be controlled and whose properties can be customized to fit specific requirements. Recent United Nations actions to eliminate "conflict diamonds" from world markets have caused the diamond industry to work on developing methods to mark or brand rough stones, techniques for analyzing chemical and physical properties to determine the point of origin of a diamond, a "certificate of origin" regime, and tamper-proof container systems for diamond shipments.

TALC—ITS RELATION TO ASBESTIFORM AMPHIBOLES AND THE ABSESTOS IN CRAYONS CONTROVERSY

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ABSTRACT

The use of talc in crayons made national headlines following a May 23, 2000 report by the *Seattle Post-Intelligencer* that government laboratories had found asbestos in the three best-selling brands of crayons. The newspaper reported the crayon samples had asbestos amounts ranging from 0.03 to 2.86 percent by volume. The asbestos was determined to be a constituent of the fibrous talc that is used to strengthen the crayons. The report caused a stir across the United States, as millions of crayons are used daily by children. Binney & Smith (makers of Crayola crayons) hired a laboratory to analyze samples of their crayons and the powdered talc; they reported that no asbestos was found. The United States Consumer Product Safety Commission (CPSC) stated their test results found trace amounts of asbestos in three crayon samples, “however, the amount of asbestos is so small it is scientifically insignificant”. As a precaution, the CPSC asked the leading crayon makers to reformulate their products within a year to eliminate the fibers.

The talc used in the three brands of crayons under scrutiny was supplied by a Gouverneur Talc Company mine in upper New York State. The Gouverneur talc deposits are known to contain tremolite and anthophyllite, and the possibility that asbestiform varieties of these amphiboles occur in the Gouverneur deposits has been debated for more than 30 years. The mining company and the United States Occupational Safety and Health Administration (OSHA) have maintained that amphiboles in the Gouverneur deposits do not meet the compositional and morphological criteria for regulated asbestos.

The debate over the amphibole asbestos content of the Gouverneur talc deposits and similar fibrous talc deposits results from inconsistently applied, ambiguous criteria for distinguishing “transitional” varieties of tremolite and anthophyllite from their clearly regulated asbestiform varieties. The “transitional” fibers, sometimes termed “intermediate” fibers, consist of unequal proportions of fibrous talc and amphibole. The fibers have mineral compositions that are intermediate between ideal talc and ideal anthophyllite or tremolite. Optical microscopy and quantitative analyses, such as energy-dispersive spectrometry, of “transitional fibers” often give dual patterns and data that range between ideal values for talc or amphibole. These fibers were formed by the partial, pseudomorphic replacement of fibrous amphibole by talc and (or) by intergrowths of amphiboles with talc. “Transitional fibers” are not defined as asbestos under current OSHA regulations.

Similarly, cleavage fragments of amphiboles are common in fibrous talc deposits, including fragments of the regulated mineral phases anthophyllite and tremolite. Although cleavage fragments are exempt from OSHA regulation, the difficulty of distinguishing cleavage fragments from asbestos fibers under high magnification has added to the debate. Also, there is no universal agreement regarding the potential long-term health impacts, particularly respiratory diseases, which could result from exposure to airborne particles of “transitional” amphiboles and cleavage fragments.

The recent controversy over asbestos in crayons and talc should not be viewed as an indictment of talc deposits as a group. Not all large talc deposits contain amphiboles or asbestiform minerals. The large United States talc deposits that are interpreted to have formed mainly by hydrothermal processes usually lack both amphibole contaminants and asbestiform minerals, while those described as metamorphic talc deposits typically contain amphiboles, often as major components. Typically these occur in a variety of crystal habits that may or may not include asbestiform types. Because several amphibole morphologies can occur within a single deposit, each metamorphic talc deposit requires a site-specific characterization study. The relationship between amphibole-poor hydrothermal talc versus amphibole-rich metamorphic talc bears further study, because it can influence the perceived or actual health effects of the talc ores and their processed products.

INTRODUCTION

The United States is second only to China in annual talc production. Mines in the United States produced about one million tonnes of crude talc ore per year during the 1990s (Virta, 1998). Talc in the United States is used

in the production of ceramics, which is the main domestic use; paint; paper, where it is used in pitch control and recycling processes; plastics, as a functional filler, providing rigidity to the plastic; roofing; rubber; cosmetics; flooring; caulking; and agricultural applications, such as a carrier for pesticides and

fungicides (Van Gosen *et al.*, 2000). In May of 2000, the little known use of talc in crayons became a headline story following a news report that asbestos was found along with talc in the world's major brands of crayons. Talc is combined with paraffins and pigments to provide strength and durability to crayons.

THE "ASBESTOS IN CRAYONS" CONTROVERSY OF 2000

On May 23, 2000 the *Seattle Post-Intelligencer* (Schneider and Smith, 2000c) reported that government laboratory tests found asbestos in the three best-selling brands of crayons. The Consumer Product Safety Commission (CPSC) commissioned Data Chem in Cincinnati and the Occupational Safety and Health Administration (OSHA) laboratory in Salt Lake City to perform the original analyses of the crayons. Four brands of crayons produced in the United States and four brands manufactured abroad were tested on the behalf of the *Seattle Post-Intelligencer*. The newspaper reported that tests on Crayola, the world's largest crayon seller, Prang, and Rose Art crayons "repeatedly showed the crayons contained asbestos". Further, the article stated: "Of the 40 crayons tested from the brands that had asbestos [Crayola, Prang, and Rose Art], 80 percent of them were contaminated above the trace level." According to the *Seattle Post-Intelligencer* (Schneider and Smith, 2000c), the amount of asbestos in the crayons ranged from 0.05 to 2.86 volume percent in Crayola samples, from 0.3 to 0.54 volume percent in Prang samples, and from 0.03 to 1.20 volume percent in Rose Art samples. The asbestos fibers were determined to be contaminants of the talc used to strengthen the crayons. According to an article in the *Seattle Post-Intelligencer* the following day (Schneider and Smith, 2000a), the laboratories reported tremolite and anthophyllite asbestos. A subsequent report by the *Seattle Post-Intelligencer* (June 13, 2000; Schneider and Smith, 2000b) stated: "The scientists found extremely low levels of anthophyllite asbestos and cleavage fragments of tremolite in some of the crayons."

The *Seattle Post-Intelligencer* report created an immediate public stir, because crayons are used daily by millions of children. Russ Rader of the Consumer Product Safety Commission (CPSC) in Washington, D.C., said "We have never heard of this being a problem with crayons before" and "our position is that asbestos should not be in any product, and that's what we're telling the companies" (Blakemore, 2000). Binney & Smith (maker of Crayola crayons), Rose Art, and Dixon Ticonderoga (maker of Prang) responded immediately as crayon usage dropped across the United States following the reports. Binney & Smith hired RJ Lee Group, Inc., a contract laboratory and materials testing firm accredited by the United States Environmental Protection Agency (EPA), to analyze samples of Crayola crayons and the powdered talc used in the crayons. The laboratory used polarized

light microscopy, transmission electron microscopy, and scanning electron microscopy techniques (Moran, 2000). The RJ Lee Group, Inc. reported that no asbestos was found in the talc or crayon samples provided by Binney & Smith (Moran, 2000). The CPSC performed additional analyses of crayons and released their test results on June 13, 2000 (*Press Release #00-123*), stating that they "found a trace amount of asbestos in two Crayola crayons made by Binney and Smith and one Prang crayon made by Dixon Ticonderoga"; they added "however, the amount of asbestos is so small it is scientifically insignificant." The CPSC press release also stated the following:

"...CPSC tests concluded that the risk a child would be exposed to the [asbestos] fibers either through inhalation or ingestion is extremely low and there is no scientific basis for a recall...In a simulation of a child vigorously coloring with a crayon for half an hour, no fibers were found in the air. The risk of exposure by eating crayons is also low because the fibers are imbedded in wax and pass through a child's body. However, CPSC concluded that these fibers should not be in children's crayons in the long term. As a precaution, because crayons are intended for use by children, CPSC asked industry to reformulate crayons using substitute ingredients. Binney and Smith and Dixon Ticonderoga quickly volunteered to reformulate within a year to eliminate the fibers."

Rose Art announced that they had not used talc in their crayons for at least 15 months prior to the *Seattle Post-Intelligencer* crayon report because they had coincidentally found a preferable synthetic substitute earlier (Schneider, 2000b). The company felt that the Rose Art crayon samples analyzed and found to contain asbestos must have come from old stock (Schneider, 2000b).

The talc used in Crayola, Prang, and, earlier, in Rose Art crayons, was supplied by a talc mine of the Gouverneur Talc Company, owned and operated by R.T. Vanderbilt Company, and located in the Gouverneur district of northeastern New York State (Figure 1). Gouverneur talc is used widely in paints and ceramics. The Gouverneur talc deposit is known to contain the minerals tremolite and anthophyllite (Engel, 1949, 1962; Ross *et al.*, 1968), but the possibility of asbestiform varieties of these particular minerals in this deposit has been a matter of much debate between R.T. Vanderbilt Company and some human health experts since the early 1970s. The company has been accustomed to scrutiny about the safety of their talc for almost 30 years (see Occupational Safety and Health Administration, 1992).

- The Research Triangle Institute (RTI), located in Research Triangle Park, North Carolina, conducted an independent quantitative examination of various Crayola crayons purchased from retail stores, and of samples of the Gouverneur talc used in the crayons, which were supplied by Binney & Smith. They

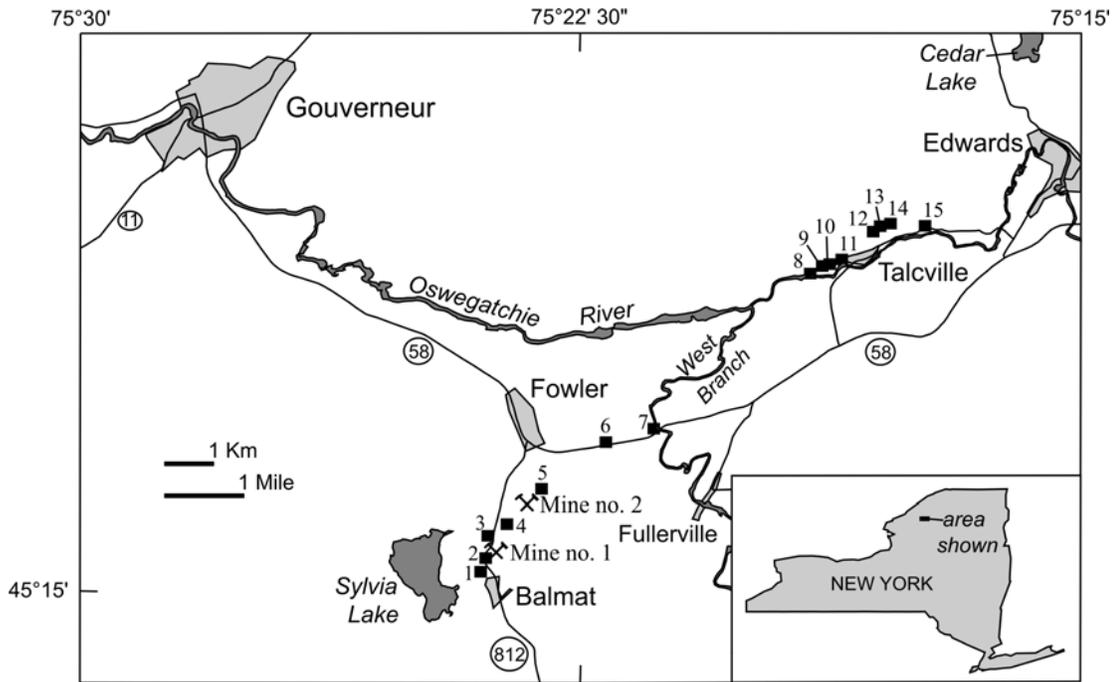


Figure 1. Index map of the Gouverneur (Balmat-Edwards) talc mining district. Refer to Engel (1962) for descriptions and mapping of the geology and talc deposits of this area. Recent open-pit talc mines of the Gouverneur Talc Company (mine symbols) include their Mine no. 1 (inactive in 2001) and Mine no. 2 (active in 2001). Past talc production from underground mines (black squares) included the:

- | | | |
|--------------------|--|---|
| 1. American mine | 6. Johnson mine | 11. International Talc Co. shaft no. 2½ |
| 2. Gouverneur mine | 7. Ontario mine | 12. International Talc Co. shaft no. 3 |
| 3. Woodcock mine | 8. Wintergreen Hill mine | 13. International Talc Co. shaft no. 4 |
| 4. Wight mine | 9. International Talc Co. shaft no. 2 | 14. International Talc Co. shaft no. 5 |
| 5. Arnold mine | 10. International Talc Co. shaft no. 1 | 15. Newton Hill mines |

analyzed the talc and the residues of ashed crayons using polarized light microscopy, X-ray diffraction, and transmission electron microscopy (TEM). A report produced by RTI (Beard and others, 2001) reported the following results from their TEM analyses:

- The crayons contained on average 0.067% (volume percentage of the crayon) fibrous talc, 3.8% tremolite cleavage fragments, 0.56% anthophyllite, and 1.9% “transitional fibers.”
- The talc contained on average 0.81% fibrous talc, 13% tremolite cleavage fragments, 4.4% anthophyllite, and 16% “transitional fibers.”

THE RELATIONSHIPS OF FIBROUS TALC, ASBESTOS, TRANSITIONAL AMPHIBOLES, AND AMPHIBOLE CLEAVAGE FRAGMENTS

The R.T. Vanderbilt Co. released news updates following the crayon-asbestos reports on their website (<http://www.rtvanderbilt.com/>). They said in part “the reports of asbestos contamination in crayons are based on the misidentification of minor amounts of talc fiber and

mixed or transitional fibers found in its talc” and further “the source of the problem is linked to inadequate protocols and proficiency testing.” The term “fibrous talc” is often used to describe talc-rich rocks that consist of an intergrowth of talc and acicular amphiboles, such as tremolite and anthophyllite (Goodwin, 1974; Greenwood, 1998). The assemblage commonly includes pseudomorphous replacements of these amphiboles by talc (Figure 2), thereby giving the talc-rich rock a generally fibrous rather than massive appearance. Identification, classification, and regulation issues surrounding the “transitional fibers” mentioned in the R.T. Vanderbilt Co. statement are at the core of decades of debate regarding the mineralogy and safety of talc ores that contain acicular amphiboles. The “transitional fibers,” sometimes termed “intermediate fibers,” are composed of fibrous talc and amphibole in various proportions. They include mineral fibers “caught in the act” of transformation, such as the partial, incomplete replacement of anthophyllite by talc. These fibers characteristically have mineral compositions intermediate between ideal talc and ideal anthophyllite or tremolite (Greenwood, 1998), and thus do not fit well with the precise mineralogical definitions of talc or amphibole (Occupational Safety and Health Administration, 1992,

page 24319). X-ray diffraction, optical, and chemical analyses of transitional fibers often reveal data characteristics that range between the ideal values for talc or amphibole, and sometimes show dual patterns. These “transitional” or “intermediate” fibers may have formed

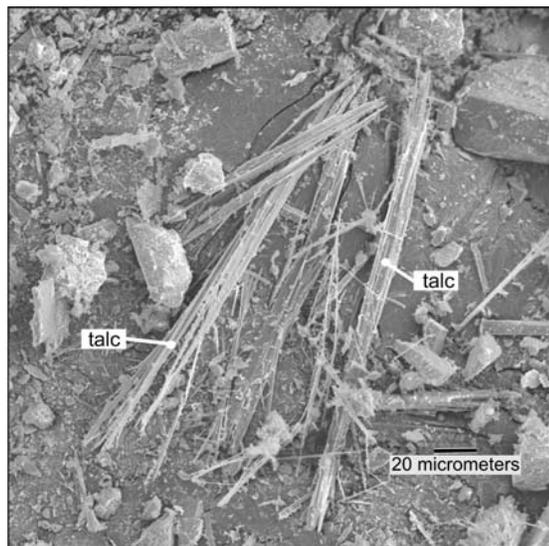


Figure 2. Scanning electron microscope (SEM) photograph of fibrous talc found in the mineral residue of an orange crayon of one the three best-selling brands. The crayon was ashed at low temperature over several days, oxidizing the organic materials and leaving the mineral residue, which was examined by SEM. Compositional analyses were conducted by energy dispersive X-Ray spectroscopy (EDS), which determined a nearly pure talc composition (based on stoichiometry) for these fibers (see table 1). SEM photography and EDS analyses were performed by the authors.

by partial, pseudomorphic replacement of fibrous amphibole by talc and (or) may be microscopic intergrowths of amphibole with talc (Virta, 1985). For example, in the tremolite-anthophyllite-rich, fibrous talc deposits of the Gouverneur district, Engel (1962) determined that acicular tremolite was the primary metamorphic mineral of the talc ore assemblage, which was replaced locally by pseudomorphous anthophyllite; both tremolite and anthophyllite were then subsequently replaced by fibrous talc and serpentine (Figure 3).

Engel (1962) provides a number of photographs that show the macroscopic characteristics of the Gouverneur talcs and the associated mineral assemblages. The “transitional fibers” of much debate in “fibrous talc” are acicular forms of the minerals tremolite, anthophyllite, and talc (Figure 3). These may be slender and needlelike, and are often described as fibrous. However, when they are characterized as asbestos (or “asbestiform”), much controversy results (Goodwin, 1974; Occupational Safety and Health Administration, 1992). In the *Seattle Post-Intelligencer* story of June 13, 2000 (Schneider and Smith, 2000b), the paper quoted Ronald Medford, Assistant Executive Director of hazards identification at the CPSC, as saying: “We’re considering the asbestos [in the crayons tested] scientifically insignificant when we compare it to the much larger amount of anthophyllite-like fibers we also found in the crayons.”

ASBESTOS AND TRANSITIONAL AMPHIBOLES

The term “asbestos” is a commercial term that refers to a group of silicate minerals that will easily separate into strands of thin, strong fibers that are flexible, heat resistant, and chemically inert, thus well suited for applications such as heat insulation (Cossette, 1984; Ross, 1981; Ross *et al.*, 1984; Skinner *et al.*, 1988; Zoltai, 1981). In a mineralogical sense, the two groups of asbestos minerals are (1) serpentines, with the only asbestiform variety called chrysotile, and (2) certain amphiboles, including crocidolite (riebeckite asbestos), cummingtonite-grunerite asbestos (commercially called amosite), and the asbestiform varieties of tremolite,

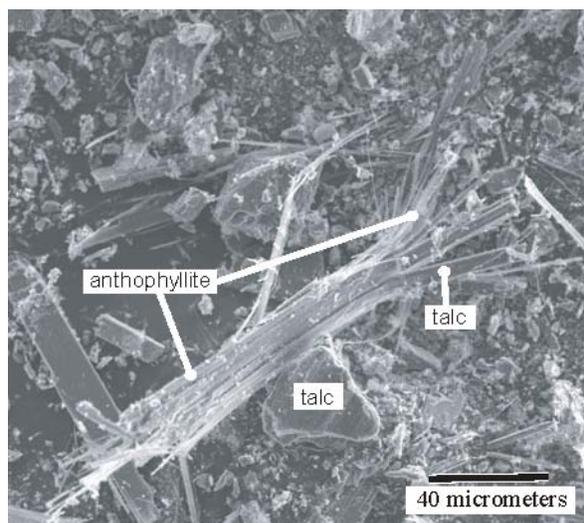


Figure 3. SEM photograph of a “transitional” particle found in the mineral residue of the orange crayon sample described in figure 2. Analyses by EDS determined the mineral compositions and identified phases based on stoichiometry at the spots indicated in the photo (see table 1). SEM photography and EDS analyses were performed by the authors.

anthophyllite, and actinolite. Chrysotile is not a common constituent in the major talc deposits, but is found in some talc deposits associated with the serpentinization of ultramafic rocks. Actinolite is locally a trace constituent of some metamorphic talc deposits. Tremolite and anthophyllite occur as major constituents in some types of large talc ore deposits, such as in the Gouverneur talcs, and can occur as blocky crystals (massive variety) grading to the fibrous varieties (Dorling and Zussman, 1987). The non-fibrous varieties of these amphiboles are simply referred to as tremolite and anthophyllite, while the asbestiform varieties are termed “tremolite asbestos” and “anthophyllite asbestos” or alternatively as “asbestiform tremolite” and “asbestiform anthophyllite.” Defining the transition point between asbestiform forms of tremolite and anthophyllite and their non-fibrous, potentially less toxic and unregulated, varieties is a major source of debate. The issue has remained unresolved since the 1970s, and resurfaced in 2000.

TABLE 1. COMPOSITIONS DETERMINED FOR THE MINERAL PARTICLES SHOWN IN FIGURES 2 AND 3, AS COMPARED TO THE “IDEAL” COMPOSITIONS OF PURE TALC AND ANTHOPHYLLITE. THE STOICHIOMETRIC PROPORTIONS WERE CALCULATED FROM ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDS) ANALYSES.

<u>Mineral Particle</u>	<u>Normalized Cation Ratios</u>
ideal talc	$Mg_3Si_4O_{10}(OH)_2$
ideal anthophyllite	$(Mg, Fe)_7Si_8O_{22}(OH)_2$ [from $Mg_7Si_8O_{22}(OH)_2$ to approximately $Fe_2Mg_5Si_8O_{22}(OH)_2$]
fibers in fig. 2	$(Mg_{2.8}, Al_{0.1}, Ca_{0.1}, K_{0.1})Si_{4.2}[O_{10}(OH)_2]^*$
platy talc, fig. 3	$(Mg_{2.4}, Ca_{0.1})Si_{4.3}[O_{10}(OH)_2]^*$
talc spindle, fig. 3	$(Mg_{2.6}, Ca_{0.1})Si_{4.1}[O_{10}(OH)_2]^*$
anthophyllite bundle, fig. 3	$(Mg_{6.8}, Ca_{0.1})Si_{8.1}[O_{22}(OH)_2]^*$
anthophyllite tuft, fig. 3	$(Mg_{6.8}, Al_{0.1}, Ca_{0.1})Si_{8.0}[O_{22}(OH)_2]^*$

*Cation ratios were calculated by stoichiometry on the basis of 11 oxygen atoms for talc and 23 oxygen atoms for anthophyllite. (OH) was assumed to be 2 for both phases.

According to OSHA asbestos regulation standards, in order to determine the “asbestos” content of a particular mineral assemblage, an analyst must count only those minerals that display asbestos growth habit, by first identifying the particles with length-to-diameter (aspect) ratios of at least 3:1. Most asbestos fibers have aspect ratios greater than 100:1. The mineral fiber must also be compositionally consistent with one of the six regulated asbestos “mineral” phases. OSHA regulation 1910.001, App. J defines asbestos fiber as “a particulate form 5 micrometers or longer, with a length-to-diameter ratio of at least 3 to 1.” Regulatory agencies worldwide have generally agreed that the mineral fibers most hazardous to the human respiratory system are those with diameters of about 3 micrometers or less (see Cossette, 1984, pages 34 to 36). The OSHA asbestos regulation also notes that: “asbestos fibers exist in bundles that are easily parted...and may be tufted at the ends showing ‘bundle of sticks’ morphology.” Another guideline, although apparently unofficial in its application, is that asbestos fibers are flexible, which is typically indicated by long, thin fibers that appear to bend but not break. True asbestos is thought to be extremely flexible and not brittle (Zoltai, 1981). Some studies (for example, Wylie, 1979) suggest that when asbestos is examined by optical microscopy, it shows characteristic parallel extinction in all orientations in the [001] crystal zone. Other studies (Dorling and Zussman, 1987) indicate that this relation is inconsistent, and that undulate extinction can occur in bundles of twisted asbestos fibers.

A large part of the talc-asbestos debate results from the lack of consistently applied, unambiguous criteria to distinguish the “transitional” and “nonasbestiform” varieties of acicular tremolite and anthophyllite from “asbestiform tremolite” and “asbestiform anthophyllite”

(Goodwin, 1974; Campbell *et al.*, 1977; Cossette, 1984; Ross *et al.*, 1984; Dorling and Zussman, 1987; Case, 1991; Occupational Safety and Health Administration, 1992; Beard *et al.*, 2001). “Transitional” fibers, as represented in the fibrous Gouverneur talcs (Greenwood, 1998), are not treated as deleterious under current Occupational Safety and Health Administration (OSHA) regulations. In 1992, OSHA released a ruling (Occupational Safety and Health Administration, 1992, page 24310) that “amends the revised asbestos standards to remove nonasbestiform tremolite, anthophyllite and actinolite (ATA) from their scope.” Further, “...OSHA’s determination to remove nonasbestiform ATA from the scope of the asbestos standards is based on the insufficiency of evidence to support determinations that their further inclusion would protect exposed employees from a risk of disease which was the equivalent in incidence and gravity to asbestos related disease, and that removing coverage would pose a significant risk to exposed employees.” Thus commercial OSHA standards for regulated asbestos were limited to chrysotile, amosite (cummingtonite-grunerite), crocidolite (riebeckite), anthophyllite, tremolite, and actinolite asbestos. These minerals were encountered in occupational asbestos exposures. Unfortunately, the fine compositional distinctions between “transitional” and “asbestiform” varieties of the regulated amphiboles were not explained in the 1992 OSHA ruling; instead they referred back to their previous definition of asbestos (29 CFR 1910.1001(b)), which did not define “transitional” or “intermediate” fibers.

AMPHIBOLE CLEAVAGE FRAGMENTS

Cleavage is the proclivity of crystalline solids to fracture preferentially along parallel, closely spaced

planes that are controlled by the crystal structure. Amphibole minerals have well-developed elongated cleavage planes (Zoltai, 1981), and tend to fracture and fragment along these cleavage planes when the amphibole particles are crushed and ground. The resulting elongate particles are referred to as “cleavage fragments” (Campbell and others, 1979; Zoltai, 1981). The 1992 OSHA ruling (Occupational Safety and Health Administration, 1992, page 24320) determined that cleavage fragments of the amphiboles would not be regulated. In their ruling, OSHA said: “In summary, the discussion indicates that populations of fibers and populations of cleavage fragments can be distinguished from one another when viewed as a whole. For example one can look at the distribution of aspect ratios or even widths for a population of particles and can then generally identify that population as being asbestiform or nonasbestiform” (Occupational Safety and Health Administration, 1992, page 24319). They further stated: “The record also indicates that populations of particles derived from mining, crushing or processing these minerals [cleavage fragments], are also distinctly different (for example, in the distribution of widths and aspect ratios). However, on an individual particle basis, which is often the case for particles from air monitoring samples, these distinctions may become less clear” (Occupational Safety and Health Administration, 1992, page 24319). Based on these observations, OSHA decided that: “...the mineralogical forms are sufficiently distinctive to be treated differently for regulatory purposes” (Occupational Safety and Health Administration, 1992, page 24320). The scientific distinction, difficult to resolve based on the examination of individual fibers (Campbell, 1979; Dorling and Zussman, 1987), is that asbestiform varieties of the amphiboles grew into their asbestos habits during mineral deposit formation (Zoltai, 1981), while cleavage fragments formed as a result of subsequent man-made processes, such as crushing, grinding and milling. Thus, under current OSHA rules, in terms of talc deposits and their products, cleavage fragments of amphiboles (as well as pure fibrous talc) are exempt from regulation. Only those amphibole particles with asbestiform habits (lengths of greater than 5 micrometers, maximum diameter of 3 micrometers, large aspect ratios, and tufted ends if visible, fibers bent and not broken) that are determined to consist of cummingtonite-grunerite (amosite), riebeckite (crocidolite), tremolite, anthophyllite, or actinolite compositions, would be regulated. Correct identification of both crystal habit and species of microscopic minerals is most thoroughly completed by comparing the results of polarized light microscopy, x-ray diffraction, transmission electron microscopy, scanning electron microscopy, and microprobe analyses of representative samples (Dorling and Zussman, 1987). The complex identification and sampling procedures explain why laboratories can report conflicting results regarding the presence or absence of “asbestos” from a particular industrial mineral deposit or its processed products.

DEBATES REGARDING THE HEALTH EFFECTS OF GOUVERNEUR AMPHIBOLES AND TALCS

In addition to the controversy of distinguishing the cleavage fragments and “transitional” varieties of amphiboles from the asbestiform varieties, another area of disagreement is the potential respiratory impacts of transitional amphiboles (Case, 1991; Davis *et al.*, 1991) and fibrous talc, particularly in the Gouverneur district (Occupational Safety and Health Administration, 1992, page 24322). A Symposium on Talc held May 8, 1973 in Washington, D.C. (Goodwin, 1974) hosted a number of talks that presented contrasting views regarding the potential health impacts of talc and associated particles of tremolite and anthophyllite. Several speakers discussed pro and con case studies specific to the talc deposits of the Gouverneur district. In 1980, the National Institute for Occupational Safety and Health (NIOSH) published a study (Dement *et al.*, 1980) that examined the health and mortality rates of miners and millers who worked in the talc operations of the Gouverneur district between 1947 and 1960. The NIOSH study indicated that the death rate for the study group due to non-cancerous respiratory disease was almost three times (273 percent) the expected rate (Dement *et al.*, 1980, page 31). More recently, the *Seattle Post Intelligencer* (June, 22, 2000; Schneider, 2000a) interviewed doctors at NIOSH who feel the 1980 study proved asbestos exists in Gouverneur district talc, and this asbestos is the cause of respiratory diseases in past and present Vanderbilt talc workers.

Despite more than three decades of study and debate, there is no universal agreement regarding the potential long-term health effects of the airborne “transitional” anthophyllite-talc particles and tremolite cleavage fragments (Goodwin, 1974; Ross, 1981; Case, 1991; Davis *et al.*, 1991; Occupational Safety and Health Administration, 1992), especially those found in the deposits mined and milled in the Gouverneur district. On its product website, Crayola (<http://www.crayola.com/>) quoted Dr. William Robertson, medical director of the Washington Poison Center, and a specialist in medical toxicology, about the safety of amphibole cleavage fragments and fibrous talc. According to Dr. Robertson: “There is no data that indicates these particles are a risk. They are not regulated by federal authorities because of that fact. There are no known health effects from exposure to these particles.” In contrast, the Mount Sinai School of Medicine of the City University of New York in Brooklyn, where studies of the potential hazards associated with fibrous talc have been conducted since the early 1970s (Goodwin, 1974, pages 77 to 88), believe the Gouverneur talc deposits do contain asbestiform minerals. According to the hospital’s director of the Center for Children’s Health and the Environment, pediatrician Dr. Phillip Landrigan, a leading critic of the Gouverneur talc operation: “The proof of it [asbestos in the talc] is

Vanderbilt's own workers. They have been shown to have excess lung cancer, excess asbestosis and excess rates of malignant mesothelioma...In good conscience I don't know how Vanderbilt can say that their talc doesn't contain asbestiform fibers" (*Seattle Post-Intelligencer*, May 30, 2000; Schneider and Smith, 2000d). Because of such contradictory testimony, OSHA deferred regulation of the Gouverneur talc deposits and similar industrial deposits in their 1992 ruling (Occupational Safety and Health Administration, 1992, pages 24322 and 24323) by stating "OSHA believes that the epidemiological studies, as a whole, provide insufficient evidence to inform as to the carcinogenicity of nonasbestiform ATA." Thus, despite the complexities in such analyses, it is left for the medical research community to provide a more definitive

recommendation on the potential toxicity of airborne "transitional" amphiboles, cleavage fragments, and talc (Case, 1991; Davis *et al.*, 1991).

ALL TALC WAS NOT CREATED EQUAL

Ultimately, Binney & Smith (Crayola) and Dixon Ticonderoga (Prang) found a synthetic, less contentious replacement and voluntarily removed talc from their crayons. The focus in 2000 on asbestos in crayons should not be viewed as an indictment of talc as a whole. All talc was not created equal and not all talc ores contain amphiboles or asbestiform minerals. For geologic summaries of the major United States talc districts noted

TABLE 2. LIST OF SELECTED MAJOR TALC DISTRICTS IN THE U.S. LIST IS DIVIDED INTO TALC DEPOSITS FORMED MAINLY BY LARGE-SCALE HYDROTHERMAL PROCESSES VERSUS THOSE DEPOSITS FORMED BY METAMORPHIC PROCESSES.

District	Primary host rock(s)	Amphiboles forming major constituents of the talc ores	References
<i>Hydrothermal Talc Deposits</i>			
(1) southwestern Montana area	dolomitic marble	none reported	Berg (1979); Olson (1976); Perry (1948); Van Gosen <i>et al.</i> (1998)
(2) Talc City district, Inyo Range, Inyo County, California	dolostone, quartzite	none reported	Close (1985); Gay and Wright (1954); Hall and Mackevett (1958); Page (1951); Wright (1957)
(3) Palmetto and Sylvania districts, Esmeralda County, Nevada	dolomite, limestone	none reported	Papke (1975)
(4) Allamoore district, west Texas	dolostone	none reported	Bourbon (1981, 1982); Edwards (1984); Kyle and Clark (1990); Price <i>et al.</i> (1983)
(5) Winterboro area, Talladega County, Alabama	dolomite	none reported	Blount and Helbig (1987); Blount and Vassiliou (1980); Dean (1994); Helbig (1983); McMurray and Bowles (1941); Reed (1950); Rheams (1990, 1992)
<i>Metamorphic (Regional or Contact) Talc Deposits</i>			
(1) Gouverneur district, upstate New York	dolomitic marble	tremolite, anthophyllite	Engel (1949, 1962); Ross <i>et al.</i> (1968)
(2) Llano Uplift area, central Texas	schist, gneiss, serpentinite	tremolite, anthophyllite	Barnes (1943); Claybaugh and Barnes (1959)
(3) Silver Lake-Yucca Grove area, California	metasedimentary dolomitic strata	tremolite	Wright (1954, 1957)
(4) southern Death Valley-Kingston Range area, California	dolomite	tremolite	Evans <i>et al.</i> (1976); Wright (1952, 1968)

below, the reader is referred to Piniakiewicz and others (1994) and Berg (1995). On the basis of talc ore formation, significant United States talc deposits can be separated into deposits that formed primarily by (1) intense hydrothermal alteration and replacement of carbonate-rich metamorphic and sedimentary rocks, or (2) regional or contact metamorphism of carbonate-rich rocks, ultramafic rocks, or serpentinite (serpentinized mafic rocks). Investigations of deposits interpreted to have formed dominantly by hydrothermal processes indicate that no asbestiform minerals are present, and report only minor amounts of amphibole contaminants in their ores, if any. Some examples of hydrothermal talc deposits (Table 2) include (1) the large, bulk-mined deposits of high-purity talc in southwestern Montana, the largest current talc producing region in the United States; (2) deposits of the Inyo Range of Inyo County, California; (3) the Palmetto and Sylvania districts in Esmeralda County, Nevada; (4) the Allamoore district of Texas; and (5) the deposits near Winterboro, Alabama.

In contrast, large talc deposits interpreted to have formed primarily by regional or contact metamorphic processes consistently contain amphiboles, often as a major component. The habit of tremolite and/or anthophyllite and/or actinolite may range from massive to asbestiform, and sometimes several crystal habits occur at a single site. Thus, each metamorphic talc deposit requires a site-specific study to determine the precise composition and habit of the amphiboles within that particular deposit. A few examples of metamorphic talc deposits (Table 2) are (1) the tremolite-anthophyllite-bearing talcs of the Gouverneur district of upstate New York, which formed by regional metamorphism; (2) tremolite-bearing soapstone in the Llano Uplift of central Texas, also thought to have formed by regional metamorphism; (3) the tremolitic Silver Lake talc deposits north of Baker in San Bernardino County, California, interpreted to have formed by contact metamorphism when dikes and irregular igneous bodies intruded sedimentary carbonates; and (4) tremolitic talc deposits of the southern Death Valley-Kingston Range region, which formed by contact metamorphism next to diabase sills.

The protolith hosting the talc does not seem to be the primary control on the presence or absence of amphiboles (Table 2). For example, the large high-purity talc deposits of southwestern Montana, which lack amphiboles, formed by hydrothermal alteration and replacement of dolomitic marbles. Yet, the tremolite-anthophyllite-rich talc deposits of the Gouverneur district of northeastern New York also replaced dolomitic marble. Large hydrothermal talc deposits appear to share at least two genetic characteristics: (1) early regional metamorphic event(s), which may have formed amphiboles (especially tremolite) were followed sometime later by overprinting hydrothermal activity that involved high water/rock ratios, and (2) volume-for-volume replacement of the host

rock by the talc ore bodies (Anderson *et al.*, 1990; Blount and Vassiliou, 1980; Blount and Helbig, 1987; Moine *et al.*, 1989; Page, 1951). Moine *et al.* (1989) suggest that high salinity in the talc-forming hydrothermal solutions favors talc stability and the absence of tremolite. The distinct and consistent relationship between amphibole-poor hydrothermal talc versus amphibole-bearing metamorphic talc requires more study. The environment of formation appears to have had a direct impact on the composition and morphology of talc that formed at a particular site. This in turn affects the talc's uses in everyday products and its perceived or actual health effects.

SUMMARY STATEMENT

The complex mineralogy of many fibrous talc deposits, which often contain acicular anthophyllite and (or) tremolite, presents a challenge to regulatory agencies who must define and regulate asbestos (Occupational Safety and Health Administration, 1992). The controversy in 2000 over asbestos in crayons reinvigorated debates that extend back to the early 1970s, regarding the potential health impacts of acicular amphiboles in fibrous talc deposits. The fibrous talc ores of the Gouverneur district, in upstate New York, demonstrate the difficulty of resolving debates over "asbestos". "Transitional" (or "intermediate") fibers in these deposits have compositional characteristics of both talc and amphibole, and they can display analytical data values that lie between those for ideal talc and ideal anthophyllite or tremolite. Cleavage fragments of amphiboles, also common in some fibrous talc deposits, are difficult to distinguish from asbestiform fibers, especially on a microscopic, individual-particle scale (Dorling and Zussman, 1987; Occupational Safety and Health Administration, 1992). The scientific distinction is that asbestos varieties of the amphiboles grew into their asbestiform habits during mineral crystallization (Zoltai, 1981), whereas cleavage fragments are formed by crushing and grinding during mining, milling, and processing. The compositional complexities caused by "transitional fibers," plus the morphological variations of cleavage fragments, present quite a challenge to writing and applying a precise regulatory definition for "asbestos." These complications, in combination with the lack of an unambiguous, consistently applied, mineralogical definition of "asbestos," explains why government-certified laboratories can report seemingly conflicting results on asbestos content in a talc-rich material. Under the OSHA asbestos rules of 2001, in relation to talc deposits and their products, "transitional" fibers, cleavage fragments of amphiboles, and fibrous talc are exempt from regulation as hazardous materials.

Similarly, there is no universal agreement on the potential respiratory impacts of transitional amphiboles,

cleavage fragments, or fibrous talc. It is left to medical toxicologists to reach a consensus on the degree of health risk, or lack of risk, that these particles represent. To conduct meaningful, comparable toxicology studies that use fibrous talc as reference materials, the researchers should be very aware of the compositional and morphological variations that can exist in the test materials. Careful characterization of the reference material will best insure that the test results obtained from talc- and amphibole-rich products are comparing materials that are similar in mineralogy and crystal habit.

An observation that may help simplify the complex, microscopic relations of talc and fibrous amphiboles is that not all types of United States talc deposits contain amphiboles or asbestiform minerals. Consistently in the literature, deposits interpreted to have formed mainly by hydrothermal processes lack the mention of asbestiform minerals or describe no more than trace amounts of amphiboles. In contrast, deposits formed by regional or contact metamorphism consistently contain amphiboles, commonly as a major constituent, and in a variety of habits that range from massive to asbestiform. The consistent relationship of amphibole-poor hydrothermal talc versus amphibole-bearing metamorphic talc deserves further study. As demonstrated by the crayon-asbestos issue of 2000, the existence of fibrous amphiboles in an industrial talc deposit can quickly affect the marketability of a product that uses the talc, and in the long term, could affect human health.

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INDUSTRIAL MINERAL PRODUCTS FROM MINING WASTE

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ABSTRACT

The utilization of waste from mining activities generates revenue, and may give environmental and socio-economic benefits. Although the composition of mining waste varies according to the nature of the mining operation and many other factors, where the same mineral is extracted from a similar style of metalliferous, industrial mineral or coal deposit, the waste usually has similar characteristics (for example, fluorite and barite rich waste from Mississippi Valley Type deposits). Waste from one mine may be a by-product or co-product in another location. There is much published research on the potential utilization of mining waste. Many proposed uses involve complex manufacturing processes. However, the product is usually inferior, and manufacturing costs are higher compared with products made from primary industrial mineral sources. It is unlikely that a successful business could be developed using low value mine waste of a variable quality in a complex manufacturing process. There are three possible scenarios where an industrial mineral product made from mining waste could be marketed successfully. These are: as a bulk product made with minimal or no processing; by extracting an industrial mineral that offers a cost-effective alternative source of supply for local industry; or can be traded nationally or internationally; and through extraction of a high-value rare mineral as a by-product from a mining operation. Any processing of the waste must be consistent with the value of the mineral produced. The first scenario is the most significant. Examples are presented of clay waste, armour stone from dimension stone waste, aggregates from china clay waste, fluorite and barite from waste associated with base metal extraction, feldspar, mica and rare minerals in waste from pegmatites, and tantalum from kaolinized granite waste from china clay.

INTRODUCTION

Mining generates waste by excavating overburden and other materials to gain access to the ore; and from interburden, residues from beneficiation, and inferior quality or sub-grade minerals. Some waste is used to backfill open pits, to build haul roads, and for landscaping or other uses within the mine site, but much remains in waste piles or tailings heaps. These take up valuable space and may even sterilize future reserves. Fine residues from processing or other beneficiation activities in particular create problems in their containment and disposal. They usually remain at the mine site long after mining has ended. Often they require ongoing monitoring, including physical and chemical stability, and for potentially hazardous elements or minerals that could be released into the wider environment through leaching or erosion by water or wind. Vast quantities of mining wastes have accumulated worldwide. By 1978, some 20 billion tonnes was estimated to have been amassed in the U.S. with a further 326 000 tonnes added per day (Aleshin, 1978).

Production of waste costs a mining company money, therefore any revenue that can be made from it that exceeds further handling, processing and transport costs is a benefit. In some cases, legislation or permitting regulations may require that a waste pile is reduced in size, removed, rendered less visible, or treated in some

other way to protect the surrounding environment. In this case, any income from selling a product made from the waste may reduce the financial burden on the mining company or other body responsible for on-going monitoring. Taxation designed to maximize the use of resources, and/or to regulate waste piles also provides an incentive for mineral producers to extract mineral by-products from a waste stream or existing pile. The European Commission are currently (September, 2001) consulting with interested parties on an initiative for the management of waste resulting from prospect evaluation, extraction, treatment and storage of mineral resources (European Commission, 2001). It proposes extending existing controls on landfill to mining waste. As a result, conditions dealing with permits, upgrading of standards, financial security for closure and aftercare will be introduced. The landfill requirement for pre-treatment may be applied to mining waste to promote its minimization, segregation and recovery.

There is an obvious environmental benefit in reducing or removing a waste pile. There can be also a socio-economic advantage, especially in a developing country. Indigenous populations often congregate around a working mine site. The mine provides some direct and indirect employment, and a general improvement in both living conditions and the local economy. However, when a mine closes, managerial and skilled staff leave, and the local population sinks into poverty. Production of

saleable mineral products from the waste can provide further employment, and sustain the population, at least for as long as there is a market and the waste resource is available.

The aims of this paper are to provide an overview of the types of waste found in extractive operations, and to give examples where income generation is possible from waste utilization. The scenarios considered are pragmatic; they take advantage of appropriate market conditions, rather than relying on novel developments in technology. Secondary recovery of the primary mineral from mining waste is generally excluded from the discussion, although this can provide an additional source of revenue for a mining company. For example, a tailings heap might be re-processed using a new, more efficient extraction procedure. Manufactured waste from metal production, such as slags, and other down-stream processes, such as fly ash from coal fired energy utilities, are also excluded.

COMPOSITION OF MINING WASTE

Obviously the composition of mining waste varies with the type of mining operation, the mineral extracted, the nature and structure of the ore body, the overburden, and many other factors related to the geology and mining of the ore. It is also affected by developments in technology and improvement in methods of extraction and processing, so waste composition and structure can vary with time. Where other factors are the same, the policy of a mining company, and a country's minerals legislation may have an influence on the potential utilization of waste even if the waste contains a significant amount of a marketable industrial mineral. For example, an organization exploiting a metal ore, especially gold, frequently has had little or no interest or knowledge whether any marketable industrial minerals are present in its waste stream. In another instance, a supplier of a high priced industrial mineral product might be unwilling to develop a market for another high volume, but perhaps low grade industrial mineral within its deposit, because of the negative image it might portray. In some countries the mineral rights legislation and/or permitting regulations allow exploitation only of named minerals regardless of the nature of the deposit. For example at Woburn, Bedfordshire in the United Kingdom a seam of fullers' earth (Ca-montmorillonite) that is up to 3.5 metres thick is extracted from beneath 24 to 30 metres of overburden sand (Dunham *et al.*, 1978). Permitting regulations, driven by a need to protect the environment, dictate that all of the sand is backfilled. A few kilometers away in Leighton Buzzard (Wyatt *et al.*, 1988) the same sand, with an identical composition, is extracted in large amounts (around 250 000 tonnes per annum) as building, filtration and silica sand. These factors in various combinations mean that the waste from every extractive operation in every country is likely to be

unique. Thus, the potential for extraction will differ from place to place, even if similar market conditions exist.

Where the same mineral is extracted from the same or a similar style of deposit, there will be similarities in the waste. This applies to many metalliferous ores, coal, and several industrial minerals. Table 1 gives details of the nature of the waste, the current practice for disposal and some potential markets for a large number of different types of mineral deposits. The information is derived from the literature and the authors' collective experiences. Some is expanded in Harrison *et al.* (2001). With several of these deposit types, the waste material may already constitute an established product from operations in some countries, but elsewhere it may not be used. For example, maximizing the efficiency of exploitation and revenue from a bulk commodity such as aggregates or limestone involves making a wide range of products (see for example, Scott and Dunham, 1984), such as using crusher scalplings for bulk fill applications, and limestone fines for agricultural lime. Thus, few waste materials remain. There are also well know examples of dual or multiple industrial mineral products from a single deposit, for example, mica, feldspar, quartz and spodumene from pegmatites in North Carolina (Tanner, 1994; Kauffman and Van Dyk, 1994); and silica sand and kaolin from a kaolinized arkose (Bristow, 1989).

The same geological process which concentrates one mineral to form an economically viable reserve, may also create concentrations of other potentially exploitable minerals. For example fluorite, barite and calcite may be extracted (Table 1) from wastes in Mississippi Valley Type deposits (Harrison *et al.*, 2001). Such deposits in Derbyshire and the Northern Pennines in England (Dunham, 1948, 1974; Ford, 1976) were exploited for lead and zinc for hundreds of years, and especially in the 19th and early 20th Centuries. Through most of the 20th Century there were profitable operations exploiting fluorite and barite from the much dispersed waste piles. This, and primary extraction of fluorite and barite from veins and replacement deposits supplied the steel and artificial cryolite, and oil-well drilling industries respectively in the United Kingdom and Europe (Mason, 1978). Tailings from the sediment-hosted, stratiform copper-lead-zinc mine at Tynagh, Ireland were reprocessed for barite, also for use in drilling muds (Down and Stocks, 1977)

Fine grained waste remaining after separation of industrial minerals from clastic sedimentary deposits, like silica sand or sand and gravel operations, may contain concentrations of heavy minerals. Shaffer (1996) showed that processing of sand and gravel from glacial deposits in Indiana, United States, produced 15 to 20% fine grained waste that was discarded. These fines contain heavy mineral concentrations averaging about 2.5% by weight, and are made up of ilmenite, garnet, zircon, magnetite and traces of other economically important minerals,

Type of mineral operation	Nature of waste	Current practice for disposal	Potential markets	Notes
Sand and gravel	a. silt and/or clay fines (<63µm)	tailings pond	bricks (ceramic or adobe), tiles asphalt filler. armour stone	1 1 2
	b. oversize boulders	remain in quarry		
Crushed rock aggregate (excluding limestone and dolomite)	a. silt and/or clay fines (<63µm)	tailings pond	asphalt filler bituminous paints filler. pipe bedding bulk fill, filler in paints and plastics. bulk fill	2 3 5 3 5
	b. flaky particles	waste pile		
	c. Primary crusher scalplings	waste pile, or used for haulage roads		
Limestone and dolomite aggregates	a. Primary crusher scalplings	waste pile, or used for haulage roads	bulk fill agricultural lime agricultural lime, asphalt filler all weather sports surface	5 6 6 2 4
	b. Secondary scalplings and other fines	waste pile or tailings pond		
Limestone / marble dimension stone	a. Large blocks (> 1 m ³)	waste pile	marble tiles, terazzo tiles, armour stone, aggregate. as for large blocks. white mineral filler, small scale lime production	8 7 9 10
	b. Cut stone waste	waste pile		
Igneous and metamorphic rock dimension stone	a. Large blocks (1 m ³)	waste pile	armour stone aggregate aggregate	11 12
	b. Other waste except overburden	waste pile		
Slate	Substandard slaty rock and processing waste	waste pile	aggregate, mineral filler	13 14
	a. hydrosizer underflow b. spiral concentrator residue	waste pile waste pile		
Silica sand	a. clay/silt fines from washer and attrition scrubber	tailings pond	building sand building sand TiO ₂ and/or other heavy minerals bricks asphalt filler all weather sports surface	1 2 4

Type of mineral operation	Nature of waste	Current practice for disposal	Potential markets	Notes
Bentonite	Sub-standard or out-of-specification bentonite	waste pile or not extracted	pond / reservoir lining landfill site lining animal bedding	
Common clay for ceramic bricks and tiles	a. Substandard clay	waste pile or not extracted	adobe bricks	
	b. Mis-shaped bricks or tiles	waste pile	pond/reservoir/landfill lining recycle into clay body	15
Kaolin (sedimentary)	a. Sand from processing	waste pile or tailings pond	silica sand, feldspar, building sand	20
	b. silt/clay underflow from hydrocyclone	tailings pond	TiO ₂ and/or other heavy minerals fine quartz for ceramics mica	20 20 20
Kaolin (residual from granite)	a. sand from processing	waste pile	silica sand, feldspar, mica Nb/Ta minerals, cassiterite, zircon, other rare element minerals	16
	b. silt/clay underflow from hydrocyclones	tailings pond	kaolin, Na/Ta minerals, cassiterite, zircon, other rare element minerals	16
Pegmatites	In quarry waste from selective mining	remains in quarry	other pegmatite minerals (eg. quartz, mica, feldspar, rare lithophile metals (Li, Be etc)	17
Phosphate (sedimentary)	a. Limestone interburden	waste pile or backfilled	agricultural lime aggregate	6 12
	b. Crusher scalplings	waste pile	low grade direct application fertiliser	
	c. Clay/silt fines	tailings pond	low grade direct application fertiliser	
Phosphate (carbonatite)	a. sand-sized material from flotation plant	tailings pond	Rare lithophile metals (e.g. REE, Nb, Ba), fluorite	20
	b. clay/silt fines	tailings pond	low grade direct application fertiliser	

Type of mineral operation	Nature of waste	Current practice for disposal	Potential markets	Notes
Coal	a. Overburden and interburden clay b. Overburden and interburden sandstone c. Coarse residue from washing plant d. Fine residue from washing plant e. Burnt colliery spoil	backfilled or waste pile backfilled or waste pile waste pile tailings pond waste pile tailings dump	ceramic / refractory kaolin clay silica sand, building sand bulk fill secondary coal recovery clay for bricks and tiles unbound pavement aggregate	18
Gold in quartz veins	From heap leach pile	tailings dump	quartz powder for ceramics, glass, or low grade filler for paints, plastics	19
Epithermal gold	a. In quarry waste from selective mining b. from heap leach pile	remains in quarry tailings dump	alunite, kaolin for white cement low grade mineral filler	19
Alluvial gold	Gravel and sand from processing	remains on site	Sand and gravel	3
Base metal mining (pyrite absent, carbonate absent)	Fine residue from flotation	tailings pond	low grade mineral filler	16, 19
Base metal mining (pyrite absent, carbonate present)	Fine residue from flotation	tailings pond	agricultural lime	19
Base metal mining (pyrite present (e.g. Volcanogenic massive sulfides) Mississippi Valley-Type Pb/Zn	Fine residue from flotation	tailings pond	sulphuric acid	21
Talc (dolomite host)	Fine residue from gravity separation or flotation	tailings pond	Fluorite, barite or calcite	
Talc (ultrabasic host)	Fine residue from flotation	tailings pond	dolomite (mineral filler) agricultural lime	
Cement	a. See limestone and common clay b. waste clinker	tailings pond tailings pond	low grade magnesite, or low grade mineral filler agricultural lime	
Potash	Residue from flotation	waste pile	bulk fill recycle into cement kiln	6
Ti-mineral sands	Sand	tailings pond left on site as disturbed ground	halite for road de-icing zircon, garnet, monazite, silica sand	

Type of mineral operation	Nature of waste	Current practice for disposal	Potential markets	Notes
Gemstones in alluvial sands	a. Sand	left on site as disturbed ground	building sand	
	b. Gravel	left on site as disturbed ground		
Bauxite	Below grade bauxitic clay	waste pile	concreting aggregate ceramic or refractory clay red/yellow mineral pigment	
Iron ore	Below grade ore	waste pile	red mineral pigment secondary recovery of Fe ore	
Fluorite and barite veins	Residue from jigging / tabling / flotation	tailings pond	galena, calcite (mineral filler)	22
Uranium in sandstone	a. tailings from crushing	tailings pond	silica sand	

Note: Every extractive operation is unique. Thus, the waste will be unique in its nature and properties.

The list of potential markets takes no account of practical difficulties, or economic viability. In many extractive operations, where a major amount of waste is generated, it may be suitable for backfilling and/or re-instatement of land for agricultural or other purposes. In low-wage economy countries secondary recovery of the primary mineral product may be possible using hand sorting or other labour intensive separation or mineral selection procedures

1. Blending with more clay may be needed.
2. Processing needed to remove clay.
3. Grinding and classification needed.
4. If sufficient clay present it may make a suitable material for making a sports surface after compacting, rolling and levelling.
5. Will need to be capable of being compacted.
6. Requires further crushing.
7. Requires further crushing and screening. Most suitable uses are as exposed aggregate (marble chippings) or as filler stone (eg. for sewage), may require secondary blasting.
8. Will require crushing and screening to approx. 20-40mm.
9. Source material requires to be free from other quarry waste and overburden, and to be homogeneous and white or very pale coloured.
10. Requires a kiln nearby, but stone may dehydrate during burning.
11. Requires crushing and screening. May require secondary blasting for initial size reduction.
12. Requires crushing and screening.
13. Requires crushing and screening, but flakey particle shape is likely to restrict potential market.
14. Requires crushing and grinding. Only suitable for use where colour is not important.
15. Requires crushing and grinding.
16. Depends on original rock composition.
17. Assumes pegmatite is currently mined only a source of one mineral. other minerals can be selected by hand sorting.
18. Hand sorted.
19. Toxic metal levels may be high and restrict uses.
20. Will require much further processing.
21. Chemical plant nearby required.
22. Possibly other metalliferous minerals (eg. sphalerite).

primarily chromite, monazite and gold. Similarly, the heavy minerals in waste from processing silica sand for the float and container glass industries in the United Kingdom are dominated by Ti-rich minerals (ilmenite, rutile, 'leucoxene') and zircon, irrespective of the geological setting and age of the deposit. These minerals concentrate in the waste stream from spiral classifiers or hydrosizing.

PROBLEMS ASSOCIATED WITH MINE WASTE UTILIZATION

There is a large volume of literature on mine waste utilization, including papers in a series of biennial conference reports from 1968 to the early 1980s (see for example Cutler and Nicholson, 1970; Mindess and Richards, 1970; Heins and Geiger, 1970; Collings *et al.*, 1974; Collins, 1978; Collings, 1980; Rampacek, 1980). Many of these studies refer to the use of mine waste in manufacturing processes, for example in ceramics, refractories, concretes, bricks, and glass. Others describe use in road construction and as aggregates. Some of the technical studies are very detailed. Many show that mine waste can be used as a substitute for a primary mineral but products have inferior properties and often additional research is required to modify the properties of the waste or to overcome technical difficulties. Thus it is unlikely that a successful business could be developed using the mining waste.

Reprocessing some of the vast amount of accumulated material from slate mining in the United Kingdom (400 to 500 million tonnes (Whitbread *et al.*, 1991)), especially that from North Wales, has been partly successful. A good market of 40 000 tonnes per year has been developed for pulverized slate waste granule and powder products (Richards, Moorehead & Laing Ltd., 1995). Technical studies on the Welsh slate waste show that it can be used to make an expanded lightweight aggregate, be fused with additives for ceramic flooring, autoclaved with lime to make bricks, as a raw material for aluminum metal, and be melted, spun and woven as fibrous insulation material (for example, Gutt *et al.*, 1974; Crockett, 1975; Anon, 1989; Harries-Rees, 1991). Similar studies have been undertaken on slate waste from North America (for example Vermont slate waste; Mackenzie and Horiuchi, 1980). Processing requires a major investment of capital, even though the cost of the raw material is very low. Manufacturers would normally seek the most suitable minerals for their process, rather than chose something which is inferior, solely because it is a waste material. For example, slate waste is not the ideal material to make an expanded lightweight aggregate because its bloating capacity is far lower than that of many clays, and it usually requires a higher temperature for reaction. If aluminum metal could be extracted in large quantities economically from any aluminosilicate

mineral, it is likely to have been achieved several centuries ago. A manufacturing plant was established in the 1970s to produce an expanded lightweight aggregate from slate waste in Wales, but it closed down after a short period of time. None of the uses for slate waste which involve a costly manufacturing process have proved to be commercially viable (Richards, Moorehead & Laing Ltd, 1995).

Slate waste is a source of bulk fill for the construction of highway embankments and other similar areas where it is available locally, and a road sub-base product (Type 1) can be made and successfully marketed (Whitbread *et al.*, 1991). There are other examples of successful use of locally available mine waste in the construction of highways (Pettibone and Kealey, 1972; Emery and Kim, 1974) and as crushed rock aggregates and sand (Anon, 2000). The waste's convenient location and the very low cost involved in mining the waste pile is likely to be a major consideration in its use.

It may not be possible to use mining waste if it is likely to create a potential or actual environmental hazard. This could apply to the use of waste from base metal mining, where trace elements, such as cadmium or selenium, might be present and potentially leachable, for example, when the waste is used in bulk fill applications. Studies have shown that some micas in the waste from kaolin extraction in South-west England contain up to 2.5% lithium, and that beneficiation could produce a mica concentrate assaying about 2% Li. Unfortunately, Li-rich micas (zinnwaldite and lepidolite) contain significant fluorine in their structure, which precludes using the mineral as a substitute for petalite or spodumene in ceramics or glass because the fluorine would be emitted on melting. However, the mica could find use as a mineral filler. Lithium carbonate from brines is the major source of elemental lithium.

For a time in the middle of the 20th Century mine waste containing sulfides from tin, copper and other base metal mining in South-west England was used locally as the coarse and fine aggregate in the manufacture of concrete building blocks. In some towns a significant number of domestic houses were built with these blocks. A careful regime of maintenance to prevent any ingress of water into the walls of these houses can prevent oxidation of the sulfides that leads to decay of the blocks and resulting structural weakness; but, these houses (referred to as having 'mundic' from a name given by miners to sulfide-bearing waste) are not acceptable to banks and other mortgage lenders as security for loans, so their real estate value is very low compared with other houses in the same area. Once decay is initiated, it permeates through the wall; ultimately the house may have to be demolished. Although present understanding of cement-aggregate reactions would not allow the use of such material in concrete products, this quasi-environmental and socio-economic problem illustrates the importance of fully characterizing the waste and assessing all the

implications before it is put to use. This should involve an element of technical as well as financial risk assessment.

MARKET SCENARIOS FOR INDUSTRIAL MINERAL PRODUCTS FROM MINING WASTE

As with all industrial minerals, a product made from mining waste is only of value if there is a market. The consumer will compare the quality of the potential product from waste with that of an existing industrial mineral extracted from a primary source. Without a favorable comparison the waste is unlikely to find a market. Other technical, economic or legislative factors may be involved before the consumer can be persuaded to accept the product made from waste materials, and these factors may positively or negatively distort the market. However, waste characteristics are often highly variable, especially on an existing heap that has accumulated over a large number of years. Processing of the waste may require a large outlay of capital with associated risk before a product can be made. Markets for industrial minerals are constantly changing, and industrial minerals from new sources become available continually to replace those from existing sources. Advancing technology also results in changes in patterns of use of raw materials. Thus, any industrial mineral product made from mining waste must be considered in the same way as a new source of a primary industrial mineral would be considered.

In our view there are three scenarios where an industrial mineral product made from mining waste may be marketed successfully. These are:

I. Produce a bulk product for a local market that is made from the waste with minimal or no processing.

II. Extract an industrial mineral product that can provide either a cost-effective alternative local source of a mineral, or be traded nationally or internationally.

III.. Extract a high value, rare mineral that is in high demand internationally from the waste.

In each scenario processing of the waste is minimal, consistent with the value of the mineral product. That is, if the mineral is of high value, some extended processing can be undertaken; but if the value is low, only size separation by screening would be possible. Note that product manufacture, other than mineral grain separation if it is necessary, is not part of any of these scenarios. The number of situations for each scenario where a successful market for an industrial mineral product made from mining waste can be established may be few. Producing a bulk product for a local market is the most likely scenario to succeed. More waste is likely to be consumed, and the low unit value of the product is compatible with a customer's perception that it is being made from waste. The geographical extent of the market will be limited by

the cost of transport, but could be enlarged if favorable tax regimes or other inducements encouraged the use of the waste in preference to a mineral from a primary source. Scenario II is likely to be successful only where a high concentration of the industrial mineral is found in the waste. Examples of each scenario are discussed below. In several cases, the free market situation is distorted by other factors.

a. Examples of Scenario I, producing a bulk product.

1. *Clay waste.* The waste from several mineral operations listed in Table 1 is rich in clay, which will be plastic to varying degrees. Successful utilization of such material would involve selling it to an existing brick or tile manufacturer, who would blend or otherwise incorporate it into the clay body. Today, major brick manufacturers in the United Kingdom are actively using mineral wastes for blending so that they can achieve a wide range of products and make more efficient use of their primary raw material sources (Smith, 2002). However, establishing a brick manufacturing plant solely for the purpose of consuming waste does not form part of this scenario because the capital cost is too high.

2. *Armour stone.* Production of dimension stone creates a large amount of waste. The waste varies in size, but much is often in 100kg to 10 tonne irregular blocks. It is generally unsuitable for primary use because of its shape, the presence of irregularities in color or texture, or because it has planes of weakness. A small amount may be used as a secondary source of dimension stone, for dressed stone masonry or walling stone, or for artisanal sculptures and art work, where irregularities in color or texture could be of benefit for the latter applications. When the quarry is suitably located, dimension stone waste can find a market as armour stone or rip-rap, or in the case of blocks that are 200mm maximum size (Smith, 1999, p.261) for use in gabion cages.

The overall market for armour stone in United Kingdom is in excess of 1.5 million tonnes per year (Rees-Jones and Storhaug, 1998), mostly for marine uses. With sea level rising, there is an increasing need to protect high value coastal properties and amenities. Consequently, the demand for armour stone worldwide is increasing. Since 1991, the region around the coastal town of Larvik in Norway has become a major source of armour stone with sizes ranging from 20 kilograms to 20 tonnes (Rees-Jones and Storhaug, 1998). This rock used is waste from the major dimension stone operations in that area. Market penetration has included providing material for coastal defenses in the United Kingdom. Woodstock-Deering (2001) report that 2 million tonnes have been purchased since 1990. One advantage of using waste dimension stone, which is extracted principally by means of drilling and diamond cutting, is the absence of

incipient fractures, which would likely be present in rock obtained through blasting.

Waste produced in dimension stone quarries may also be suitable as crushed stone aggregate, and in special circumstances, as raw material for a higher value industrial mineral. An example of the latter is the successful use of waste Carrara Marble from Italy as a source of white marble for high brightness white pigment manufacture. In the United Kingdom, the Mineral Planning (Permitting) Authorities (Smith, 1999, p.133) generally do not allow dimension stone waste to be used as a source of aggregates. The large volume of traffic associated with aggregate production compared with building stone extraction is normally deemed unacceptable. Thus, legislation, driven by environmental impact, can sometimes prevent the use of mining waste!

3. *Aggregates from china clay (kaolin) extraction in Cornwall, south-west England.* China clay extracted from kaolinized granite is the United Kingdom's largest mineral export. It is a major world source of kaolin, with around 2.4 million tonnes annual production. For every million tonnes of china clay, two million tonnes of rock, six million tonnes of sand and gravel sized material, and one million tonnes of feldspar, mica and quartz (mixed fines) and overburden are produced (Kessell, 2001). Around 20 to 24 million tonnes of waste are produced annually, and there is a stockpile of 450 to 600 million tonnes (Kessell, 2001; see also Whitbread *et al.*, 1991). The waste rock is mainly unkaolinized granite, tourmalinized granite, greisenized granite, porphyries, and tourmaline and quartz-rich vein material. Some waste also consists of hydrothermal breccia containing granite, porphyry, metasediments and a tourmaline rich matrix. No sulfides are present. The sand is mainly quartz, with some unkaolinized feldspar, and minor mica and tourmaline. There are some technical constraints in using the waste in concrete. These include poor workability and the need to use more cement to achieve equivalent strengths compared with some primary aggregates (Whitbread *et al.*, 1991).

China clay waste supplies 45% of the three million tonne local aggregate market in Cornwall (Kessell, 2001), the china clay area being situated near the middle of this rural county. The aggregates have acceptable properties for most applications. Further markets for this waste exist but only outside south-west England. Although the china clay areas are not located at the coast, they are only a 10 to 15 kilometers from the port of Par, where much of the china clay is exported. Since 1999, the considerable demand for aggregates in the area surrounding London in southern and south-eastern England and in Germany) has resulted in the successful marketing of aggregates made from china clay waste to these regions. The waste is transported by ship (Kessell, 2001). The United Kingdom Government imposed a tax of £1.60 per tonne on primary aggregate production from 1 April, 2002 that will enable aggregates from china clay waste, which is not subject to

the tax, to compete even more favorably with crushed rocks and sand and gravel from primary sources closer to southern and south-eastern England. It is predicted (Kessell, 2001) that the market for aggregates transported by ship from Par will extend to as much as 440 nautical miles (i.e. towns both sides of the whole of the English Channel and southern North Sea). The target is to achieve sales of five million tonnes per annum within a few years. The primary aggregate tax, which represents 35% of the transport costs by sea to the River Thames estuary (London), should allow a thriving market for aggregates from china clay waste to develop.

b. Examples of Scenario II, producing an industrial mineral product for a local or international market.

1. *Fluorite and barite from base metal mining.* The successful extraction of fluorite and barite in waste from former lead-zinc mining areas in the United Kingdom and Ireland has already been discussed. Waste from other metal mining operations in the United Kingdom also contains a significant amount of fluorite. For example, the large waste tailings lagoon at Wheal Jane, Cornwall, south-west England, was created from the former tin mining nearby. It contains up to 2.5% fluorite as liberated particles 20 to 80 microns in size. However, the current fluorite market is dominated by extraction from primary sources in China (2.25 million tonnes in 1999; Stockwell, 2001), with much less production from Mexico (561 265 tonnes in 1999), South Africa (217 540 tonnes in 1999), Mongolia (153 693 tonnes in 1999) and elsewhere. In each of these countries production costs are low compared with those in Europe and North America, which has resulted in a significant reduction in fluorite production from areas in recent years (Burger, 1991). Fluorite prices (chemical grade or acidspar) are relatively low at about US\$140 per tonne (Industrial Minerals, July, 2001) delivered from China to ports in Europe (Rotterdam) and to the United States Gulf ports. It is unlikely, therefore, that fluorite extracted from any mining waste, including that in Cornwall, could successfully compete internationally; but, if a high grade fluorite concentrate with low arsenic levels could be produced with only minimal processing, and there is a consumer located nearby, separation of a product might be feasible.

2. *Feldspar and mica from pegmatites.* Although pegmatites are an important source of feldspar and mica in their own right, these minerals are often ignored when metal ores, such as tin and tantalum, and lithium minerals are produced from this source. The feldspar and mica waste accumulates as sand and silt sized particles from gravity separation processes. The individual minerals are already liberated, and a further processing stage, such as air or froth flotation could create a product. Quartz may

also be present, and available for concentration as a high purity silica product. Sulfide minerals, which would require a separate, additional processing stage, do not usually occur in significant amounts in most pegmatites.

An example is waste from former mining of pegmatite for tin in Uis, Namibia, (Richards, 1986). About 75 million tonnes of waste, which consists of quartz, feldspar and mica with very minor amounts of other minerals, accumulated during mining of the low grade primary ore, which had a mill-feed of 1250 ppm Sn (Richards, 1986). Iron oxide bearing minerals are present but in very low amounts. It is a significant potential resource of feldspar and mica, and possibly of a mixed feldspar-quartz product (Scott and Power, 2001). Processing using flotation without further grinding yields a feldspar product, and a mica concentrate can be produced by air classification (Harrison et al., 2002a; 2002b). World feldspar production is approximately nine million tonnes per annum, with major amounts from industrialized nations, such as the United States, Japan, Italy, France, Germany, and Spain (Stockwell, 2001). Other industrialized nations, such as the United Kingdom, have no commercial feldspar resources. International trade is significant; nearly one third of world production is exported from the country of origin. Mica production is similarly dispersed through several countries and there are significant exports. In 2001, ceramic grade feldspar was US\$150 per tonne FOB Durban (Industrial Minerals, July, 2001) and dry ground mica, 20-60 mesh, was US\$325-355 from the same port (Industrial Minerals, July, 2001). Uis is 200 km from the nearest port at Walvis Bay, so transportation costs to the port would be a major expense in supplying feldspar and mica. There is scope for further investigation of the economics of production of feldspar and mica from this waste material. Governments of developing countries such as Namibia are keen to develop further their mining activities and are willing provide favorable taxation arrangements. They are also becoming aware of the environmental damage created by past mining activities, especially in areas where there is an emerging tourist interest. Thus, they might provide additional support for initiatives to recover minerals from waste. Quartz is unlikely to be a potential product as a source of silica for the glass industry from such a remote location because its unit value is too low, and there are no glass manufacturer nearby.

c. Examples of Scenario III, extraction of a high value, rare mineral.

1. *Rare minerals from pegmatites.* This scenario is a potential way of providing a small revenue for a mining company or other organization responsible for the management, treatment or removal of a waste pile. It might also support an indigenous population remaining after a primary mining activity has ceased. This type of processing does not reduce a waste pile significantly in

volume. Pegmatites often contain rare minerals and crystal forms worthy of extraction as mineral specimens from large sized mining waste. Gemstones like tourmaline and beryl may also be present. For example, colorful minerals found in pegmatites in Brazil are extracted in areas of former mining. These minerals are used in the production of ornaments, jewelry and other artifacts (Rao, 2002), and are marketed internationally.

b. *Tantalum minerals.* Tantalum continues to be in high demand for use in capacitors in mobile telephones and other electronic consumer products. The price in 2001 was very high, somewhere between US\$200 and 300 per kilogram of ore concentrate, although it has subsequently reduced to its pre-2000 levels of around US\$30-50 per kilogram. Highly evolved alkali-rich granites and associated pegmatites provide a primary source of tantalum (Cerny et al., 1986; Cuney et al., 1992; Schwartz, 1992). Tantalum is also present, along with niobium, titanium and tin, in the silt-sized tailings from china clay extractive operations in the most evolved topaz granite in the St. Austell region of Cornwall, England. Columbite-tantalite, Nb-Ta rutile, and cassiterite that are accessory minerals in the granite become concentrated into one size fraction during processing of the china clay (Scott et al., 1998). A tantalum enriched concentrate can be recovered by gravity separation from the fine grained waste.

Other rare metals in mining waste that might be in demand in the future are rare earth elements concentrated in phosphate wastes from carbonatites. Waste from other mining activities where rocks of a highly fractionated nature, such as nepheline syenites, are involved, and waste from processing of ore bodies created through extreme chemical weathering, such as secondary oxide ores and bauxites, may also contain increased concentrations of uncommon elements and minerals.

CONCLUSIONS

Waste from many mining operations for both metal ores and industrial minerals contain other industrial minerals that might be economically recovered.. Geologically similar primary mineral extractive operations contain similar waste. Some waste piles contain large quantities of industrial minerals and should be considered as a potential resource. Detailed technical studies of the economic potential of many mining wastes, usually find that the market is poorly defined and/or the waste is not the most suitable raw material for a given manufacturing process. However, there are good examples of successful use of mining wastes, especially for bulk products, and there are other scenarios where industrial mineral products and rare metal ore concentrates made from mining waste have found markets. Successful reprocessing of waste from past mining activities can provide revenue to make

environmental improvements in an area, to give employment to the nearby population, and can provide further income to a mining company.

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WASTE SLAG RECYCLING IN THE NEW MILLENNIUM

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ABSTRACT

The annual worldwide production of slag is estimated at 300 million tonnes. Almost 80% is produced by the iron and steel industry and the remainder by nickel, copper, lead and zinc producers. In the past, it was standard practice to “dump” slags without further treatment. The need to make use of the blast furnace slag was first recognized by iron producers in the 1950s, and subsequent research efforts paved the way for several additional uses, including its use as “concrete aggregate”. It was primarily due to these developments that blast furnace slag increasingly found its way to the market instead of a dump. However, producers of non-ferrous slag have not followed the example set by the iron producers and, as a result, the stockpiles of non-ferrous slags keep growing.

This study aims to develop uses for non-ferrous slag by producing industrial products from this waste material. A review of slag chemistry and processing options indicates that it has several potential applications, such as clinker ingredient, asphalt concrete additive, roofing granules, cemented mine backfill, and binder for base stabilization. Most of the proposed uses take advantage of the latent pozzolanic properties of the non-ferrous slag. The authors conclude that environmental considerations and economic factors favor processing of non-ferrous slag rather than dumping it. Environmental pressure will continue to increase in the new millennium and force industry to find ways and means of depleting ever-growing stockpiles of non-ferrous slag.

INTRODUCTION

During the early 1900s, it was standard practice to dump slag and pay no further attention to it (McCarl *et al.*, 1985). In most instances, the molten slag was disposed of either by pouring the molten material in the specified disposal area for cooling; or by rapidly cooling the slag by means of high-pressure water jets to form granules.

As a result, enormous stockpiles of waste material, which occupied premium land adjacent to smelter plants, developed. The slag produced was commonly classified as either ferrous slag, or non-ferrous slag.

The ferrous slag, which consists of Blast Furnace Slag (BFS) and Steel Slag (SS), was generated during the production of iron and steel respectively. Non-ferrous slag is a byproduct produced during pyro-metallurgical extraction of copper, nickel, tin, lead and zinc metals from ores (Fine and Gaskell, 1984).

Historically, the rate of ferrous slag generation has exceeded that of non-ferrous slag by a factor of 4 to 1 (Douglas and Hemmings, 1987). The magnitude of the stockpiles of ferrous slag may have served as a driving force to find alternate uses of this material, partly because of the problem of storing it.

Environmental considerations do not favor stockpiling slag; consequently, governments are applying

pressure to both the ferrous and non-ferrous slag producers to find ways of recycling slag.

UTILIZATION OF FERROUS SLAG-PAST AND PRESENT

In the early 1950s, BFS was used only as railway ballast and road base material; and uses for SS did not emerge until 1965, (Kalyoncu, 1997). However, during the last few decades, iron and steel producers have attempted to develop a range of products that would deplete waste slag stockpiles. To meet this goal it was necessary to modify specific physical properties of slag, such as density, porosity, hardness and crystallization. This was achieved by controlling the cooling rate of the molten slag. This approach enabled development of various slag processing alternatives and new products, such as expanded slag, mineral wool, roofing granules and “Ground Granulated Blast Furnace Slag” (GGBFS) (Solomon, 1993).

In the early 1980s, ASTM standards were developed primarily to promote acceptance of BFS as a cement and concrete additive (Werner *et al.*, 1994). As a consequence, not only did the demand for fresh slag increase it also found its way to the market instead of to a dump, but companies like Lafarge began efforts to enter this segment of the market, (Lafarge, 2000).

Although the construction sector remains a major consumer of BFS, its applications in other areas is gaining wider acceptance. Table 1 lists known applications for BFS and shows a similar pattern of usage for SS. The chemical compositions of BFS and SS are similar to that of Portland cement (Table 2) implying a possible

application as “low quality clinker”. However, its use for this application is limited because mineralogical components of steel slag are primarily complex solid solutions, and their effect on hydraulic properties is not fully understood (Ionouscu, 1999).

TABLE 1. MARKETS FOR BLAST FURNACE SLAG AND STEEL SLAG SOLD IN USA, (KALYONCU, 2000).

Use	Blast furnace slag		Steel slag	
	Quantity Thousand tonnes	Value* Thousand US\$	Quantity Thousand tonnes	Value* Thousand US\$
Asphaltic concrete	1,790	11,300	1,110	5,620
Concrete aggregate	1,260	9,090		
Concrete products	198	1,330		
Fill	1,540	8,110	1,390	3,400
Glass manufacture	W	W		
Mineral wool	483	3,750		
Railroad ballast	83	425	171	530
Road base	4,140	22,500	2,450	8,330
Roofing and shingles	49	586		
Soil conditioning	W	W	1,060	5,060
TOTAL	10,300	63,100	6,180	22,900

Note: W withheld to avoid disclosing propriety data and * Value based on selling price at plant in 1998.

TABLE 2. TYPICAL COMPOSITION OF FERROUS SLAGS AND THE PORTLAND CEMENT (IONOUSCU, 1999)

Chemical species	Blast Furnace slag (BFS)	Steel slag (SS)	Portland cement
% SiO ₂	33 – 39	20 – 25	20 – 22
% Al ₂ O ₃	7 – 14	8 – 24	4 – 6
% Fe ₂ O ₃	< 1	8 – 18	2 – 4
% CaO	32 – 44	30 – 40	60 – 65
% MgO	6 – 20	8 – 10	1 - 4
Other oxides	< 5	< 5	< 2

TABLE 3. COMPOSITIONS OF INDUSTRIAL WASTE PRODUCTS (CHASKAR, 1992, ONER 2000 AND SINGH AND GARG, 2000).

Major Elements (%)	Non-ferrous slag	Blast furnace slag	Fly ash
SiO ₂	18 – 42	32 – 39	45 – 50
Al ₂ O ₃	3 – 10	7 – 14	16 – 25
Fe ₂ O ₃	4 – 5	< 2	7 – 25
FeO	40 – 50	-	-
CaO	2 – 20	32 - 44	5 – 8
MgO	2 – 3	6 – 20	1 – 5

USES OF NON-FERROUS SLAG

The major difference between the ferrous and non-ferrous slags is the proportion of iron oxide species. Table 3 shows the composition of fly ash, which is another waste product that is now accepted as a supplementary additive in cement and concrete. There is no large-scale usage of the non-ferrous slag at this time; however, there are many potential applications of this waste material.

SLAG RECYCLING IN THE NEW MILLENNIUM

In the new millennium, many governments are establishing legislation to increase the acceptance of recycled products. This is prompting industries to attempt to find suitable applications for many products hitherto considered as waste. For example, in the construction industry three former waste products, BFS, fly ash and silica fume, have been used successfully as additives in many products. In fact consumption has grown consistently over the past decade (Mehta, 1994), which is a testimony of the success of efforts to recycle these materials.

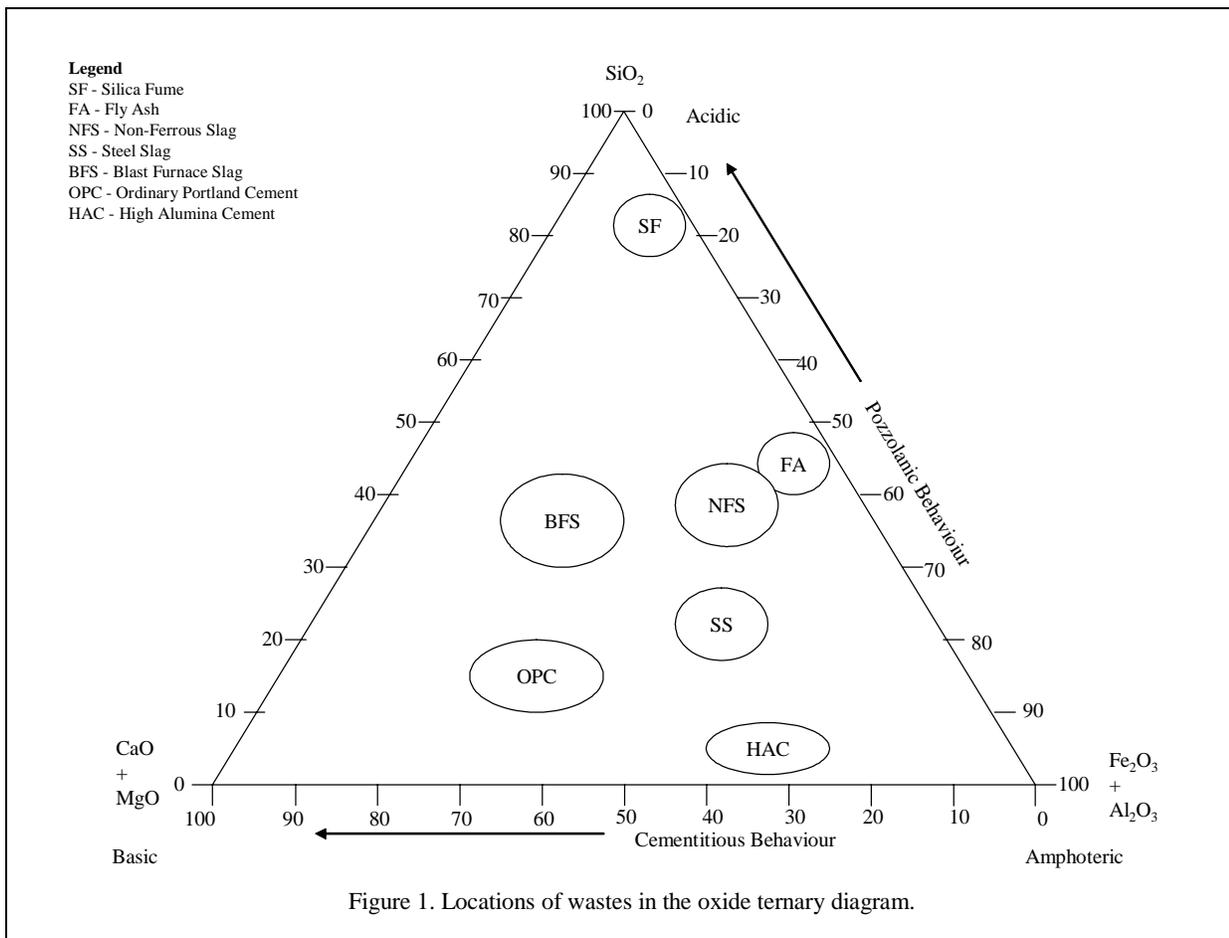
Published data indicates an annual worldwide production of ferrous slags in the range of 250 to 280 million tonnes, of which approximately 60% is processed for consumption (Kalyoncu, 2000). In comparison, of the estimated 50 million tonnes of non-ferrous slag produced, only about 5% is consumed. In Canada more than 4

million tonnes of non-ferrous slag is generated annually, and less than 3% is processed (Ripley *et al.*, 1978). These statistics suggest that there is a need to re-examine and re-evaluate policies relating to stockpiling nonferrous slag. In the new millennium, recycling of slag waste dumps will become a necessity due to environmental and ecological concerns arising from potential leaching of heavy metals entrained in the slag (Wilson, 1995; Koran *et al.*, 1998); the need to conserve energy and resources; and because it is a source of untapped revenue.

CURRENT AND POTENTIAL APPLICATIONS OF NON-FERROUS SLAG

Today, non-ferrous slag is under-utilized. It is used mainly as railway ballast, as fill material and as abrasive media. The main reasons cited for this are the remote locations of slag producing smelters with respect to potential markets; variations in the chemical compositions of slags that are caused by processing parameters, which in turn are dictated by the sources of various raw materials; and wide variations in the physical properties of the solidified slag, which are dependent on its rate of cooling (Emery, 1982, Ripley *et al.*, 1978).

Thus it should be possible to improved utilization of non-ferrous slag by producing a more consistent and uniform product. This could be achieved by re-processing and by keeping transportation costs within an acceptable



range. Furthermore, research should be carried out to seek new ways of using the slag, as was done by producers of blast furnace slag and fly ash. The chemical compositions of these materials are comparable (Table 3 and Figure 1), which should allow non-ferrous slag to be used in similar applications.

Re-processing options

Due to its high silica content (Figure 1), non-ferrous slag may possess latent pozzolanic properties and serve as an alternative to fly ash; and pozzolanic and cementitious properties could be imparted to the slag by adding silica, lime and magnesium oxide.

Both these factors make a strong case for research into reprocessing of slag to produce products similar to those created from BFS, SS and fly-ash.

For the past two decades, non-ferrous slags have been reprocessed to recover entrained metallic values (Snelgrove and Taylor, 1981, Hastie *et al.*, 1984, Floyd and Conochie, 1984). This operation, commonly termed as “slag cleaning”, often generated even more slag due to

the addition of flux and other ingredients during reprocessing.

Proposed reprocessing options involve either oxidation or reduction to alter the chemistry of the slag to create a desirable composition. Such high temperature reprocessing could either precede or follow the slag cleaning operation, and would allow production of a range of non-hazardous products for existing markets. An added benefit of such a processing option is that products could be manufactured to meet specifications set by end users.

Potential uses of non-ferrous slag

Potential uses for products that may be developed by oxidative or reductive reprocessing of nonferrous slag include: (1) clinker ingredient; (2) asphalt concrete additive; (3) cemented mine backfill; (4) lightweight aggregate; (5) slag wool; (6) roofing granules; and (7) slag cement. The potential benefit of such treatment is partial cost recovery from the recovery and sale of base metals, and sale of the reprocessed slag. Since blast furnace slag markets have already been successfully

developed, development of non-ferrous slag products should have fewer obstacles.

SUMMARY

An estimated 200 to 220 million tonnes of non-ferrous slag has accumulated in the vicinity of smelters in Canada, and the biggest stockpile is in the Sudbury area where INCO Ltd has accumulated in excess of 110 million tonnes of nickel slag (Udd and Annor, 1993). There is growing concern that smelter slag may not be as inert as originally believed (Wilson, 1995). For this reason it is necessary to test different slag compositions and ascertain their leaching characteristics. Current regulatory leach protocols are based on a 95% municipal and 5% industrial co-disposal mismanagement scenario which does not reflect disposal practices for non-ferrous smelters (Koren *et al.*, 1998). Therefore, the issue of slag reprocessing is overdue and should be addressed.

Globally, there is an increasing emphasis on producing pozzolanic cements, to reduce unit energy costs and to produce concrete with improved alkali-reactive-aggregate resistance (Dodson, 1990; Malhotra, 1987). Non-ferrous slags could play an important role in this area as a slag cement ingredient. Furthermore, as a clinker additive, it could help reduce emissions of green house gases by reducing the need for lime calcining (Mehta, 1994). In the new millennium, the prospects of converting non-ferrous slag from an industrial waste into either aggregate or other products seems extremely promising.

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OPEN PIT SURGICAL MINING OF BERTRANDITE ORES AT THE WORLD'S LARGEST BERYLLIUM DEPOSIT!

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INTRODUCTION

Exploration for a domestic economic beryllium resource in Utah began in 1960 and resulted in discovery of a commercial natural mineral identified as "bertrandite" ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$). The first open-pit mine in the Topaz-Spor Mountain area was designed and developed to exploit this resource in 1968. This deposit, which is now the largest commercial deposit of beryllium known in the world, contains enough proven ore reserves to sustain the operation for the next 60 years.

The construction of the Delta, Utah mill started in 1968 and production began in September 1969. Previously, the beryllium industry derived most of its beryllium feed supply from imported high grade (3.6 to 4.7% Be) beryl ore. Beryl supply varied greatly in both availability and price, which restricted the use of beryllium in the alloying industry. The mining of the large, low grade bertrandite (less than 0.4% Be) deposits of Utah stabilized the prices and supply of beryllium oxide and metal.

Work conducted at Elmore during the sixties developed an acceptable process for extraction of the bertrandite. The Company received the J. C. valor award in the category of chemical processing for the period 1968 to 1970 in recognition of the success of the process developed. In 1968 the company decided to use this process as the basis for design and installation of a mill at Delta. Since operations were initiated in September 1969, most of Brush Wellman's beryllium feed supply has been from Delta.

MINE

The techniques used to mine beryllium-bearing ore from the company's properties in western Utah are unique.

Mineralized and barren tuffs are virtually indistinguishable. Bertrandite is colourless and crystals that comprise the ore are too small to be seen with the naked eye. Associated minerals, Fluorite and manganese oxides are commonly associated with bertrandite. These minerals help to focus exploration, however, their presence does not assure significant beryllium concentrations.

To locate beryllium mineralization and determine its abundance and grade, the mining division of the company first carries out geological and geochemical studies on an area. This work is followed by an extensive exploration and development drilling to delineate the deposit and to prove the ore reserves.

EXPLORATORY DRILLING/SEARCH FOR ORE

Exploration and development holes are drilled on a grid with 100 feet (30.5 metre) spacing. Data collected provides information on the size of the ore body, its thickness and grade. Information on faults and related alteration is also collected.

A typical drill log is shown in table 1. From top to bottom, it consists of alluvium, rhyolite, altered rhyolite, tuff, and limestone-dolomite.

TABLE 1: TYPICAL GEOLOGIC CROSS SECTION IN THE MINE AREA

Alluvium	Sand and gravel—Lake Bonneville deposits
Rhyolite	An igneous extrusive rock having essentially the same chemical composition as granite, tightly bound and hard
Altered Rhyolite	Partially decomposed, rhyolite, altered by mineralizing solution
Tuff	Volcanic ash, a host rock with high porosity (that can be impregnated by mineralizing solution) the tuff is in both a welded and non-welded state depending on depositional environment
Dolomitic-Limestone	A dense sedimentary calcareous rock that underlies the mineralized tuff

The tuff, which is sandwiched between the low-permeability rhyolite and dolomitic-limestone acts as an aquifer, provides access for mineralized hydrothermal solutions and acts as a host rock to the beryllium mineralization.

DESIGNING AN OPEN-PIT

Once an ore body has been delineated, the optimum pit design is selected.

Facts considered in pit design include:

- Tonnes and metallurgical type of ore to be recovered,
- Volume of rock to be removed,
- The weighted average grade of the ore and its spatial distribution.

Once the final pit design is chosen, in-house work begins with preparation of maps, awarding of an overburden removal contract, and the mining may begin.

OPERATIONAL PARAMETERS

Present employment at the Utah Operation totals approximately 100. Maintaining the health, safety and environment of our employees has been a top priority for the past thirty-one years of operation.

WOLLASTONITE SKARN GENESIS IN THE GRENVILLIAN CENTRAL METASEDIMENTARY BELT, SE ONTARIO, CANADA

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ABSTRACT

Potentially economic wollastonite skarns are widespread in the Central Metasedimentary belt of southeastern Ontario. Their genesis is evaluated through a comparative study of the Platinova-Cominco skarn (*ca.* 4 million tonnes grading 35% wollastonite), hosted by greenschist facies marble in the Elzevir terrane; the Olden skarn (*ca.* 2.8 million tonnes; 35%) in amphibolite facies marbles of the Sharbot Lake domain; and the St. Lawrence skarn (*ca.* 9 million tonnes; 40%) in granulite facies strata of the Frontenac terrane. Calcitic marble, locally containing impurities, is the protolith for all of the wollastonite skarns, although dolomitic marble may have been present at St. Lawrence. Each skarn is contiguous with an intrusive complex ranging from gabbro to granite in composition, and displaying megascopic fabrics indicative of magma co-mingling and mixing. The plutons are, however, of different ages and exhibit different geochemical characteristics.

In each skarn, wollastonite is associated with varying proportions of diopside-hedenbergite and grossular-andradite. Skarn development is ascribed to the incursion of magmatogene, silica-rich, CO₂-poor (XCO₂ between 0.1 and 0.3) fluids rather than to regional metamorphism. The fluids were emplaced at temperatures between 500 and 650°C and at pressures ranging from 200 MPa at Platinova-Cominco to 400 MPa at Olden. The Olden skarn has been dated at 1074 ± 5 Ma (⁴⁰Ar/³⁹Ar, phlogopite). U-Pb on titanite and ⁴⁰Ar/³⁹Ar on amphibole separates from the St. Lawrence skarn yielded 1147 ± *ca.* 8 Ma and 1159 Ma ± 6 Ma dates, respectively.

INTRODUCTION

Despite their considerable and increasing economic importance, industrial mineral deposits have traditionally been neglected by economic geologists, and are only rarely the subject of the detailed analysis widely lavished on metallic mineralization. However, during the last decade, research on several wollastonite deposits has contributed to clarification of the factors that lead to the formation of large, high-grade wollastonite bodies. Examples of such studies are given by Gerdes and Valley, 1994; Dipple and Gerdes, 1998; Simandl *et al.*, 1999; and Grammatikopoulos *et al.*, 2003. Progress was also made in documenting the relationships between wollastonite-rich rocks and their hosts (Simandl, 1987 and 1989; Simandl *et al.*, 1990).

Eastern North America has become the centre of world wollastonite production, mainly from the Grenville Province. Wollastonite is a critical mineral in the ceramics, plastics and paint industries. It is often viewed as being abundant and readily generated in impure limestone through the metamorphic reaction of calcite and quartz or other siliceous constituents. However, a “closed system”

does not permit formation of the large, essentially monomineralic wollastonite deposits in limestone or marble host-rocks that contain few siliceous impurities. An “open system” is required in such geological settings (Simandl, 1992). The formation of these high-grade wollastonite skarns is more likely due to infiltration metasomatism (Korzhinskii, 1970), during which invading fluids generate a series of specific reactions that destroy the mineral or mineral assemblage of the host rock.

PROPERTIES, APPLICATIONS, AND OCCURRENCE OF WOLLASTONITE

Wollastonite is a naturally-occurring calcium silicate of the pyroxene group (Deer *et al.*, 1992). It is hydrophilic, has low water content and oil absorption, and is largely chemically inert. Wollastonite has a theoretical composition of 48.3 wt. % CaO and 51.7 wt. % SiO₂, but most occurrences have impurities such as iron or manganese that replace calcium.

The mineral commonly occurs as coarse bladed masses, but seldom shows good crystal form. Normally it is brilliant white, light green, or beige on

a fresh surface, with acicular (needle-like) or fibrous habit; both properties are important in its commercial uses. In commercial products, the length-to-width ratio of the grains is commonly 5:1 to 8:1, but may be as high as 20:1 (Westphal *et al.*, 2002).

A large number wollastonite projects have been evaluated during the last 10 years; only a few have been brought into production. In the spring of 1998, the massive new NYCO operation at Hermosillo, Mexico came on stream, increasing world capacity by about 30%. This new operation supplies products for the ceramic, coatings, cement, metallurgical and board industries, whose specifications are less rigorous than those of the plastic industry. Other potential producers in regions as diverse as Canada, the United States, Morocco, Greece, Spain, Turkey, Russia, Cuba and New Zealand have either been abandoned, shelved or are “barely simmering on the back burner” (Bolger, 1998). The reasons vary but the major concern is that the wollastonite market has not mushroomed as was predicted. Project start-up costs are high, and it takes time and perseverance to

have new products accepted by consumers, especially at the high end of the market. Several Canadian wollastonite projects that belongs to this category include the St. Lawrence skarn in Ontario (Grammatikopoulos *et al.*, 2003), the Isk deposit in British Columbia (Westphal *et al.*, 2002), and a number of deposits in Québec, particularly a deposit located in St.-Onge township in the Lac-St.-Jean area (Jacob and Bélanger, 2002).

FIELD AND PETROGRAPHIC RELATIONSHIPS OF WOLLASTONITE SKARNS

The Platinova-Cominco, Olden and St. Lawrence skarns in the Central Metasedimentary belt (Figure 1) will be discussed. A summary of the most important field, mineralogical, petrological and age characteristics of the studied skarns is presented in Table 1.

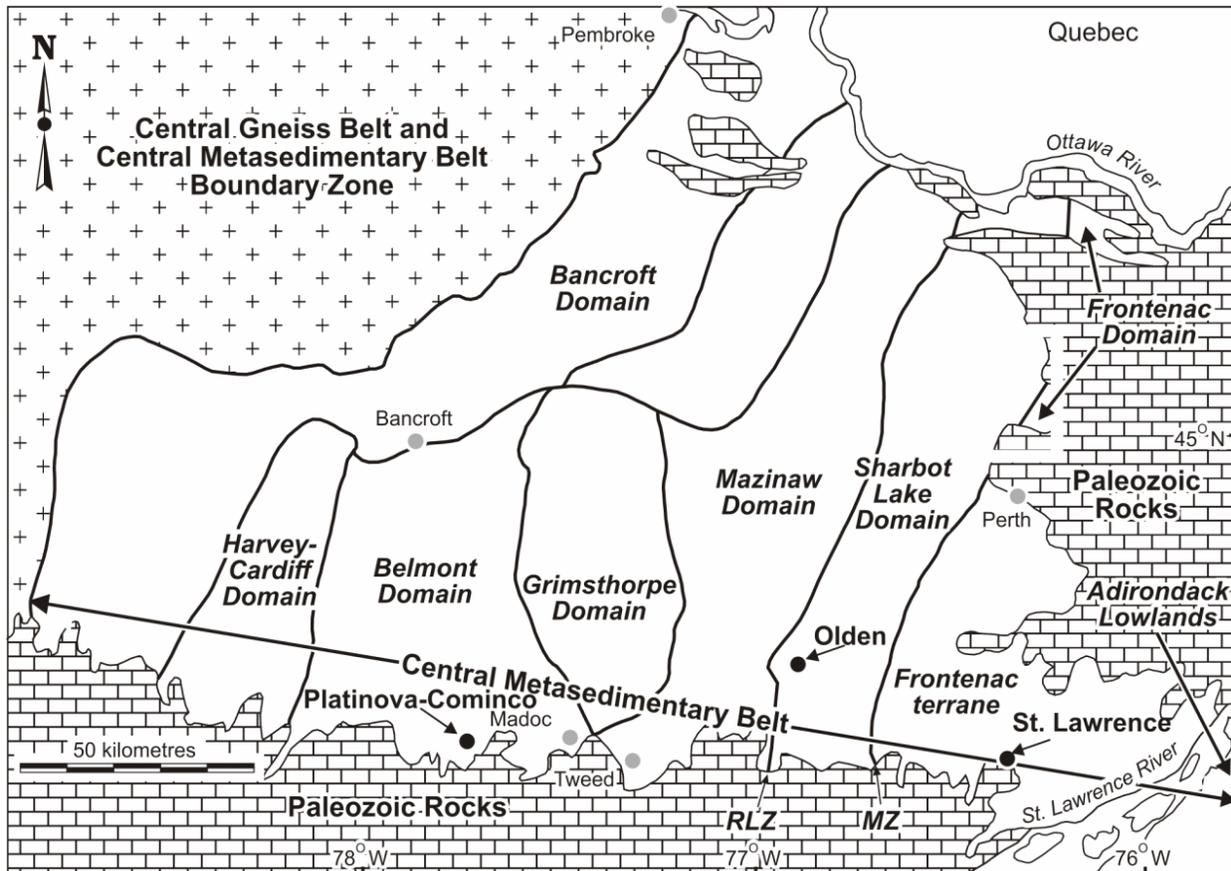


Figure 1. The Central Gneiss Belt and Central Metasedimentary Belt Boundary Zone.

TABLE 1. SUMMARY AND COMPARISON OF THE MAIN FIELD, MINERALOGICAL AND AGE CHARACTERISTICS OF THE PLATINOVA-COMINCO, OLDEN AND ST. LAWRENCE SKARNS.

	Platinova-Cominco	Olden Skarn	St. Lawrence Skarn
Intrusive Rocks	granite, syenite and gabbro	diorite, monzonite, granite and syenite	gabbro and syenite
Host Rock-Protolith	mainly calcitic marbles	calcitic marbles	possibly calcitic and dolomitic marbles (?)
Regional Metamorphism	greenschist facies	amphibolite facies	granulite facies
Size	20-100 × 1200 metres	20 to 50 × 150-200 metres	1 to 30 × 800 metres
Resource Estimate	4 Mt., grading 35% wollastonite	2.8 Mt., grading 35% wollastonite	9 Mt., grading 41% wollastonite
Structural Controls	mainly lithologic contacts	unconformable to bedding	mainly lithologic contacts
Skarn Facies	Wollastonite-rich and wollastonite-poor	endoskarn, wollastonite - garnet - clinopyroxene - garnet, skarn veins, phlogopite skarns	Wollastonite, wollastonite-clinopyroxene, clinopyroxene, clinopyroxene -feldspars, amphibole-phlogopite, sulphides
Mineral Chemistry	Gr _{S17-98} Di ₄₁₋₁₀₀ * Hd ₀₋₅₇ * Jo ₀₋₃	Gr _{S25-83} Di ₄₃₋₉₉ * Hd ₁₋₅₃ * Jo ₀₋₈	Gr _{S87-99} Di _{66.5-100} * Hd _{0.4-33} * Jo ₀₋₁
Zonation	Wollastonite-poor and -rich zones	intrusion-endoskarn → clinopyroxene → garnet → wollastonite → marble	alternating zones of wollastonite and clinopyroxene-rich skarns
Crystal Form	elongated, fibrous and, less commonly, tabular	tabular, stubby and, less commonly, elongated	tabular, stubby and, less commonly, elongated
Mineral Assemblages	Wollastonite + clinopyroxene ± quartz ± garnet abundant calcite	Wollastonite + clinopyroxene + garnet ± quartz abundant calcite	Wollastonite + clinopyroxene + titanite + abundant feldspars, quartz, minor calcite
Retrograde assemblages	calcite, prehnite	calcite, prehnite	calcite, prehnite
Age (million years)	ca. 1240	ca. 1153 or 1070	ca. 1150
Origin	infiltration metasomatism XCO ₂ (<0.1)	infiltration metasomatism XCO ₂ (<0.3)	infiltration metasomatism XCO ₂ (<0.1)
Oxido-Reduction Conditions	variable conditions (for example, pyrrhotite, garnet variations)	oxidized conditions (andradite-rich garnet, magnetite, pyrite)	reduced conditions (grossular-garnet, pyrrhotite and graphite)

Platinova-Cominco Skarn

The Platinova-Cominco skarn (Figure 2) is one of seven known significant wollastonite occurrences in the Belmont domain of the Elzevir terrane. All are adjacent to Deloro and Malone plutons, and display

similar geological and mineralogical characteristics (Grammatikopoulos, 1999).

Platinova-Cominco reserves were estimated initially at 2 million tonnes grading 40% wollastonite, but further geological work indicated potential for a further 2 million tonnes grading 28 to 38% wollastonite (Bauer *et al.*, 1994).

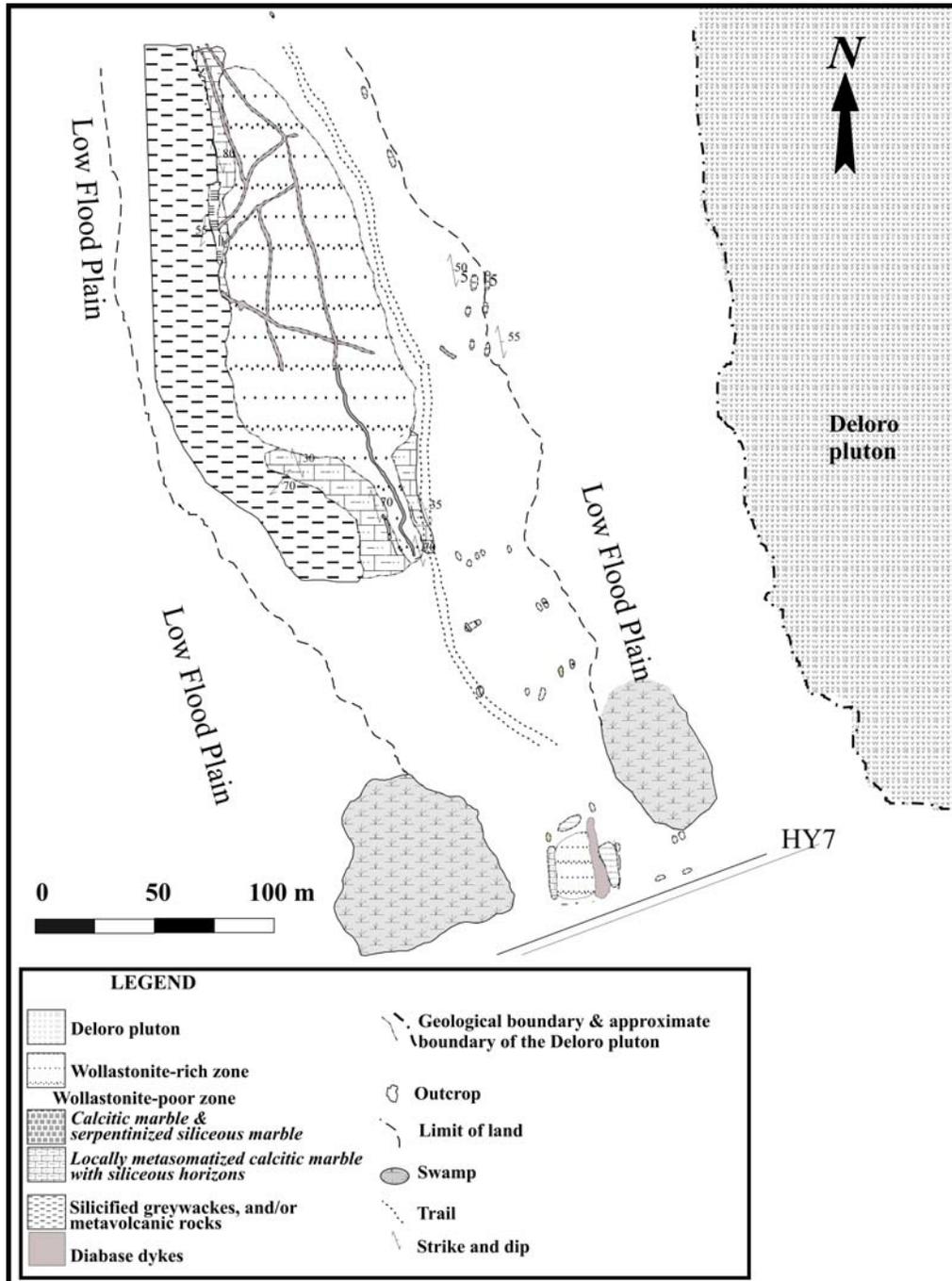


Figure 2. Geological map of the north part of Platinova-Cominco skarn. The wollastonite zone trends north-northwest and dips to the east, towards the Deloro pluton (after Grammatikopoulos, 1999).

The property is underlain largely by metavolcanic, carbonate and clastic metasedimentary rocks of the Grenville Supergroup. The eastern part of the Belmont domain, which is within the "Hastings Metamorphic Low", is characterized by middle-to-upper greenschist facies assemblages (Anovitz and Essene, 1986); however amphibolite facies assemblages occur adjacent to the Deloro pluton (Abdel-Rahman and Martin, 1987).

The carbonate-rich metasedimentary rocks in the study-area include both calcitic and dolomitic units that display considerable variation in colour, mineralogy, and texture (MacKinnon, 1990). Near wollastonite zones, pale-green or grey, fine-grained, serpentine-bearing calcitic marble is common.

The wollastonite skarn unit trends north-northwest and dips moderately-to-steeply to the east. It lies along the western margin of the Deloro pluton, and is broadly conformable with the surrounding rock-units. In map-view, it is about 1 200 metres long and 70 to 100 metres wide in the centre of the property; it thins to the north and south. The strike extent of the wollastonite-rich zone is not well constrained due to lack of exposure. The drill data suggests the wollastonite-rich zone is a single unit. There is evidence of small-scale folding, but no major fold structure. No distinct map units could be delimited. Wollastonite forms crudely ovoid pods or nodular aggregates. The pods generally range from 20 to 40 centimetres, but locally reach 80 centimetres in maximum dimension. The surrounding material is calcitic; some pods are rimmed by clinopyroxene, and some have quartz-rich cores. Wollastonite crystals are typically less than 3 millimetres in length, and occur as fibres and, less commonly, tabular grains. The wollastonite-rich unit consists of up to 80% wollastonite, 5 to 60% calcite, 2 to 30% clinopyroxene and 0 to 5% quartz with sparse garnet (0 to 15%) and vesuvianite (less than 5%), and traces of clinozoisite, magnetite and goethite. Sulphides include up to 5% fine-grained pyrrhotite, and lesser pyrite and chalcopyrite.

The wollastonite skarn has sharp to gradational boundaries with the marbles and wollastonite-poor units, which consist of calcite (60 to 90%), clinopyroxene (1 to 30%), quartz (0 to 25%), plagioclase (0 to 5%), wollastonite (0 to 15%), vesuvianite (0 to 10%) and garnet (0 to 10%). They also contain trace amounts of quartz, tourmaline, apatite, epidote, serpentine, pyrrhotite, chalcopyrite, pyrite, magnetite and goethite.

Wollastonite, clinopyroxene, garnet, vesuvianite, plagioclase, tourmaline, epidote and calcite-wollastonite-garnet veins formed in the prograde and main stage of skarn development. Calcite, prehnite, clays and calcite veins replaced the main skarn minerals during a retrograde stage.

Olden Wollastonite Skarn

The Olden skarn (1074 ± 5 Ma) is located in the Sharbot Lake domain (Figure 1) in Olden Township, Frontenac County, and approximately 6 kilometres south-southeast of Mountain Grove village. It covers an area of about 0.5 square kilometres. The oldest rocks in the area are mafic to felsic gneisses, and mafic to intermediate metavolcanic and metasedimentary rocks. The metasediments include units of mainly calcite, dolomite and calcite-dolomite marble. The largest outcrops of the marble occur along the western margin of, and as enclaves within, the Mountain Grove pluton (1153 ± 2 Ma). The latter, a gabbro-anorthosite-syenite body, is intruded by the McLean syenite-granite pluton (1070 ± 3 Ma).

The Olden wollastonite skarn zone lies within an inlier of predominately calcitic marble within the Mountain Grove pluton. The skarn is hosted by medium- to very coarse-grained, white to grey calcitic marbles and minor dolomitic units. The marbles strike northwest and dip moderately to steeply to the northeast. They are intruded by diorite, monzonite, syenite and granite, and by several generations of aplitic and pegmatitic dykes. Field mapping and diamond drilling have traced the wollastonite-rich zone for 200 metres along strike and show that its width varies from 15 to 50 metres. The skarn extends to a depth of at least 75 metres. Wollastonite-rich skarns crosscut the bedding of the host marble at a 20° angle. It strikes northwest and dips moderately to steeply to the northeast. The skarn contains 30% to 80% by volume wollastonite. Its resource was estimated at 2.8 million tonnes of 35% wollastonite.

The skarn consists of exoskarn, endoskarn and veins. In detail, drill-core intersections show that contacts between the intrusive rocks, the marble and the skarns are highly irregular, scalloped and interfingering.

The marble-hosted exoskarn constitutes by far the greatest part of the exposed skarn system and comprises wollastonite-, clinopyroxene-, garnet- and garnet-clinopyroxene-wollastonite facies, as well as vein-skarn. Garnet-clinopyroxene-wollastonite and garnet skarns, small volumes of phlogopite- and sulphide-rich skarn, and serpentine and brucite have been observed in drill-core. The skarn facies constitute metre-scale zones, and are distributed as irregular layers that are locally elongated sub-parallel to the intrusive contacts.

The wollastonite exoskarn is white, pale-grey or pale-beige in outcrop, and crystals range from 1 to 2 millimetres up to 5 centimetres in size. It is hosted exclusively by calcitic marble and in several places contacts with the host-rock are gradational. Other components of the skarn are calcite, clinopyroxene and

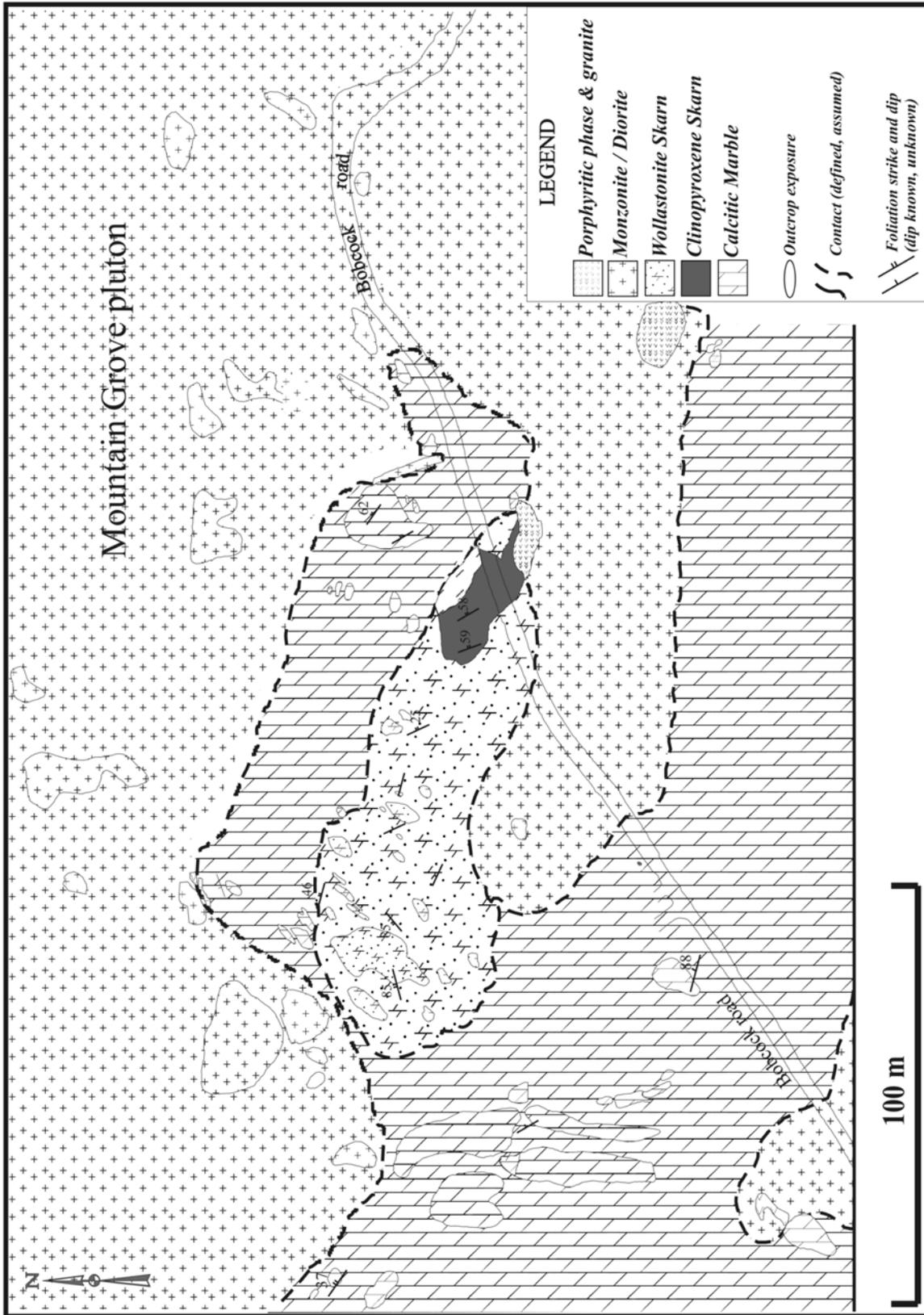


Figure 3. Geological map of the Olden wollastonite skarn. Modified after MacGregor (1993).

The St. Lawrence skarn occurs immediately north of the Leo Lake gabbroic intrusion (Figure 4). Regionally, the horseshoe-shaped band of quartzite, which closes to the southwest, is enclosed by biotite-quartz-feldspar gneiss described as rusty-weathering, quartz-diopside-feldspar gneiss (Crouse and Akerley 1994). The Leo Lake pluton crops out within 20 metres of the wollastonite skarn, but no gabbro-skarn contacts were seen either at the surface or in drill-core. Skarn outcrops close to the pluton are intensely folded and characterized by medium- to coarse-grained titanite and green hedenbergite.

The St. Lawrence wollastonite skarn contains a resource greater than 9 million tonnes grading more than 40% wollastonite. It has been divided into wollastonite-dominant (greater than 40% wollastonite), clinopyroxene-dominant (greater than 40% clinopyroxene), and wollastonite-clinopyroxene skarns. There are minor units including clinopyroxene-pyrite-quartz zones; feldspathic skarn; a “mixed” skarn consisting of variable amounts of clinopyroxene, wollastonite, feldspars, quartz and titanite; minor amphibole-mica skarns; and sulphide bodies, mainly of pyrite, pyrrhotite and chalcopyrite (Crouse and Akerley, 1994; Grammatikopoulos, 1999).

The main skarn units are interlayered and can be traced for metres or, exceptionally, tens of metres as strike-parallel layers, with generally sharp but locally gradational contacts (Grammatikopoulos, 1999).

The wollastonite skarn layers are parallel to the strike of country rock. These range from a few centimetres to a few metres in width and up to tens of metres along strike. Two of the largest wollastonite zones average 12 metres in width, but thicken to 40 metres in fold hinges and thin in fold limbs (Crouse and Akerley, 1994). Wollastonite layers are medium- to coarse-grained, composed of 30 to 80% wollastonite, less than 20% clinopyroxene, up to 10% plagioclase, microcline and quartz, minor amounts of calcite, pyrrhotite, chalcopyrite, pyrite and graphite, and traces of titanite.

Wollastonite crystals are mainly elongate to prismatic, but may exhibit fibrous or radiating habits. Individual grains range in length from 1 millimetre to 5 centimetres. Wollastonite has inclusions of very fine-grained quartz, microcline, clinopyroxene and calcite. In most areas, folding of the wollastonite-rich layers imparted a laminated fabric. Generally wollastonite grains are aligned parallel to the strike of the skarn layers, but, locally, in fold hinges, is at an angle to the strike.

Clinopyroxene and wollastonite-clinopyroxene skarns layers range from millimetres to metres in width; they are pale-green or pale-grey and mainly medium-grained. They coarsen toward the gabbro contact, and display either a massive or a banded texture. They

consist of 20 to 70% clinopyroxene, 20 to 50% wollastonite, and up to 10% quartz, microcline and titanite, with small amounts of garnet, scapolite, calcite, graphite, apatite, pyrrhotite, pyrite and chalcopyrite.

Many samples show textural relationships suggesting equilibrium relationships, but garnet appears to have replaced clinopyroxene and wollastonite locally. Detailed mineralogy and paragenesis is given by Grammatikopoulos (1999).

MINERAL CHEMISTRY

In all skarns, wollastonite is associated with varying proportions of diopside-hedenbergite and grossular-andradite (Figure 5). Clinopyroxenes from the Platinova-Cominco skarn have the overall compositions: $Di_{41-100}-Hd_{0-57}-Jo_{0-3}$; Olden skarn, $Di_{43-99}-Hd_{1-53}-Jo_{0-8}$; and St. Lawrence skarn, $Di_{66-99}-Hd_{0-3}-Jo_{0-1}$. Garnet in Platinova-Cominco has the composition of $Gr_{S17-98}-Adr_{11-82}$; Olden, $Gr_{S25-83}-Adr_{12-67}$; and St. Lawrence,

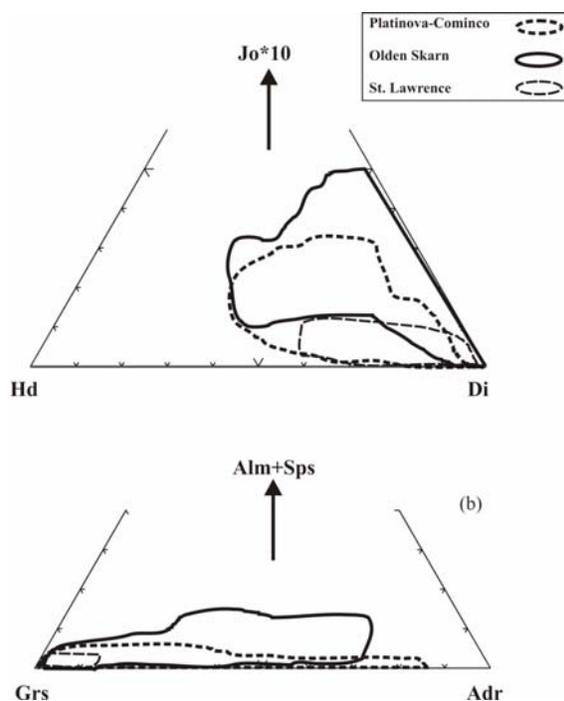


Figure 5. (a) Di-Hd-Jo*10 and (b) Grs-Adr-(Alm+Sps) diagrams for, respectively, clinopyroxenes and garnets from the Platinova-Cominco, Olden and St. Lawrence skarns. Clinopyroxenes from the Olden skarn vary the most, followed by those from Platinova-Cominco, then those from St. Lawrence skarn. Garnets from Olden and, to a lesser degree, Platinova-Cominco are more variable, than those from the St. Lawrence skarn.

$Gr_{S87-100}-Adr_{1-11}$. Sodic plagioclase ($An_{\leq 21}$), alkali feldspar, quartz and titanite are abundant in the St.

Lawrence skarn. Clinopyroxenes from the Olden skarn contain higher Mn contents than those from the Platinova-Cominco and St. Lawrence skarns.

SKARN FORMATION CONDITIONS

The Platinova-Cominco Wollastonite Skarn

The Platinova-Cominco skarn occurs at the western margin of the Deloro pluton, which consists of gabbro and associated hypersolvus granite. It is 1241 ± 2 Ma in age based on a U-Pb zircon date (van Breemen and Davidson, 1988), and therefore was emplaced near the beginning of the regional metamorphism (Elzevirian orogeny).

The wollastonite-rich units are located within the “Hastings Low” of Carmichael *et al.* (1978), which is characterized by middle-to-upper greenschist facies regional metamorphic assemblages (Easton, 1992). If the contiguous skarns were generated by magmatogene fluids, skarn formation may have taken place at $P_T = P_{fluid} = ca. 200$ MPa.

Temperatures prevailing during the prograde phase of exoskarn development were estimated from a combination of field observations, and experimentally determined and calculated phase equilibria at 200 MPa (Grammatikopoulos, 1999). Variations of pressure and temperature of skarn formation were determined by Grammatikopoulos, 1999, based on assumptions of thermodynamic equilibria. These data suggest that H₂O must have been continuously supplied during wollastonite formation to dilute the CO₂ generated by the decarbonation reaction $CaCO_3 + SiO_{2(aq)} = CaSiO_3 + CO_2$.

Field and petrological evidence do not support formation of the wollastonite skarns as a result of regional metamorphism or during contact metamorphism under closed system conditions. Devolatilization of the marble alone would not have produced low XCO₂ assemblages; these probably reflect the influx of “exotic” water-rich fluids (see for example Ferry, 1991), or at least open system permitting CO₂ evacuation. Temperatures reached during the greenschist facies regional metamorphism in the area, 375 to 425°C, are below those indicated by the mineral assemblages of the skarn.

The skarns probably formed through “open system” contact metamorphism or metasomatism related to emplacement the Deloro pluton and its satellites. Evidence of relatively shallow open system includes mirolitic cavities and pegmatitic veins; replacement of gabbroic rocks at the margin of the pluton by epidote,

and lesser calcite; development of coarse-grained epidote, calcite, amphibole, Barium-bearing potassic-feldspar and tourmaline in gabbroic rocks and mafic dykes; and the presence of thin calcite, quartz-bearing and calcite-wollastonite-garnet veins cutting the metasomatic rocks. Further, formation of both wollastonite-rich and wollastonite-poor zones may indicate that there were spatial gradients in the bulk composition of metasomatic fluid(s) with respect to at least some components, including Si, Al, Fe, Mn, Mg and H₂O.

Variations in the amount of wollastonite in both wollastonite-rich and wollastonite-poor zones are interpreted to indicate fluid infiltration and local fluid channeling at all scales in the system (Grammatikopoulos, 1999). Metasomatic fluids channeled into marble tended to migrate along bedding planes and lithological contacts, and to react with the marble to form skarn. Relative to the wollastonite skarn, calcite + quartz-bearing marbles are stable at higher XCO₂ at any temperature.

Olden Wollastonite Skarn

The pressure of skarn formation is inferred to have been the same as the emplacement of the Mountain Grove pluton, estimated using amphibole geobarometry at between 310 and 470 MPa (Grammatikopoulos, 1999).

The occurrence of garnet (Grs₄₀₋₆₀) with wollastonite suggests temperatures of approximately 550 to 600°C at XCO₂ less than or equal to 0.1-0.3 (see Buick and Cartwright, 1995). Constraints on XCO₂/XH₂O concentrations in the fluids during formation of the skarn veins and of clinopyroxene exoskarn may be similar to those indicated by the vesuvianite-bearing assemblages. Valley *et al.* (1985) argued that the coexistence of magnesian vesuvianite and wollastonite in the system CaO-MgO-Al₂O₃-SiO₂-H₂O-CO₂ limits XCO₂ to less than or equal to 0.03.

Development of the Olden skarn primarily involved replacement of calcitic marble by a variety of wollastonite-, clinopyroxene- and garnet-rich assemblages. These are imperfectly zoned with respect to the igneous contact, although the spatial sequence, plutonic rock-endoskarn-exoskarn (including the garnet, clinopyroxene and wollastonite zones)-calcitic marble was found across several pluton-marble contacts.

Garnet, clinopyroxene, scapolite, epidote and, less commonly, chondrodite endoskarn is developed in the granitic and dioritic rocks of the Mountain Grove pluton adjacent to areas of extensive exoskarn formation.

Endoskarn-exoskarn association, the skarn facies, the skarn veins and the variable mineralogical characteristics indicate high fluid content and disequilibrium conditions.

Field and laboratory data suggest that replacement features are functions mainly of activity gradients in hydrothermal solution of components such as Si, Al, Fe²⁺, Fe³⁺, Mg, Mn, Na, Cl, K, and also fluid/rock ratio variations. Silica metasomatism is supported by mineral assemblages, such as wollastonite + calcite, wollastonite + clinopyroxene, and wollastonite + clinopyroxene + garnet + calcite in the marble (Chenhall and Mazaheri, 1993; Gerdes and Valley, 1994).

It is suggested that cooling and crystallization of the Mountain Grove pluton resulted in local concentration of water-rich fluids in certain portions of the pluton, followed by late exsolution of this Si and H₂O-rich aqueous phase. Fluids may have been released episodically and traveled along dike-contacts or zones of hydrofracturing. Involvement of hydrothermal fluids is reasonable because components such as Al, Cl, Fe and Mg are abundant in the skarns but there are no impurities in the marble to supply the elements mentioned above.

St. Lawrence Wollastonite Skarn

The genesis of the St. Lawrence wollastonite skarn is less clear due to the poor exposure and the absence of carbonate rocks. Granulite facies rocks in the Frontenac terrane record temperatures ranging from 630 to 800°C, pressures from 350 to 750 MPa, and α (H₂O) less than 0.5 (Wynne-Edwards, 1972; Carmichael, 1976; Lonker, 1980). Amphibole geobarometry, which yielded pressures of approximately 300 to 400 MPa for the Leo Lake pluton adjacent to the St. Lawrence skarn, are considerably lower than those derived from the metamorphic rocks.

Mineralogical and calculated and experimental data indicate that the fluid was water-dominant. For a pressure of 350 MPa, the mineral assemblage constrains the temperature of skarn formation to about 560°C, and XCO₂ to less than or equal to 0.05. For a pressure of 550 MPa, the same mineral assemblage yields a temperature of close to 630°C, although the XCO₂ remains less than 0.05. If skarn development was directly related to intrusion of the Leo Lake pluton, then formation at the lower pressures is more probable. However, these calculations imply that large volumes of H₂O must have been continuously supplied in order to dilute the CO₂ generated by the decarbonation reaction during wollastonite formation or the CO₂ must have been allowed to escape. Furthermore, plagioclase in the St. Lawrence wollastonite skarn is sodic (An₂₁), whereas that stable in granulitic facies siliciclastic rocks is commonly anorthite-rich (Lonker, 1980). Plagioclase with An₃₁₋₆₁ is reported from various metamorphic units in the Frontenac terrane (Lonker, 1980).

Determination of the processes responsible for the St. Lawrence skarn is hampered by the lack of exposed contacts between the skarn and the plutonic rocks, and

the uncertainty about the timing and conditions of metamorphism. However, available evidence suggests that the crystallizing intrusion was the source of the fluid(s) involved in skarn formation (Grammatikopoulos, 1999). Another line of evidence is presented by isotopic dating. The Leo Lake pluton has been dated at 1162 ± 3 Ma (van Breemen and Davidson, 1988), whereas U-Pb dating of titanite from the skarn adjacent to the pluton yields an average age of 1147 ± ca. 8 Ma, and ⁴⁰Ar/³⁹Ar of amphibole an age of 1159 ± 6 Ma (Grammatikopoulos, 1999). Thus, formation of the skarn followed shortly after crystallization of the Leo Lake pluton.

SKARN GENESIS

The model presented in Figure 6 explains the origin of the St. Lawrence, Olden, and Platinova-Cominco wollastonite skarns. Schematic presentation of the relationships between fluid discharge, contact metamorphism and skarn formation is shown in Figure 6. Host rocks become brittle near the contact of the pluton due to contact metamorphism. Fracture systems develop either due to cooling, pluton forcing, or hydrofracturing. This process will result in strongly focused fluid circulation and the formation of high-grade wollastonite deposits.

Discharging fluids are focused along permeable zones. In the wollastonite skarns studied, heterogeneous flow apparently dominated during generation of the wollastonite skarns (Grammatikopoulos, 1999).

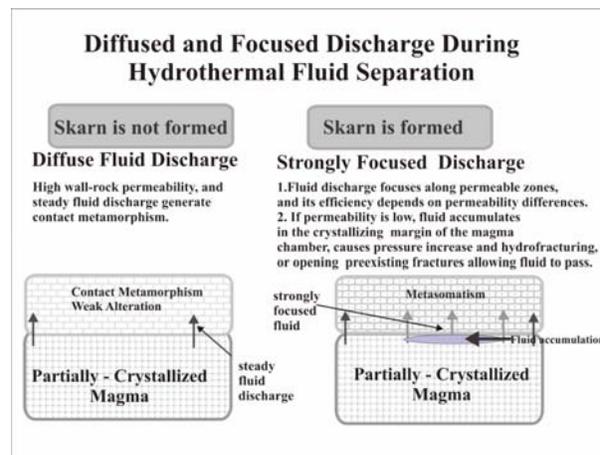


Figure 6. Model for formation of St. Lawrence, Olden, and Platinova-Cominco wollastonite skarns.

CONCLUSIONS

Formation of the skarns is attributed to the incursion of magmatogene, silica-rich, and CO₂-poor fluids. The fluids were channeled through the marbles and tended to migrate along permeable zones, such as bedding planes, fractures, and igneous contacts.

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CATEGORIZATION AND EVALUATION OF INDUSTRIAL CLAY RESOURCES

(WITH EXAMPLES OF RESOURCES IN THE PACIFIC NORTHWEST)

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INTRODUCTION

Population growth, together with urbanization and industrialization in North America during the 20th century prompted much interest in developing indigenous clay resources. In the Pacific Northwest, the very large paper industry is a potentially large market for industrial clays. Current trends within the paper industry towards higher quality newsprint, filled, and coated papers offers an incentive for exploration in the region since supplies of kaolin from Georgia in the southeastern United States attract freight rates in excess of US\$100/tonne. A local market also exists for refractory clays and adsorbent clays are used in a variety of applications.

CATEGORIZATION OF INDUSTRIAL CLAY RESOURCES

Categorization of industrial clays is a useful precursor to any technical and economic evaluation of potential resources. It can also help identify the most suitable development strategy and work program. Previous attempts to categorize industrial clays in the region have been based solely on mineral characteristics. Here we propose new criteria to categorize clay resources. The implications of timetables, development costs, and process economics are also discussed.

Four categories of industrial clay resources are proposed based on resource volume, market size, capital investment and level of technological input needed to reach processing and product quality requirements.

Category 1 Clays

Category 1 clays are of high quality and require significant technological input. Major capital investment is required to produce a large tonnage to supply both local and international markets. Currently there are three regions around the world where Category 1 clays (kaolin) are produced: Georgia in the United States, Cornwall in the United Kingdom, and the Amazon Basin in Brazil. The limited number of identifiable kaolin resources of this quality indicates their rarity worldwide.

Category 2 Clays

Category 2 clays are relatively rare and are considered as specialty materials. Advanced technologies are required to produce small tonnages for niche markets (special industrial applications), both locally and internationally. Such deposits are typically of high purity and are found in relatively uncommon geological settings. An example is hectorite, which is the product of hydrothermal alteration of lithium-rich volcanic rocks. Hectorite, either wet or dry processed, is used in a wide variety of industries (coatings, greases, adhesives and paints) where properties of high viscosity, high gel strength, and temperature stability are required. The most significant deposits are located in Nevada, United States (Odom, 1992; Pulliam-Fitzgerald and Kendall, 1996). The halloysite deposits of New Zealand, which are also hydrothermal in origin, are another example that commands a premium position in production of high quality porcelain worldwide (Harvey and Murray, 1993). White bentonites and some sodium bentonites are also Category 2 clay materials.

Category 3 Clays

Category 3 clays are of moderate quality. Relatively low level technologies are required for their production. They supply mainly local markets. Clays in this category do not match the quality standards set by Category 1 and Category 2 clays. They are further sub-divided into:

- Category 3A, which denotes moderate quality clays that meet the specifications for some paper coating or similar markets
- Category 3B, which are relatively low quality clays that are suitable for most filler applications

Category 3 resources are numerous and widespread throughout the world. Since their specifications are typically not rigid, only a moderate level of processing is generally needed to meet market quality requirements.

Category 4 Clays

Category 4 includes low quality clays that are not valuable enough to justify much processing. They provide

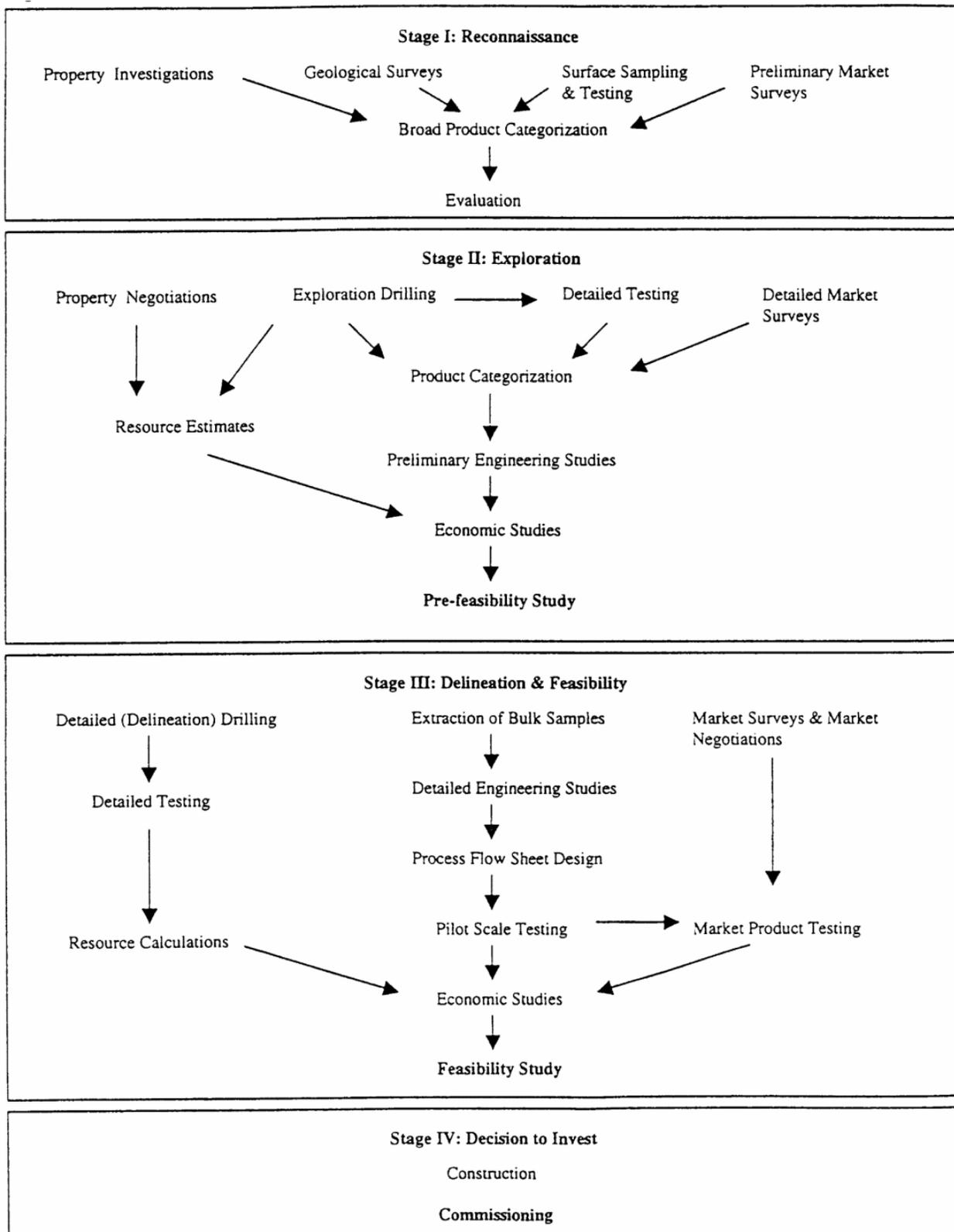


Figure 1. Flow sheet of project development

products to local markets, such as heavy clay products. In addition, clay resources that are currently uneconomic due to physical, political or geographic factors may also be classified under Category 4.

THE ROLE OF CATEGORIZATION IN THE ASSESSMENT OF INDUSTRIAL CLAY

In any assessment of an industrial clay resource, various stages of resource evaluation, from raw material testing, to the assessment of product quality, market size, and market demand, are necessary. These data must then be integrated into a feasibility study that will recommend proceeding or abandoning the project (Figure 1).

Early categorization of the materials is a useful precursor for the establishment of development strategies and the prediction of project costs. It can provide a useful insight into the complexities of resource development because the different categories have different requirements with respect to the work program needed to move from exploration through to project feasibility studies (Figure 1).

Development timetables

Table 1 presents a summary of typical development timetables. The extended time required to work through Category 1 projects relative to Categories 2, 3, and 4 is clearly illustrated.

Annual tonnage

Significant economic advantages can be obtained by having larger production volumes and by shipping in larger vessels. Larger tonnage operations can operate with fewer man hours per tonne while capital costs for larger machines are less than the multiples of smaller units. In the kaolin industry, for example, in the 1970s, a 100 000 tonne per year Category 1 operation was considered to be a reasonably-sized commercial operation. For current developments in Brazil, minimal plant sizes are 300 000 tonnes per year.

For Category 2 clays, annual tonnages are governed by market size or by accessible market share rather than 'benefits of the economy of scale'. Annual productions from such processing operations typically fall between 10 000 and 100 000 tonnes per year. The size of Category 3 operations are also governed by market size or accessible market share.

Resource confidence

Based on the above criteria, the development of a Category 1 resource requires a very high level of confidence in the quality and quantity of the raw material. If a minimum resource life of 20 years is required at 300 000 tonnes per year, then the resource size must be sufficient to produce 6 million tonnes of product. For Categories 2 and 3, the tonnage requirements may be significantly less and the level of resource confidence may also be reduced. Category 1 clays require careful detailed drilling and testing to confirm quality and uniformity. For example, exploration drilling at 300 metres spacing is typically required. Production drilling in Georgia is usually on 30 metres (100 feet) spacing (Harvey and Murray 1997).

Pre-investment capital

Category 1 projects require significant pre-investment or 'risk' capital. The level of confidence in the resource and markets has to be very high, because the level of pre-investment capital may well exceed US\$1 million. The pre-investment capital requirements for Categories 2, 3 and 4 are progressively lower towards the lower quality clays.

Investment capital, product value and investment returns

The investment capital requirements for large tonnage, high-complexity Category 1 kaolin projects are quoted to be as high as US\$300 per processed tonne (Pleeth 1997; Harvey, 1995). For Category 2 clays, figures of US\$100 per processed tonne are typical, whereas for Category 3 clays, the investment level may be of the order of US\$50 per processed tonne.

Although Category 1 kaolin products command the largest tonnage and high value-added positions in the industry, Category 2 products may command the highest value position, although their tonnages are generally small. Category 3 clays are intermediate in value between Category 1 and Category 4 clays.

The pay-back time for Category 1 investments may be many years, both because the time needed to move from reconnaissance through to commissioning can be large (Table 1) and there is also a large capital investment. Payback times for Category 2 and 3 projects are generally shorter than for Category 1 ventures.

TABLE 1: TIMETABLE OF ACTIVITIES AND INVESTMENTS

Activity	Category 1	Category 2	Category 3	Category 4
Stage I: Reconnaissance Geological reconnaissance, property surveys, testing, broad categorization of materials, market surveys and evaluation				
Decision to Proceed	12 months	9 months	6 months	3 months
Stage II: Exploration (Pre-feasibility) Property negotiation, drilling, testing, market surveys, precise material characterizations, process flow sheet development, resource calculations, economic studies and evaluation				
Pre-feasibility study and decision to proceed	18-24 months	9 months	9 months	6 months
Stage III: Delineation and feasibility Drilling, testing, market surveys, bulk samples, engineering studies, assessment of products in the marketplace, economic studies and evaluation				
Feasibility study	24 months	12 months	9 months	3 months
Stage IV: Decision to invest Total elapsed time since project initiation	4-5 years	2-2.5 years	2 years	1 year
Design, construction and commissioning	1-2 years	1 year	1 year	1 year
Typical overall project time	5-7 years	3-4 years	2-3 years	1 year

REDUCING RISK AND SHORTENING TIMETABLES FOR CATEGORIES 1 AND 2 DEVELOPMENTS

Several approaches can be taken to minimize risk and shorten the time necessary to establish Category 1 or Category 2 ventures:

- Associate or form a joint venture with established producers in the industry,
- Associate, or form a joint venture with major market users of the product,
- Engage specialist consultants for resource evaluation, market surveys, and engineering studies,
- Develop resources that are adjacent to proven resources that are already established in the marketplace.

THE CATEGORIZATION OF KAOLIN RESOURCES IN THE REGION

As far as the author is aware, no attempt has been made to categorize the clay resources of the Northwest Pacific region in this manner. However, he is familiar

with many of the resources of the region and has attempted to categorize them.

British Columbia

At Lang Bay, 80 kilometres north of Vancouver, Harvey and Farris (1992) described a small primary kaolin resource (approximately 6 million tonnes of crude ore) located close to tidewater 8 kilometres south of the Powell River township. It formed from low temperature hydrothermal alteration and weathering of Coastal Plutonic complex rocks. The resource is located beneath 20 to 30 metres of glacial till, and the crystallinity of the kaolin is low. It is considered a Category 3B resource.

In Abbotsford a small kaolin resources has been exploited for many years and used locally in refractories. There are no detailed studies of this material but it is provisionally categorized as a Category 3B resource.

Idaho-Washington kaolins

A series of primary and secondary kaolin deposits associated with weathering and perhaps some hydrothermal alteration of the Idaho batholith are located

TABLE 2: IMPORTS AND EXPORTS OF CATEGORIES OF KAOLIN AND HALLOYSITE CLAY IN THE ASSOCIATION OF SOUTHEAST ASIAN NATIONS (ASEAN) REGION 1994 (ANALYZED FROM UNITED NATIONS DATABASE)

	Major Sources of Supply	Tonnage '000 tonnes	Major User	Industrial Use	Tonnage '000 tonnes	Average Value (CIF)/ tonnes in US\$
Category 1	United States	1 200	Japan	Paper	841	Ranging between \$165 and \$240
	Brazil	100	Korea	Paper	146	
	Australia	100	Taiwan	Paper	125	
Category 2	New Zealand	20	Japan	Ceramics	9	Ranging between \$500 & \$600
			Korea	Ceramics	6	
			Taiwan	Ceramics	4	
Category 3 Kaolin	China	*200	Japan	Paper & Ceramics	*128	Ranging between \$80 and \$160
	Indonesia	160	Taiwan	Refractories	40	
			Malaysia	Refractories	20	
				Ceramics		
Category 4 kaolins & other clay	China (often re-exported via Hong Kong)	*1,000+	Taiwan	Refractories	800+	Ranging between \$25 and \$70
			Japan	Ceramics	320	

* Tonnages estimated from compiled statistical data in which the various categories have not been divided and only combined tonnage data are available.

in Latah County, Idaho. These deposits have been exploited for many years as refractory clay (Hosterman *et al.*, 1960; Pruett and Murray, 1993); they are categorized as Category 3A and 3B resources.

The Whitemud Formation kaolins of Saskatchewan and Alberta

Although these resources are located east of the Pacific Northwest region (Alberta and Saskatchewan), they have in the past been considered as possible suppliers of clay for the region (Table 3). Large exposures of white clays of the Whitemud Formation, which have been known for many years (Byers, 1969), are composed of a mixture illite, quartz and poorly crystalline kaolin (Pruett and Murray, 1991). They are categorized as Category 3B resources.

SUMMARY

Category 1 Clays

Category 1 industrial clay operations require large tonnages of proven resources of raw materials of consistently high quality. The profit potential for such clay products is high, but the risk capital required to

identify, drill and evaluate the raw materials is also high. The processing requirements for Category 1 clays are complex and markets are highly sophisticated and strongly competitive. A high level of technical expertise is needed to service these markets.

Any potential new developer of a Category 1 resource should be aware of these constraints. When examining the recent developments of Category 1 kaolin resources in Brazil, Pleeth (1997) quotes time intervals of at least 5 years to move from initial exploration to commissioning. No known regional resources in the Pacific Northwest have the potential to achieve this Category.

Category 2 Clays

Category 2 industrial clays supply much smaller niche markets and require a much smaller resources base. However, because they are specialty products, their processing requirements are typically high. They service sophisticated markets and the level of technical support required in the marketplace is inevitably high. Risk capital is therefore moderately high and it is likely to take between 2 and 3 years to move from exploration to production. At the present time there are no known kaolin resources in the Pacific Northwest in this category.

TABLE 3. CATEGORIZATION OF CERTAIN WESTERN NORTH AMERICAN KAOLIN RESOURCES

Province or State	Location	Category	Comment
British Columbia	Lang Bay	3B	Great location, limited tonnage, high overburden ratio. Low quality limited to filler clay
	Abbotsford	3B	Suitable as a refractory raw material
Washington-Idaho	Latah County	3A	Reasonable location, large tonnages spread between many deposits Quality variable but no Category 1 or Category 2 quality kaolins
Saskatchewan and Alberta	Wood Mountain and southeastern Alberta	3B	Poor location, large tonnages. Quality variable but no highly crystalline kaolins proven. Complex processing requirements

Category 3 Clays

Category 3 industrial clays have lower technical requirements and less rigid product specifications than either Category 1 or Category 2 clays. The kaolins of Lang Bay and Abbotsford (British Columbia), Latah County (Washington-Idaho), and Wood Mountain and southeastern Alberta (Saskatchewan-Alberta) belong to this Category (Table 3).

Category 4 Clays

Category 4 clays are used industrially in local markets with little or no processing. They generally have a low profit potential.

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MEASURING GRADE OF HIGH-TECH INDUSTRIAL MINERALS FOR DEPOSIT EVALUATION AND PRODUCT BENEFICIATION: QUANTITATIVE PHASE ANALYSIS USING X-RAY POWDER DIFFRACTION DATA AND WHOLE-ROCK CHEMICAL METHODS

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OVERVIEW

Assessing ore grade during exploration or production presents unique challenges for the industrial minerals geologist and engineer. The grade of an industrial mineral deposit is not necessarily directly proportional to the abundance of any single chemical species because the commodity is the mineral itself. Thus whole-rock chemical analytical techniques that are the norm in the precious metals industry are not directly applicable. For example, wollastonite (CaSiO_3) abundance in skarn is not proportional to the CaO or SiO_2 content of the bulk rock because these species are also commonly found in other calc-silicate minerals. Accurate measurement of content of an industrial mineral therefore requires either adoption of different analytical techniques, or development of new tools to convert whole rock chemical analyses into mineral abundances.

Here, we summarize the results of our search for inexpensive but accurate methods of measuring wollastonite content in skarn and in wollastonite concentrate. By applying both established and recently developed mineralogical and petrological techniques, we developed three methods for assaying wollastonite content. The accuracy and expense of these methods, and also mineral abundances estimated with the CIPW norm are compared. Detailed technical descriptions of the methods are presented in Raudsepp *et al.* (1999); Gordon and Dipple (1999); and Dipple *et al.* (2001). Not surprisingly, there is a non-linear correlation between accuracy and expense; hence the three methods may be appropriate for different stages, either exploration, deposit assessment or production. With appropriate modification, these methods could also be employed in the search for and characterization of other functional fillers and other industrial minerals.

METHODS

Mineral abundance can be calculated from three types of data: (1) the area occupied by a mineral in a thin

section or slab of rock as measured by an optical microscope, scanning electron microscope or electron microprobe (visual estimates), (2) the relative intensities of x-rays diffracted by minerals in a rock powder, or (3) the chemical composition of the rock sample and the identity and composition of the constituent minerals. For the purpose of this study, our analysis was restricted to methods that rely on data derived from x-ray powder-diffraction and whole-rock chemical analysis. We found that the acicular nature of wollastonite and the preferential settling of mineral grains during sample preparation rendered visual methods unreliable for disaggregated samples. The abundances of seven minerals (wollastonite, quartz, calcite, apatite, K-feldspar, titanite, pyroxene and garnet) were measured in samples of skarn with four independent methods: Rietveld analysis, CIPW, projection, and linear programming.

The Rietveld method is a standardless full-profile approach to quantitative phase analysis using x-ray powder-diffraction data. The structural parameters of each constituent mineral, together with experimental parameters, are refined by least-squares procedures to minimize the difference between observed and calculated diffraction patterns. The result is a single estimate of mineral abundance for each skarn sample. We evaluated the accuracy of the Rietveld method by analyzing synthetic, pre-weighed mixtures of wollastonite, quartz, calcite, feldspar and garnet. Rietveld estimates of mineral abundance compare favourably with the nominal values for minerals present in moderate to high abundance. We conclude that the Rietveld method provides an accurate measure of the abundance of minerals present in concentrations greater than about 5 weight percent.

The CIPW, projection, and linear programming methods rely on the bulk chemical composition of a sample to determine mineral abundance. The primary advantage to the CIPW norm is that it can be implemented at minimal cost because freeware programs are readily available. Although not designed to evaluate the mineral content of skarn, the CIPW norm provides a reasonable measure of mineral abundance in samples

from the Isk wollastonite deposits of northwest British Columbia.

The projection method employs a basis transformation to convert whole rock oxide compositions into mineral abundance (Thompson, 1982). This analysis does not provide constraints on the chemical compositions of the constituent minerals. Mineral abundance measured by the projection method compares favourably with that of the Rietveld method. Wollastonite and calcite contents as determined by the two techniques are consistent, although the projection method tends to underestimate wollastonite content.

The linear programming method solves for both the abundance and composition of minerals within each sample when whole-rock compositions and information on the compositions of the constituent minerals is available. The method applied here is specifically formulated for the Isk deposit and incorporates mineralogical data beyond that used by the projection method. Specifically, the linear programming technique allows for all observed chemical substitutions within each mineral but limits their abundance to be within the observed range of compositions of the mineral constituents. Results for wollastonite, pyroxene, garnet, quartz, calcite and feldspar are consistent with and bracket the Rietveld results. If the Rietveld results are taken to be representative of true mineral contents, then the linear programming method provides more accurate estimates of wollastonite, pyroxene, garnet, quartz and feldspar contents than either the CIPW or projection methods.

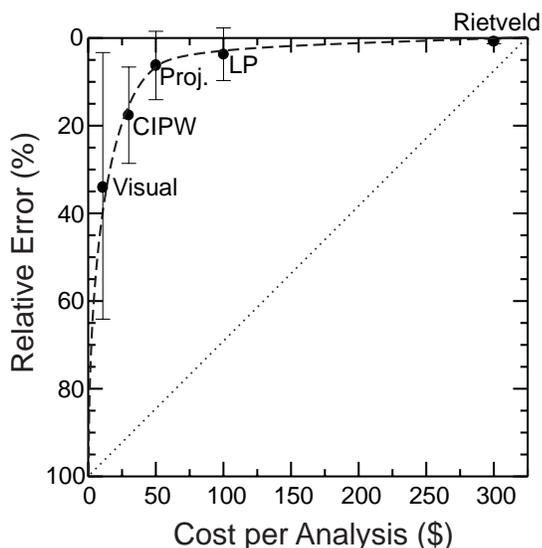


Figure 1. Relative error of each assay method plotted versus cost per analysis. Note the distinctly non-linear relationship between cost and accuracy. Visual – visual estimates from core logs, CIPW – CIPW norm, Proj. – projection method, LP – linear programming method.

RESULTS

The mean relative error of the Rietveld method in determining wollastonite content is 0.80% and one standard deviation is 0.50%. These values were deemed sufficiently accurate to be used as a standard for testing the other methods; the Rietveld determinations of wollastonite content in Isk deposit samples were taken as the ‘true’ values. The middle of the range in wollastonite for each sample was taken as the ‘measured’ value for each method. The mean relative error (in % \pm one standard deviation), for the twelve samples with wollastonite contents greater than 5 wt%, in the CIPW, projection, and linear programming methods are 17.60 (\pm 11.00), 6.26 (\pm 7.80) and 3.69 (\pm 6.01), respectively (Figure 1).

The Rietveld method clearly provides the most accurate measurement of wollastonite grade in the Isk samples. However, it also requires more data collection and data analysis than the other methods. The test results show a markedly non-linear relationship between expense and accuracy (Figure 1). Small incremental increases in analytical cost (up to \$50 - \$100 per analysis) can yield substantial improvements in accuracy. Further increases in accuracy (reductions in relative error below \sim 5%), however, require a much larger dollar commitment per analysis. Thus the CIPW norm, or visual estimates may suffice for regional exploration programs, but once a deposit or suite of deposits has been selected, accuracy gained by using the projection or linear programming method may be worth the added expense. Even at this stage, the Rietveld method should be applied systematically and regularly as a check on the projection and linear programming results. The higher accuracy of the Rietveld method may also make it useful during ore processing to optimize the mineral separation procedure.

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THE GLENOVER CARBONATITE COMPLEX 3D-MODELLING OF A NEW POTENTIAL VERMICULITE DEPOSIT

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LOCATION

The Glenover carbonatite complex is located in the Northern Province of South Africa, about 100 kilometres north-northwest of Thabazimbi close to the Botswana border.

GEOLOGICAL SETTING

The Glenover complex intrudes sediments of the upper Waterberg Group and belongs to a suite of alkaline to carbonatitic intrusive complexes that were emplaced into the Archaean Kaapvaal Craton between 1200 to 1450 Ma.

The whole region is covered by reddish sand of aeolian origin as well as a layer of surface limestone that is part of the Glenover complex.

The geology and mineralogy of the Glenover carbonatite complex resembles that of the Palabora carbonatite complex. The complex consists of a central carbonatite-pyroxenite plug surrounded by fenitized quartzite. The phlogopite-bearing pyroxenite, which is the main component of the complex, is intruded by a pipe like carbonatite body. Associated cone-sheets and irregular carbonatite dykes and sills emanate from the carbonatite. North of the central carbonatite body, an apatite-rich breccia body is situated between the contact of the pyroxenite and the carbonatite. The average phosphate content of the breccia is about 35%. Between 1967 and 1983 Glenover Phosphate Ltd., a subsidiary of Gold Fields of South Africa Ltd., produced about 1.5 million tonnes of ore from this breccia.

VERMICULITE

Weathering of the pyroxenite, which extends to a depth of 30 metres, results in the formation of vermiculite. Based on data from an intensive drilling program, a potential Vermiculite deposit with an area of 800 by 800 metres was outlined. The detailed drilling program showed that the average vermiculite content exceeds 20% in the finer fractions (superfine and micron). Percussion holes were drilled to a depth of about 15 metres, and the vermiculite content was analyzed in 3 metre sections.

Data from the 50 by 50 metre drilling program, and recent information from field studies enabled construction of a computer-aided model of the vermiculite deposit.

COMPUTER-AIDED MODELLING:

The aim of the current research is to produce an ore-grade distribution model of the deposit by means of the geologic mine planning program DATAMINE™. The model, which will include all available lithological and mineralogical data gained by test pitting, trenching and drilling on the Glenover carbonatite complex, will allow an economic evaluation of the vermiculite deposit.

The digital model will also enable us to gain a better understanding of the genesis of the Glenover carbonatite complex.

LEONARDITE AT RED LAKE DEPOSIT, BRITISH COLUMBIA, CANADA.

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George J. Simandl, British Columbia Ministry of Energy and Mines, Victoria, BC, Canada
and Jana Simandl, Department of Chemical Engineering, McGill University, Montréal,
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INTRODUCTION

“Leonardite” and “humate” are loosely used terms covering a variety of naturally occurring lithologies with high humic acid content, including weathered (oxidized) lignite, sub-bituminous coal and a variety of carbonaceous rocks, such as mudstones, shales and claystones (Kohanowski, 1957 and 1970; Hoffman *et al.*, 1993). These raw materials are used mainly as soil conditioners; however they also have applications in wood stains, drilling fluid additives and as binder in iron pelletizing (Hoffman *et al.*, 1993). To be of economic interest, raw humate or leonardite should contain a sufficient concentration of humic acid. New Mexico’s humate typically contains 12 to 18% humic acid, but materials used for drilling fluid applications typically contain more than 65% humic acid (Hoffman *et al.*, 1993). Humates are generally mined by front-end loaders, stockpiled to reduce water content, then crushed and screened (Hoffman and Austin, 1994). Materials with high humic acid content may be further processed for use as a component in water-soluble wood stains, as a drilling fluid additive (Odenbaugh and Ellman, 1967, Roybal *et al.*, 1986), as binder in iron ore pellets, and as lignite briquettes.

The greatest growth potential for humic acid-based products is in soil conditioning and agricultural applications.

RED LAKE DEPOSIT

The Red Lake deposit, located approximately 40 kilometres northwest of Kamloops (Figure 1), is currently mined for diatomite-bearing rocks. These rocks are shipped for processing to the Western Industrial Clay Products plant in Kamloops. At the plant, the ore is processed and blended with other materials to produce a variety of industrial absorbents and pet litter products that are marketed in North America and overseas.

Read (1995) described the geology of the deposit, which is interpreted to lie near the base of the Miocene Deadman River Formation. The form and geology of the deposits can be summarized conveniently in north-south and east-west sections (Figures 2a and 2b).

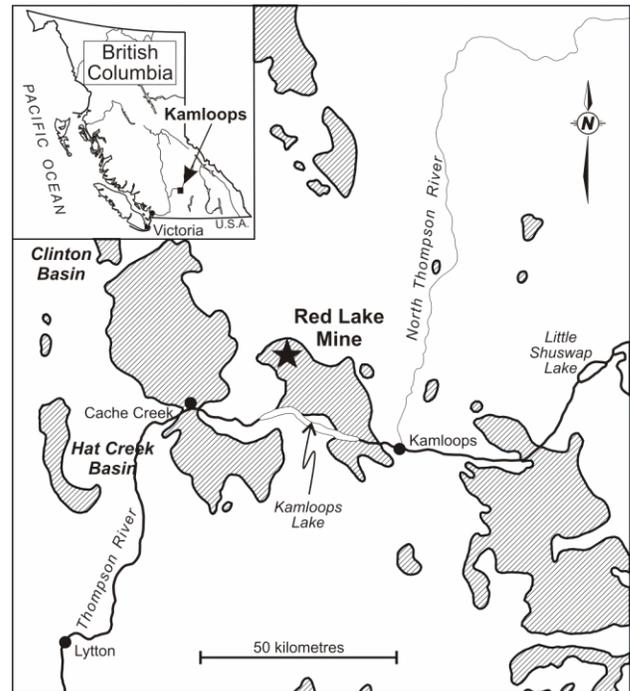


Figure 1: Geological setting of the Red Lake deposit, British Columbia, Canada. Tertiary basins are indicated by shaded areas.

Lithologies at the mine site include Grey Andesite, a basal Carbon-rich unit (*Mbc*), basal Diatomaceous Earth (*Mbd*), an upper Carbon-rich unit (*Muc*), an upper Diatomaceous Earth (*Mde*) unit, and overburden (*Qs*). These units are described in stratigraphic order (from oldest to youngest) below:

Grey Andesite (possibly basalt) is the oldest unit that crops out in the mine area and probably correlates with the Eocene Kamloops Group (Read, 1995). It is basement to the basin that contains the diatomite deposit. The andesite consists essentially of plagioclase laths (50-70%), measuring less than 0.5 millimetres, set in a glassy matrix. Medium grey, vesicular breccia consisting of angular clasts ranging from a few millimetres to a few centimetres (rarely 20 centimetres) was described by (Read, 1995); however it is not shown on the cross sections.

The **Basal Carbon-rich unit (Mbc)** forms lenses up to 2 metres in thickness (Figure 2a and 2b). This layer

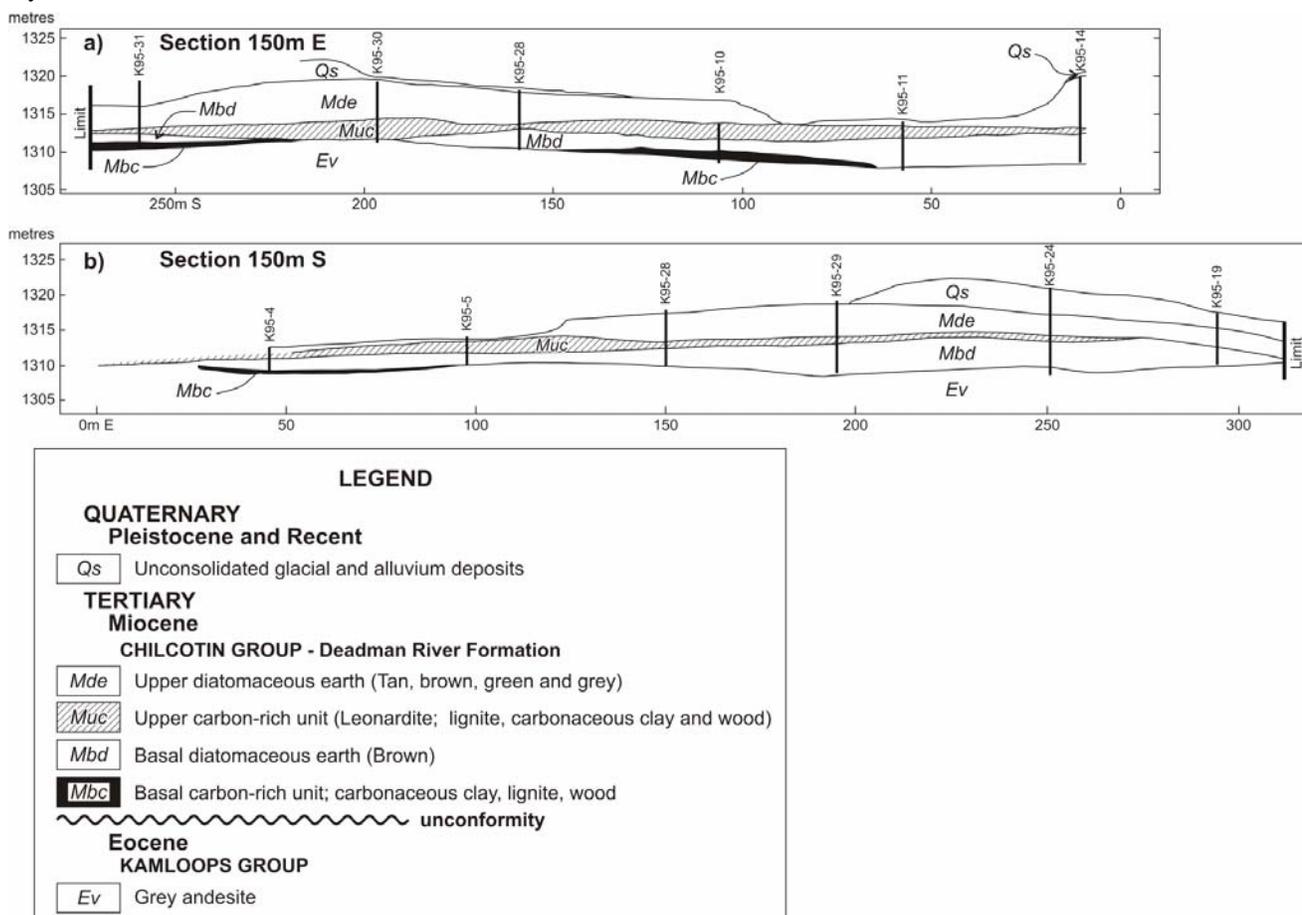


Figure 2: North-south (a) and east-west (b) sections across the Red Lake deposit (modified from Read, 1995).

was not exposed at the time of our visit and therefore was not studied or sampled.

The **Basal Diatomaceous Earth (Mbd)** unit is a brown diatomite layer, locally over 5 metres thick, that overlies the lower organic-rich horizon. This layer is porous, soft and relatively ductile. It has a massive appearance and consists mainly of clay (probably montmorillonite) and diatoms.

The **Upper Carbon-rich unit (Muc)** is described as carbonaceous shale, coal-like material and black wood fragments (Read, 1995). The unit is locally over 2 metres thick and it separates the previously described brown Basal Diatomaceous Earth from the Upper Diatomaceous Earth unit. It was exposed in the floor of the mine at the time of our visit and nine samples were collected. The unit also contains crumbly, sand-like diatomite-bearing lenses or layers and represents a potential source of leonardite or humate.

The **Upper Diatomaceous Earth (Mde)** unit is beige to pale grey or brownish in colour and up to 7 metres thick (Figure 2a and 2b). It is commonly laminated but

can be massive. Centimetre-scale parting is a dominant texture. This highly absorbent, light-weight unit (density 0.61 g/cm³) consists mainly of montmorillonitic clay, but contains 20 to 35% diatomite skeletons. Up to now, this rock has provided the bulk of the raw material shipped to the Western Industrial Clay Products plant.

Overburden (Qs) consists mainly of unconsolidated glacial and alluvial deposits. Local areas are covered by material that was relocated during mining.

GEOCHEMISTRY OF THE UPPER CARBON-RICH UNIT (*Muc*)

The nine samples of **Upper Carbon-rich unit (Muc)** that were selected and described in the field were analyzed for their humic acid content. Determinations made using both the colorimetric and chemical precipitate methods on air-dried samples are shown in Table 1.

The data indicates extreme variations in humic acid concentrations perpendicular to the strike and possibly along strike. These variations indicate that a much broader systematic sampling is required to obtain a representative humic acid content for the *Upper Carbon-rich unit* at the mine site. It also suggests that careful blending would be needed to obtain and maintain a consistent humic acid

TABLE 1: HUMIC ACID CONTENT OF THE UPPER CARBON-RICH UNIT (MUC) DETERMINED USING COLORIMETRIC AND CHEMICAL PRECIPITATION METHODS.

SAMPLE *	% Humic Acid Colorimetric	% Humic Acid Chemical precipitate
RED-007	5	-
RED-00-15	12	-
RED-00-16	52	75.0
RED-00-17	43	45.2
RED-00-19	9	5.8
RED-00-20	47	48.8
RED-00-22	22	7.0
RED-00-23	13	3.7
RED-00-24	20	13.8

* all samples were air-dried

content if leonardite material from Red Lake were to be mined and marketed as a soil conditioner. Some of the samples listed in table 1 were also analyzed for major and trace elements.

Major element analyses shows that SiO₂ (41 to over 80%), Fe₂O₃ (1.62 to 28.14%) and Al₂O₃ (5 to 23%) are the major constituents in the ash. High SiO₂ content was expected because the host is diatomite-bearing. The Al₂O₃ values reflect the relative clay content. There appears to be no relationship between Fe₂O₃ and SO₃, which confirms the absence of sulphides previously established by visual observation and fully expected in the highly oxidized environment.

Trace element data, reported on a "total rock" basis (not in ash), indicate that silver (Ag), arsenic (As), gold (Au), beryllium (Be), bismuth (Bi), cadmium (Cd) and selenium (Se) are below the detection limit. Other elements are present in trace, but detectable quantities including Ba (< 291 ppm), Co (< 96 ppm), Cr (< 19 ppm), Cu (< 32 ppm), La (< 119 ppm), Mn (< 187 ppm), Mo (< 44 ppm), Ni (< 107 ppm), P (< 0.087 %), Pb (< 47 ppm), Sb (< 16 ppm), Sr (< 86 ppm), Th (< 5 ppm), U (< 5 ppm), V (< 270 ppm), W (< 23 ppm), Zn (< 74 ppm). Boron levels (19 to 547 ppm) most likely reflect the original playa-type environment.

'Ultimate analysis' consists of H₂O, C, H, N, ash, S and oxygen content and is reported as A.R. (as received), A.D. (air dried) and Dry (oven dried). The ultimate analysis results indicate that within the pit, water represents 30 to over 67%, and ash 8.6 to over 50% of the unprocessed raw material from the Upper Carbon-rich unit (*Muc*). Sulphur content varies from 0.17 to 0.71%, nitrogen from 0.01 to 0.77% and oxygen from 2.64 to 16.15% on an as received basis. Upon drying the proportions of all of these constituents, except water, increase substantially.

CONCLUSION

Although this preliminary study is not based on systematic sampling, it indicates extreme fluctuations in humic acid content within the *Upper Carbon-rich unit*. Consequently, we can not speculate on its average humic acid content. Depending on the average humic acid content of this unit, the material could become a valuable co-product of diatomite-rock mining and be marketed as leonardite or humate.

Concentrations of deleterious trace elements (As, Se, base metals and radionuclides) in ash from these samples are low. Such low concentrations would not limit the use of the humic acid-bearing material from the Red Lake deposit in agricultural and horticultural applications. The *Lower Carbon-rich unit* was not sampled but it is possible that it may also have high humic acid content and should be evaluated.

ACKNOWLEDGEMENTS

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ISRAELI WHITE LIMESTONES – IMPLICATIONS FOR USES BASED UPON THEIR REACTIVITY AND OTHER PROPERTIES

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INTRODUCTION

Several industrial processes involve reactions with ground limestone. For example, the use of limestone within Flue Gas Desulphurization (FGD) filters in power plants (Minster, *et al.*, 1998). The present work is based on data collected in a project initiated by the Israeli Electric Corporation Ltd. (IEC) to find appropriate limestone for the first FGD device to be built in Ashqelon, Israel. Samples of known mineable limestone deposits were collected or supplied by a number of limestone producers. The samples were analyzed and graded according to physical and chemical properties as defined in the IEC protocols.

Limestones of Lower Palaeozoic to sub-recent ages are widespread in Israel, and are particularly abundant in the Upper Cretaceous and the Eocene. A section representing the geological units of the area is presented in Figure 1 (after Hirsch, 1983). We evaluated representative limestone samples from different sites in Israel. Although these samples represent different geological sections, most were from the Bina and Shivta formations of Turonian age (Upper Cretaceous). Most samples are from the Negev, southern Israel, and a few are from the Eocene sequence of northern Israel.

To be effective in this usage, the limestone has to be highly reactive. Chemical purity and colour are important and the energy consumption required for crushing and grinding all play a role in choosing the appropriate stone.

In order to make right decisions about the best raw materials for the FGD process, purity and energy consumption had to be examined. Thus, additional parameters studied were the trace element content, the whiteness, and the grindability. It was beyond the scope of this work to study the statistical connection between the reactivity and other physical and chemical parameters measured.

REACTIVITY

There is a pseudo-standard for reactivity assessment (Test Procedure, 1988) that is defined as the: “reaction of 500 mg of limestone ground, so more than 90% will pass through a 230 mesh sieve (that is, that 90% is less than 63µm in size) in suspension in 200 ml of reagent water. The decomposition reaction is carried out in 1N hydrochloric acid at constant pH of values of 4.0, 4.5 and

5.0 at a constant temperature of $20 \pm 1^\circ\text{C}$ in a well-stirred vessel”.

Simplified reaction equations follow. According to Wollast (1990), calcite dissolution can proceed by means of a variety of mechanisms:

- (1) $\text{CaCO}_3(\text{s}) + \text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{Ca}^{++}(\text{aq}) + \text{HCO}_3^-(\text{aq}) + \text{Cl}^-(\text{aq})$
- (2) $\text{HCO}_3^-(\text{aq}) + \text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \rightarrow \text{H}_2\text{CO}_3(\text{aq}) + \text{Cl}^-(\text{aq})$
- (3) $\text{H}_2\text{CO}_3(\text{aq}) \rightarrow \text{H}_2\text{O} + \text{CO}_2(\text{g})$

Thus the overall reaction is:



The reaction rate is expressed by the following equation:

$$\text{rate} = \frac{-d[\text{A}]}{dt} = k[\text{A}]^p[\text{B}]^q[\text{C}]^r \dots$$

After integration, different expressions may be obtained according to the reaction order. For first-order reactions: $\ln ([\text{A}_0]/[\text{A}]) = kt$, a plot of $\ln ([\text{A}_0]/[\text{A}])$ versus t , yields a straight line with a slope of k . For second-order reactions the integration yields two solutions: one for $p=q=1$ and $[\text{A}_0] \neq [\text{B}_0]$ and the other for $[\text{A}_0] = [\text{B}_0]$ or $p=2$. The mathematical expressions for the two second-order reactions are given in the literature (for example, Moore, 1956). A straight line is achieved by plotting $\ln ([\text{B}_0][\text{A}]/[\text{A}_0][\text{B}])$ or $([\text{A}_0]-[\text{A}])/[\text{A}_0][\text{A}]$ versus t , respectively. Where $[\text{A}]$, $[\text{B}]$,... are the momentary concentrations of the reactants; $[\text{A}_0]$, $[\text{B}_0]$, are the initial concentrations and the sum of the concentration constants ($p+q+\dots$) is the nominal reaction order. Similar solutions are available for reactions of third or higher orders.

In the mathematical expressions the “ k ” variables represent the reaction rate constants. As their values increase, reaction velocity accelerates. Therefore, preferable parameters for comparing the reactivity of limestones are the reaction rate constants. To calculate k it is necessary to know the reaction order. Few references to the reaction order of the system $\text{CaCO}_3 - \text{HCl}$ can be found in the literature. Zhang *et al.* (1998) investigated this system in a continuous flow stirred tank reactor. They found the reaction to be a zero-order reaction but noted that the reaction rate changes with time. Alkattan *et al.* (1998) studied the rate of the reaction and although they discussed some aspects of reaction order, they did not mention the order itself. At first glance it seems that the

THICKNESS (m)	LITHOLOGY	MEMBER / FORMATION	GROUP
0-20		Alluvium	
0-30		Nahshon Cgl.	
10		Bet Nir Fm.	SAQIYE Gr.
100		Ziqlag Fm.	
150		MARESHA Mbr.	'AVEDAT Gr.
100		ADULAM Mbr.	
0-50		Hatrurim Fm.	MOUNT SCOPUS GROUP
40		Taqiye Fm.	
10-15		Ghareb Fm.	
70		Mishash Fm.	
100		Menuha Fm.	
100		Bi'na Fm.	JUDEA GROUP
50-150		Weradim Fm.	
0-15		Kefar Sha'ul Fm.	
40-90		Amminadav Fm.	
0-15		Moza Fm.	
40-60		Bet-Meir Fm.	
0-20		Kesalon Fm.	
90-130		Soreq Fm.	
40		Giv'at-Ye'arim Fm.	
100		Kefira Fm.	
40		Qatana Fm.	
15		'En-Qinya Fm.	

Figure 1. Columnar section representing limestone-bearing geological units sampled (after Hirsch, 1983)

reaction, $\text{CaCO}_3 + 2\text{HCl} \rightarrow \text{CaCl}_2 + \text{CO}_2$, with rate = $k[\text{CaCO}_3]^1 [\text{HCl}]^2$ is of the third order ($p+q=1+2$). However, since the reaction is carried out at a constant pH, the acid concentration remains constant, so the term $[\text{HCl}]^2$ is included in the rate constant k . For these conditions, the rate equation will be of the following form: rate = $k'[\text{CaCO}_3]$, can be expressed as a first order reaction. In this study, we found that the case is not obvious and that the reaction order is more similar to a second-order one.

RESULTS

Reactivity Measurements

Reactivity values obtained vary greatly. In most of the samples the carbonate reacts promptly, but in others

reaction rates were rather slow. It should be emphasized that differences in reactivity might reflect grain size variance of the analyzed powders, although all samples were ground and sieved to less than $63 \mu\text{m}$ in accordance with the protocol. There is no detailed information about the grain size distribution of the fine powders. To follow up our work, a grain size distribution analysis test must be done to verify whether the differences in reactivity are solely related to the characteristics of the limestone or are also influenced as expected by grain-size distribution. Trace elements in the limestone samples chosen for examination are generally low and brightness values high. The grindability, like the reactivity values, varied.

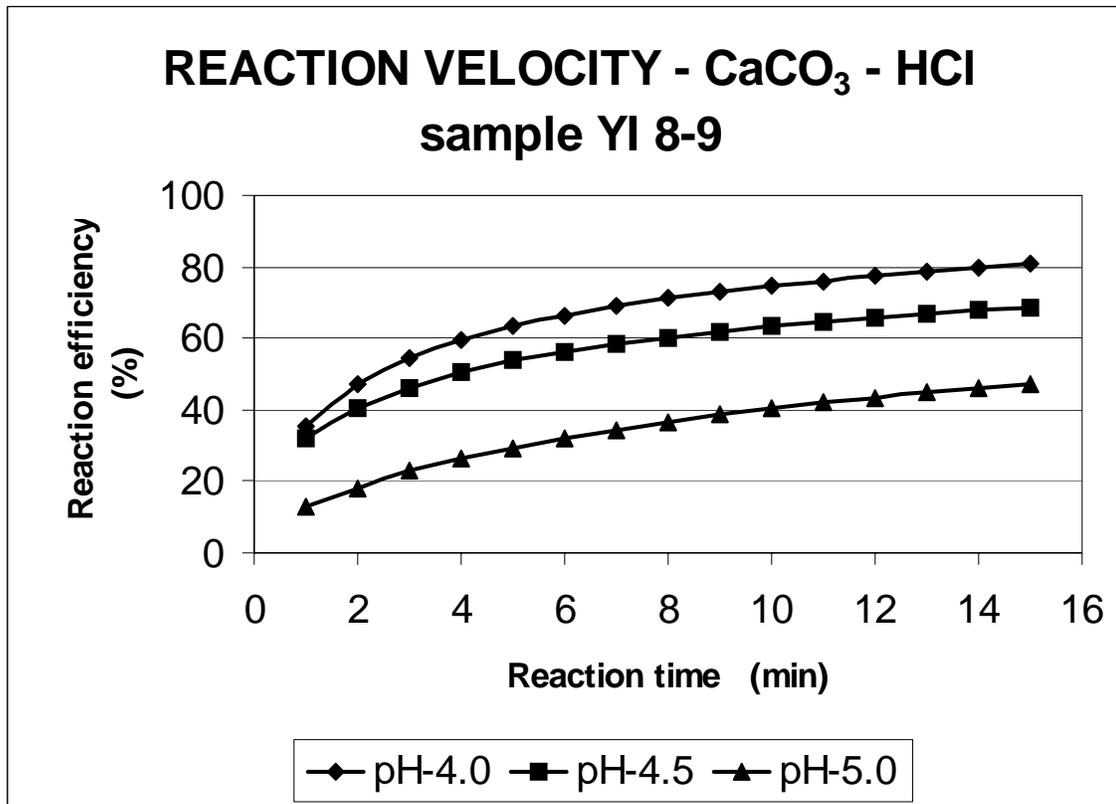


Figure 2. Dissolution kinetics of certain limestone sample at three constant pH values.

EVALUATION OF THE REACTION ORDER:

The chemical conversion rates were measured in many limestone samples in accordance with the Test Procedure protocol. Lines were plotted according to the various integration products for different reaction orders. The slopes of these lines equal k (or $-k$), which is the rate constant for the various reaction orders. The formal reaction order for the reaction is deduced from the line with a linear regression coefficient that is closest to unity. We found that the best-fit line was achieved for a second-order reaction of the second type (and the rate constant was measured from the slope of the plotted line: $t = ([A_0] - [A]) / [A_0][A]$).

The rate constant was determined as follows. A 0.5000 gram limestone sample ground to minus 230 mesh, was introduced into a well stirred reaction vessel containing 200 millilitres of reagent water. 1N hydrochloric acid was added to keep a fixed pH value. The amount of limestone dissolved at constant temperature of $20^\circ\text{C} \pm 1^\circ\text{C}$, is proportional to the amount of acid added to maintain the chosen pH value. The acid consumed was recorded for 15 minutes at one-minute intervals.

The results of this analysis for sample YI 8-9 at the pH values of 4.0, 4.5 and 5.0 are given in Table 1 and Figure 2.

The reactivity values of various limestones samples at a constant pH value of 4.5 are presented in Figure 3.

The method of evaluating the reaction order from kinetics curves is demonstrated in Figure 4. Only first and second order of type $p = q$ reaction order evaluations are given here. The order is based on the linearity of the appropriate integration product of the rate equation. The best straight line achieved (largest R squared value for the same n) for an integration product versus reaction time plot is taken to represent the reaction order, and its slope to equal k .

Calculation of the first order line value: $\ln ([A] / [A_0])$, is presented on Figure 4a. The weight of each sample is 0.500 g and the molecular weight of limestone (CaCO_3) is 100. Calculation for the second-order line is done in a similar way (see Figure 4b).

From Figure 4 it may be deduced that the reaction is of second-order, or close to it. The lines for each pH value are of more linear for the second-order reaction than any of the others (only first and second-order are given on the

TABLE 1. DISSOLUTION PERCENTAGE OF A LIMESTONE SAMPLE (YI 8-9) AT THREE CONSTANT PH VALUES, 4.0, 4.5 AND 5.0.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	REACTION TIME (MIN)
80.8	79.8	78.7	77.5	76.1	74.6	72.9	71.1	69.0	66.5	63.5	59.8	54.6	47.4	35.5	CONVERSION AT pH – 4.0 (%)
68.7	67.9	66.9	65.9	64.8	63.5	62.0	60.3	58.4	56.3	53.7	50.4	46.3	40.7	32.0	CONVERSION AT pH – 4.5 (%)
47.4	46.2	44.9	43.5	42.0	40.3	38.5	36.5	34.4	32.0	29.4	26.4	22.8	18.2	13.0	CONVERSION AT pH – 5.0 (%)

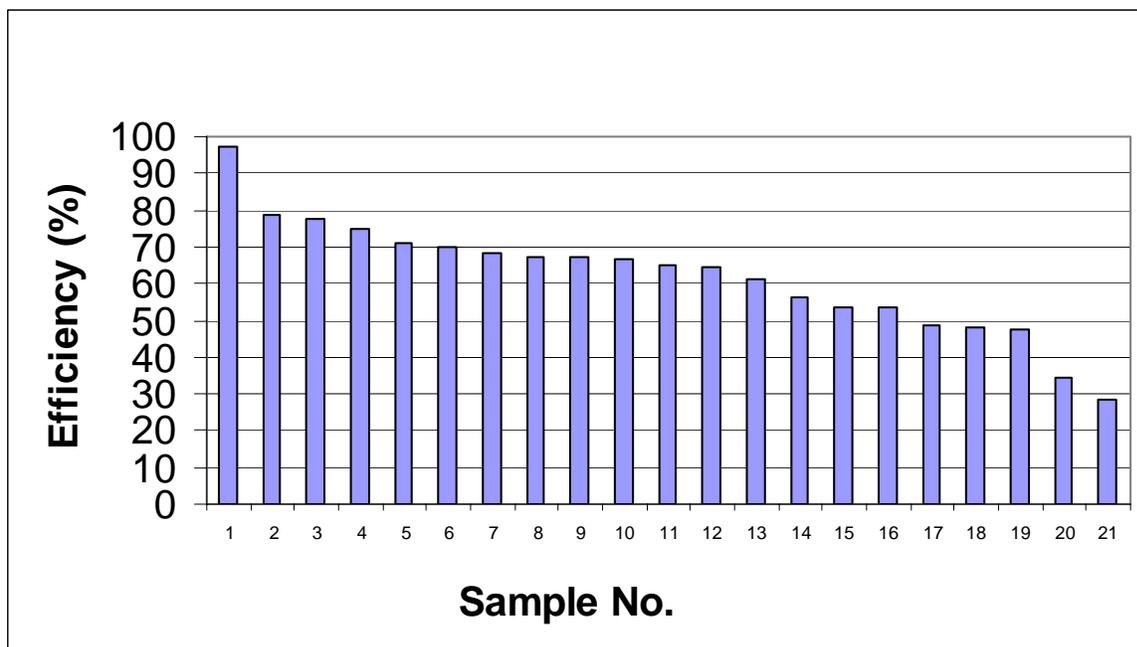


Figure 3. Reaction efficiency of various Israeli limestones (wt% of limestone converted in 5 minutes)

figure). The line slopes are proportional to the reaction rate constant (the reaction rate depends on pH, temperature and other factors). Use of rate constants for limestone characterization is more efficient than using conversion percentage after a constant time because it takes into account the values received for the whole 15-minute analysis time (in the industry, the time used is 5 minutes).

GRAIN SIZE INFLUENCE

The reaction between hydrochloric acid and limestone is carried out on the surface of the crystallites or crystal aggregates. Thus, the surface area, which is closely related to the grain size, is an important factor.

For studying the influence of grain size on reaction rate, a limestone sample was ground and separated into a series of grain size ranges as follows: 20 to 40, 40 to 60, 60 to 80, 80 to 120, 120 to 230, 230 to 325, and less than

325 mesh. The average grain size obtained in each range is therefore 640, 340, 215, 150, 95, 55 and 30 μm . The value of 30 μm was chosen arbitrarily for the finest fraction that passed a 325 mesh (< 45 μm) sieve. Each subsample underwent reactivity analysis following the protocol. The results are presented in Figure 5 and clearly show the strong influence of grain size on reactivity, as was expected.

To calculate the surface area of 0.5 grams of ground and sieved limestone, particles of cubic shape were assumed. A proportional result would be achieved for any regular body shape, such as a sphere or rhombohedron (the typical calcite crystal shape).

There is an approximately linear relation between the reaction rate and the surface area of the particles (Figure 6). The only exceptions are small particles with large surface areas. This may be because the surface area calculations are in error due to the large size distribution range.

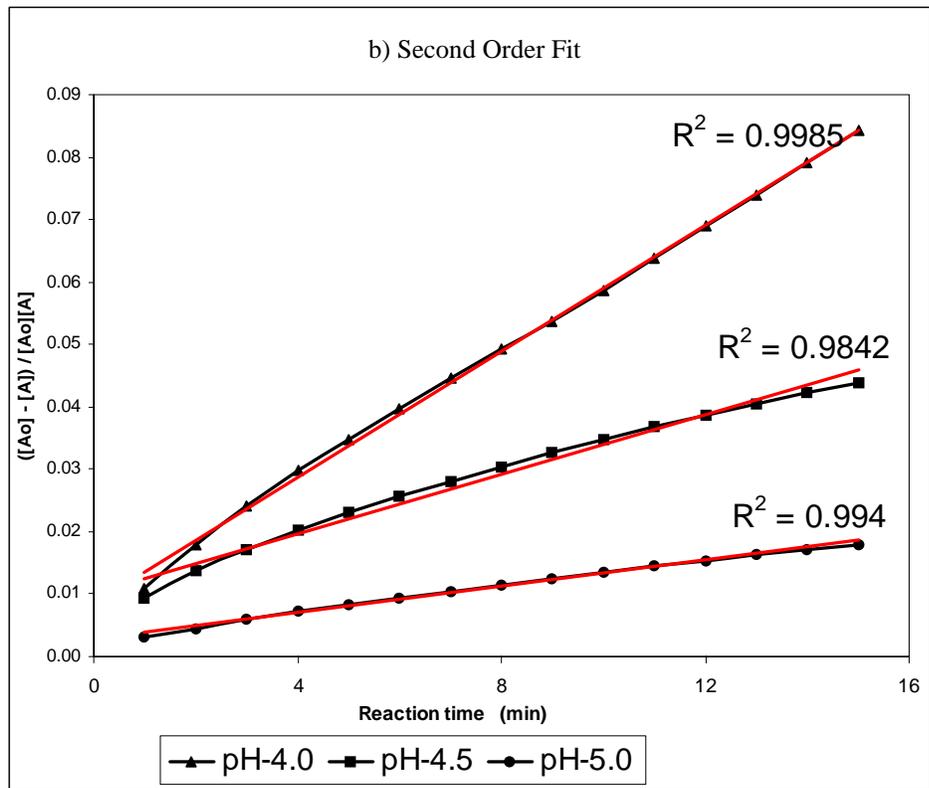
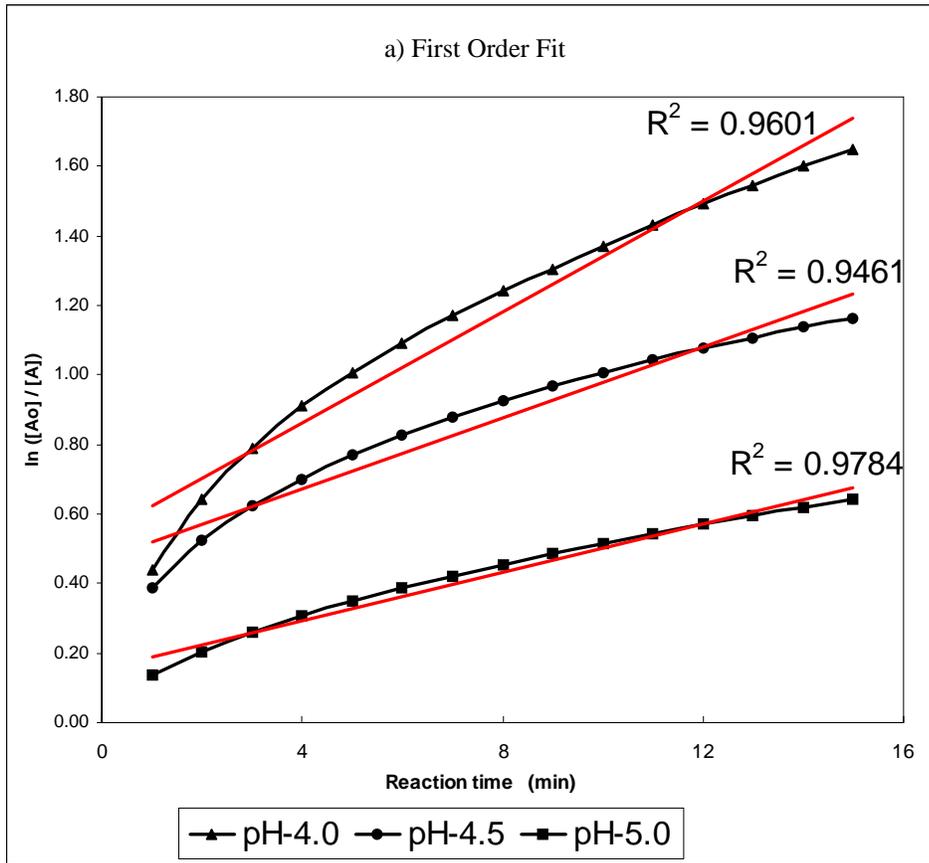


Figure 4. Graphic presentation of first (a) and second order (b) reactions and calculated R squared best-fit lines, for limestone sample Y18-9 at three pH values.

THE TEMPERATURE EFFECT

In accordance with the protocol, the reaction should take place at a constant temperature of $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$. However, dissolution reaction of CaCO_3 in hydrochloric acid is exothermic, hence the reaction mixture evolves heat as it progresses. Most of the heat evolved is absorbed by the relatively large amount of water (200 millilitres) the reaction is performed in. However, the influence of temperature on the reaction efficiency was studied and summarized in Figure 7. Further, the reaction rate constants at various studied temperatures were calculated and summarized in Figure 8. The range of the temperatures studied was small, from 16°C to 25°C , which is the actual range for the reactivity study. Results show that the reaction rate increases as temperature increases, but the temperature influence is small. The rate is relatively low at 16°C , increases at 17°C and remains almost constant in the range of 17°C to 25°C .

The rate constants of the reaction rate yield slightly different results. There is a growth in rate with temperature up to 19°C . At 20°C , the constant drops, and it does not change at higher temperatures (in the studied range).

A possible explanation is the nature of the two mechanisms that control the reaction rate: raising the temperature enhances the reaction rate. However, at higher temperatures, because the reaction is exothermic, the Le Châtelier's principle causes the equilibrium of the reaction to move to the left, which lowers the reaction rate.

CHEMICAL CHARACTERIZATION

Most samples analyzed have more than 98% CaCO_3 content, and some of the Shivta Formation samples have greater than 99.5% CaCO_3 . Some of the samples of the Shivta formation have very low MgO content (0.5-1%).

The required list of specifications for FGD filters for power plant samples imposes upper limits on the following trace elements: As, Be, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Se, V, Zn.

Trace element analyses were carried on 25 samples using ICP-MS and ICP-AES spectrophotometers. The results are summarized in Table 2.

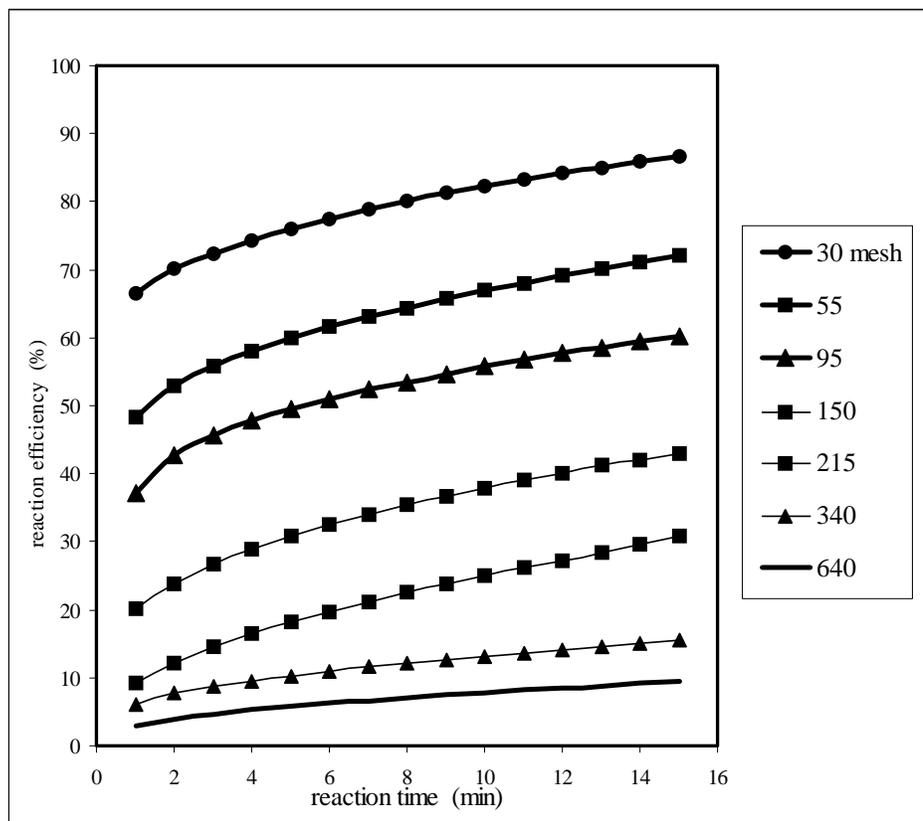


Figure 5. Influence of Grain size on reaction efficiency (at pH 4.5)

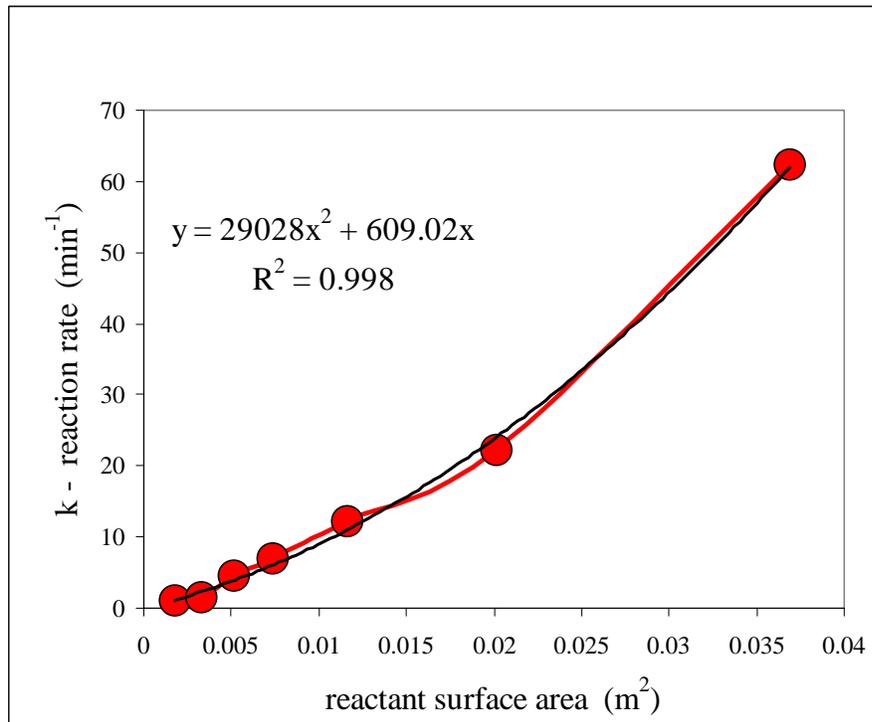


Figure 6. Relation between particles surface area and reaction efficiency (reaction rate), an almost linear dependence.

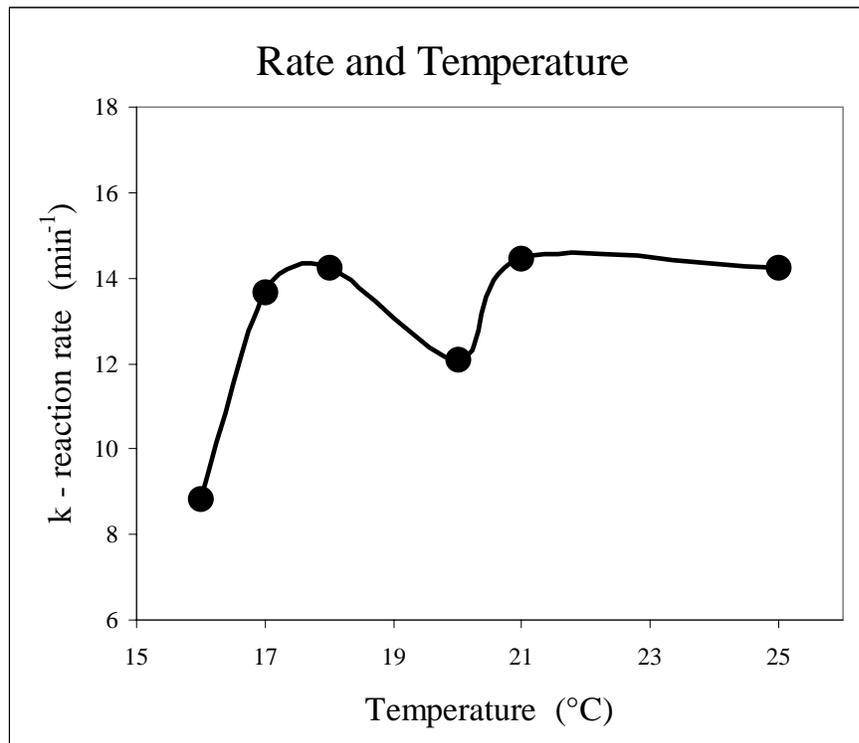


Figure 7. Temperature influence on reaction efficiency.

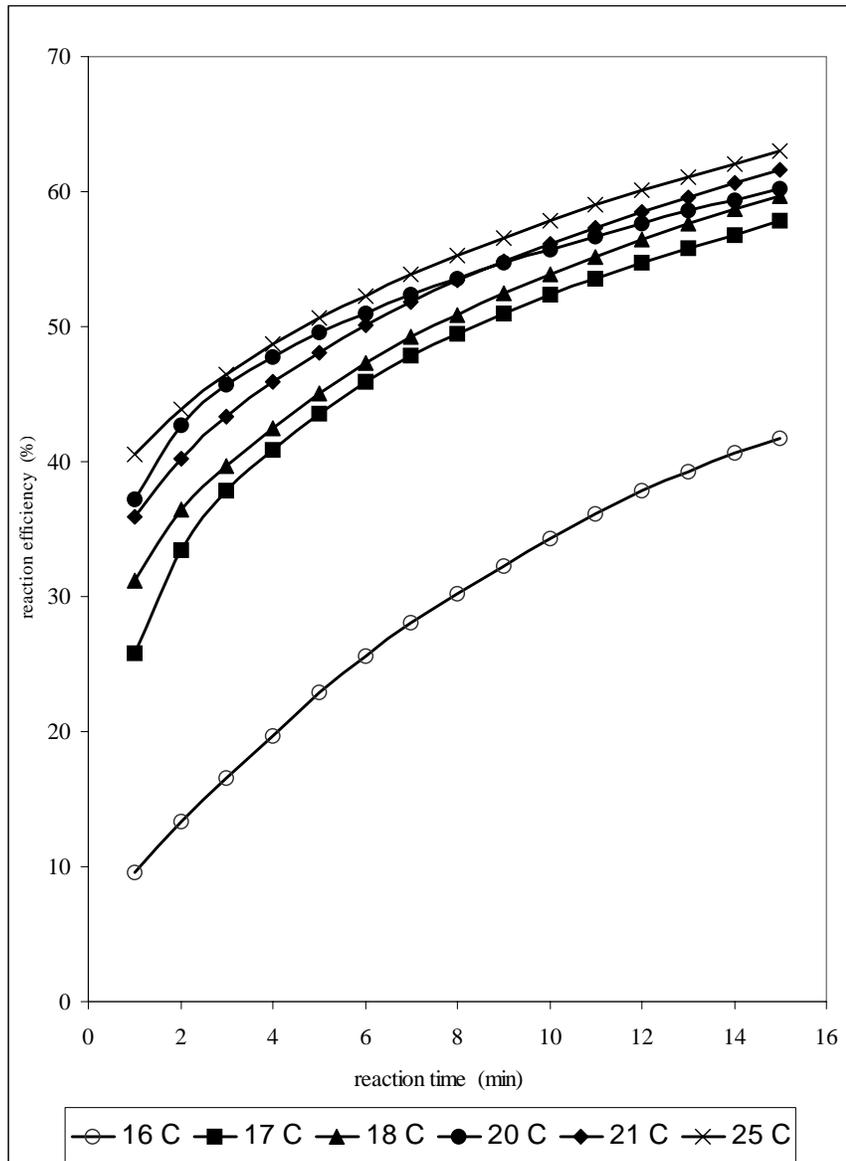


Figure 8. Temperature influence on reaction rate constants.

In general, the examined limestones have low trace element contents relative to the values that were specified.

Eocene white limestones may have somewhat higher trace element contents than those of the high-grade Turonian limestones, but more data is needed to verify this statement.

GRINDABILITY

Grindability is a routine but complex physical examination to evaluate the energy needed to crush a sample to a required size. The laboratory procedure for the standard measurement, the Bond Mill Index

(Bond, 1961), involves many crushing, grinding, sieving and weighing steps for each sample. Although it is relatively expensive and rarely carried out, we processed 16 samples. The starting amount for each sample was about 50 kilograms. The range of the results for the 16 samples is 4.66 to 11.56 kWh/t, with average of 7.35 kWh/t. Most samples meet the required specifications. In the course of the analyses it became obvious that the standard procedure used may be problematic. It does not precisely define the size distribution of the starting material. Thus it is possible that pre-analysis crushing of a sample may influence the apparent grindability energy calculation results.

TABLE 2. SUMMARIZED TRACE ELEMENT ANALYSES CARRIED ON 25 SAMPLES USING ICP-MS AND ICP-AES SPECTROPHOTOMETERS.

Element	Detection limit (ppm)	Concentration in most of the samples (ppm)	Highest concentration in samples (ppm)
As	0.2	Below detection limit	1.5
Be	0.1	Below detection limit	Below detection limit
Cd	0.2	Below detection limit	0.7
Co	1	Below detection limit	2 (one sample)
Cr	2	Below detection limit	20
Cu	2	Below detection limit	8
Hg	0.05	Below detection limit	0.25
Mo	0.5	Below detection limit	Below detection limit
Ni	3	Below detection limit	23
Pb	2	Below detection limit	2.5 (one sample)
Se	1	Below detection limit	Below detection limit
V	3	Below detection limit	13
Zn	10	Below detection limit	Below detection limit

COLOUR MEASUREMENTS

Colour is a most useful parameter of raw minerals and products that are applicable to various industrial uses. It is in particular important for an economic study of industrial limestones. Colour readings were carried out on a Photovolt Reflection Meter. Each sample was ground to a powder in which more than 90% is finer than 74 μm , and dried at 105°C for 24 hours. The analyses were conducted following the DIN 5033 standard (parts 3 and 6), and following the apparatus instructions. In 27 of the studied samples (3 readings for each one) the range was $Y=76.5 - 91$, with an average of $Y=85.46$. Most of the samples have brightness values that are higher than the minimum requirements of the specifications. It should be noted that the preparation procedure, which follows what is specified for in the DIN 5033 standard, does not reflect the true size distribution of the powder. It is possible that a relatively higher portion of finer material within a given powder could give apparently higher brightness values.

SUMMARY

The dissolution reaction of calcium carbonate in hydrochloric acid at constant pH is probably a second-order reaction. Tests indicate that the reaction rate is very sensitive to differences in grain size of the carbonate particles, and also to pH values, but relatively insensitive to small differences in temperature. In order to compare the reactivity of samples from various rocks, it is necessary to analyze powders with similar grain size distributions. It was demonstrated that many of the

high-grade limestones tested meet the crucial chemical purity (low trace element content), brightness and low energy grindability specifications for use in FGD filters for power plants.

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ORIGIN OF SODIUM SULPHATE DEPOSITS OF SOUTHERN SASKATCHEWAN: TRACER POTENTIAL OF STRONTIUM ISOTOPES

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INTRODUCTION

Sodium sulphate is an industrial mineral used in the manufacture of detergents, carpet fresheners and deodorizers, glass, paper and textiles. The Saskatchewan sodium sulphate industry is described by Broughton (1984) and Last and Slezak (1987). Saskatchewan deposits of sodium sulphate are within lacustrine evaporate sequences. To form the deposits, most previous workers agree that groundwater discharge, manifested by seeps and springs in and around the lakes, supplied and continue to supply, dissolved ions to the lakes (Ricketts, 1888; Cole, 1926; Witkind, 1952; Tompkins, 1954; Grossman, 1968; Rueffel, 1970; Last and Slezak, 1987; McIlveen and Cheek, 1994). Evaporation concentrated the ions in the lakes until they formed high specific gravity brines. Once the brines reached saturation, salts, primarily mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), were deposited.

We have started a five-year project to advance understanding of the origin of these deposits as modern ore-forming systems. Because groundwater continues to supply ions to the lake basins through spring discharge, our approach is hydrogeological. Our major objective is to quantify fluid and chemical mass balances of the systems. Our initial focus has been to test the hypotheses presented by previous workers about groundwater flow paths and solute sources to identify specific aquifer inputs to the lake systems, and to assess the amount of groundwater seepage out of the lakes. These are key elements in the mass balance calculations developed by Wood and Sanford (1990) and Donovan (1994). A similar approach to mass balance will be a principal component of a quantitative model for the genesis of southern Saskatchewan sodium sulphate deposits. We reported our preliminary findings for water isotopes and major-ion chemistry at the 1999 Forum on the Geology of Industrial Minerals (Kelley and Holmden, 1999).

STRONTIUM ISOTOPES

Although the relative mass differences between the four isotopes of Sr are too small to exhibit natural mass-dependent isotope variations, ^{87}Sr is more abundant than the other isotopes because it is the natural radioactive decay product of ^{87}Rb . By convention, differences in ^{87}Sr abundance are reported as the ratio $^{87}\text{Sr}/^{86}\text{Sr}$. Typically,

old crustal rocks have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, whereas those in younger crustal rocks and marine carbonates are lower. Strontium follows calcium in geochemical behaviour and dissolves readily in aqueous solutions. Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotope ratios are generally conservative in mixing of waters in lakes or estuaries. This is in contrast to the isotopes of H and O, which are often non-conservative in surface waters because of evaporation. By contrast, in groundwater systems, dissolved Sr isotopes are less conservative than H and O isotopes due to Sr-exchange between rocks and water along the flow path. The degree of non-conservative behaviour is a function of the groundwater velocity and the rock type. In general, faster moving groundwater is more conservative for Sr isotopes than slower moving groundwater. This Sr exchange shifts the isotopic composition of dissolved Sr in a slow moving groundwater system toward a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio that is similar to that of the rock (Bullen and Kendall, 1998; Bullen *et al.*, 1996; Johnson and DePaolo, 1997a; Johnson and DePaolo, 1997b). Strontium concentration may be changed by the precipitation or dissolution of calcite, gypsum or other Sr-containing minerals, but these reactions do not affect the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

METHODS

During 1998, we sampled groundwater for strontium isotope analysis from seeps, discrete spring orifices, and shallow wells in the immediate vicinity of four saline lakes (Vincent, Corral, Boot, and Chain) that host documented sodium sulphate resources. In 1999, we sampled groundwater and lake brine at three of the lakes that were sampled during 1998 (Vincent, Corral, Chain), and two additional lakes (Grandora N., Whiteshore). Locations of the deposits sampled and operating sodium sulphate mines and potassium sulphate production plants are presented on Figure 1.

Strontium was purified from the solution using standard cation exchange chromatography in a clean lab environment. Purified Sr was loaded onto a single Re filament with Ta-gal and measured using a multidynamic peak-hopping routine on a Finnigan MAT 261 thermal ionization mass spectrometer. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were

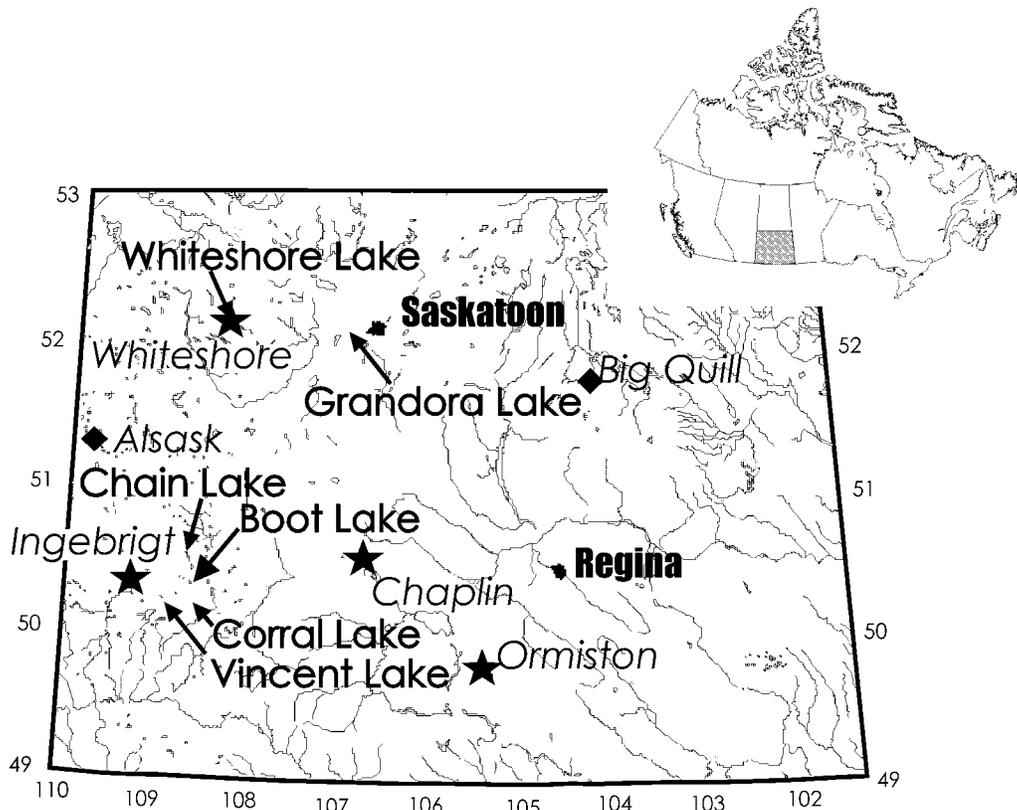


Figure 1. Locations of the deposits, operating sodium sulphate mines, and potassium sulphate production plants.

normalized to $^{88}\text{Sr}/^{86}\text{Sr} = 8.375209$. External precision is ± 0.00002 (2σ). Major element analyses were performed by ICP-AES at the Saskatchewan Research Council with external precision typically $\pm 10\%$ (2σ).

RESULTS

Each of the three lake brines (Vincent, Grandora, Whiteshore) that were sampled at a number of locations showed little spatial variation in $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 2). This indicates that the lake brines are isotopically well mixed, despite being exceedingly shallow (commonly 10 to 50 centimetres) and dense (less than 1.15 g/cm^3).

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for groundwater discharging from springs and seeps near the shores of lakes was generally similar in isotopic composition to that of the lake brine. For example, $^{87}\text{Sr}/^{86}\text{Sr}$ in Grandora Lake brine (mean $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70824) is virtually identical to that of discharge spring waters (0.70830). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Vincent Lake brine (0.70855) is close to and bracketed by that of two discharge springs (0.70836 and 0.70938). One notable exception is Chain Lake, where groundwater discharging into the lake from the only spring located had lower (less radiogenic) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than the lake brine. This result indicates that another, more radiogenic source of freshwater discharge to the lake remains to be identified.

In general, groundwater sampled from shallow wells near the lakes had lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than either lake brine or groundwater discharging from springs. Again, Chain Lake is the exception. Groundwater sampled from a lakeside municipal well that is about 50 metres deep was similar in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio to groundwater discharging directly into the lake from a spring. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of water sampled from a nearby domestic well, in which the water level is approximately equal to the level of the lake, was intermediate between the compositions of the lake brine and the spring discharge. However, these sources are still too low in $^{87}\text{Sr}/^{86}\text{Sr}$ to satisfy the isotope balance of Chain Lake, and indicate contribution from an undiscovered source with higher $^{87}\text{Sr}/^{86}\text{Sr}$.

At first glance, the Sr isotope systematics of Chain Lake seem more complicated than those of the other lakes; however, the results demonstrate the utility of using Sr isotopes as a sensitive tracer of the relative contributions of water and salts from specific aquifers.

Calcite and gypsum discriminate against Sr during precipitation (Kushnir, 1984), which causes the lake brine to increase in Sr/Ca ratio (Figure 2). For example, the $1000\text{Sr}/\text{Ca}$ ratios of Vincent Lake brine samples are all in excess of 9, while these ratios for discharge spring waters (that have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios similar to the lake brine) are about 4. This is indicative of *in situ* precipitation of calcite and/or gypsum in the lake. Therefore, lake brines

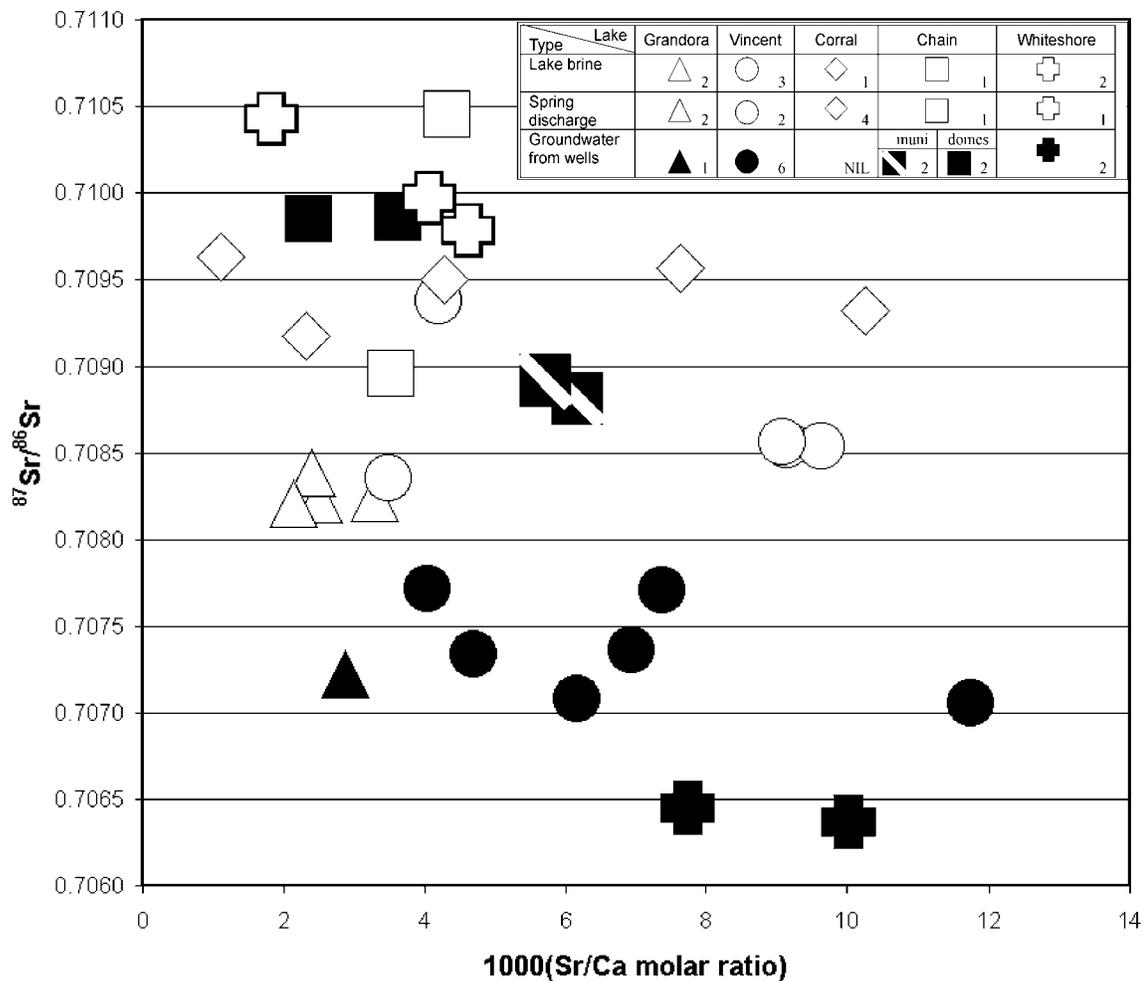


Figure 2. Relationship between $^{87}\text{Sr}/^{86}\text{Sr}$ and $1000(\text{Sr}/\text{Ca molar ratio})$ in brines

with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios similar to those of the aquifer inputs that have higher Sr/Ca ratios suggest that Ca-minerals are precipitating.

DISCUSSION/CONCLUSIONS

Strontium isotopic compositions that we found in groundwater sampled from glacial aquifers are generally within the range observed for Phanerozoic seawater (Burke *et al.*, 1982), indicating that the till is derived predominantly from underlying Cretaceous marine shales of the Bearpaw Formation. More radiogenic strontium (greater than 0.7095) found in some samples reflects a greater proportion of distally-sourced Archean and Proterozoic crystalline material in the tills. In the case of groundwater samples from the Judith River aquifer, the relatively non-radiogenic strontium isotopic ratios suggest

that the Judith River sediment is derived from the western Cordillera, which is composed of relatively juvenile crust.

Strontium isotopes hold promise for fingerprinting aquifer inputs into the saline lake basins that host sodium sulphate deposits. However $^{87}\text{Sr}/^{86}\text{Sr}$ ratios must be examined in the context of flow-path evolution, and constrained by physical hydrogeology, to be ultimately useful in identifying solute source(s) and in quantifying aquifer input(s) to the lake basins that host these deposits.

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THE DISTINCTION BETWEEN LACUSTRINAL AND VOLCANOGENIC CLAYS IN THE VICINITY OF LAKE DISTRICT (ISPARTA, SOUTHWEST TURKEY)

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ABSTRACT

Neogene clays have been investigated from the Gölcük (Isparta) and Yukarıkaşıkara (Egirdir) areas of the Lake District, Isparta, southwest Turkey. Although clay minerals within Yukarıkaşıkara (Egirdir) area are alteration products of sedimentary rocks, those in the Isparta region are derived from the weathering and alteration of volcanic and volcanoclastic rocks of the Gölcük crater lake area. The aim of this study is to correlate and to determine the mineralogical and chemical differences between the clay minerals from these two environments. The mineralogical data confirm that smectite (montmorillonite)-chlorite-kaolinite-illite-calcite-quartz and muscovite are the dominant assemblages associated with detrital clays in the Yukarıkaşıkara sedimentary rocks, whereas smectite (montmorillonite)-illite-halloysite and zeolite dominate in the Gölcük volcanic rocks. Major and trace element data from the two environments also display distinct characteristics. Yukarıkaşıkara (Egirdir) detrital clays have a relatively low K_2O/Al_2O_3 , high TiO_2/Al_2O_3 , and low Zr, Ba, Sr, Nb, Y values; in contrast, those derived from Gölcük volcanics have high K_2O/Al_2O_3 , low TiO_2/Al_2O_3 and high Zr, Ba, Sr, Nb, Y. The latter beds are interpreted to be bentonites derived from volcanic tephra.

INTRODUCTION

The mineralogical and chemical characteristics of detrital and volcanogenic clay-rich beds have been reported in Europe by Seibertz and Vortisch (1979), Pacey (1984), Deconinck *et al.* (1991), Wray (1995, 1999), Wray *et al.* (1996), and Wray and Wood (1998). Clay-rich beds are also well-known from Lake District of southwest Turkey (Bilgin and Köseoglu, 1991; Bülbül, 1993; Söylemez, 1996). The focus of this study is on clays derived from volcanic and lacustrine environments within the Isparta Angle (Figure 1).

The Gölcük and Egirdir areas extend over the western and eastern parts of Isparta within the western Tauride region. Isparta and its surrounding region is geologically referred to the Isparta Angle (Blumenthal, 1963). Bilgin *et al.* (1990), Karaman (1990), Görmüş and Özkul (1995), Yağmurlu *et al.* (1997), Kumral *et al.* (1999, 2000) and Coban *et al.* (2000) have described the geology of Isparta. Neogene volcanic rocks were erupted over a wide region and covered both Mesozoic carbonates and ophiolites, and Tertiary sediments in the hinterland of the Isparta Angle (Figure 1). The volcanics comprise potassic (trachytic / trachyandesitic) flows and related pyroclastic equivalents (Kocyigit, 1984; Bilgin *et al.*, 1990; Yağmurlu *et al.*, 1997; Kumral *et al.*, 1999; Çoban, 2000). Clay-rich occurrences from the region occur not only within the Neogene sediments in the Yukarıkaşıkara area north of Hoyran Lake (Hancer, 1990; Bülbül, 1993),

but also in the volcanic and volcanoclastic rocks situated at the Gölcük crater lake and surrounding area (Bilgin and Köseoglu, 1991; Söylemez, 1996). Clay deposits in Gölcük area are interpreted to be products of weathering and alteration of the volcanoclastic rocks. The volcanic rocks, which consist of trachyandesite, ash tuff, welded tuff and pumice, weather and alter mainly to reddish-brown and grey clays. Clays in the Yukarıkaşıkara area that are believed to be of residual origin coexist with the lignite layers in the marls. Clays were subdivided into three zones on the basis of colour. The zones are termed white, blue-green, and yellowish. The presence of freshwater gastropod fossils confirms a lacustrine environment for the sediments (Bülbül, 1993).

Genetic interpretation and correlation of clay-rich beds in Yukarıkaşıkara and Gölcük basins is based on both new and previously published chemical and mineralogical data. For this study, XRD, Differential Thermal Analysis (DTA) and chemical analyses of clay samples collected from exposures in the Gölcük volcanic area were carried out in the geochemistry laboratories of Eutvos Lorand University, Budapest, Hungary.

MINERALOGY AND GEOCHEMISTRY

The sediment-related Yukarıkaşıkara clay-rich beds are composed predominantly of smectite (montmorillonite), chlorite, kaolinite, illite, calcite, quartz and muscovite. In contrast, the volcanic-related Gölcük clay-rich zones are composed of smectite (montmorillonite), illite, halloysite

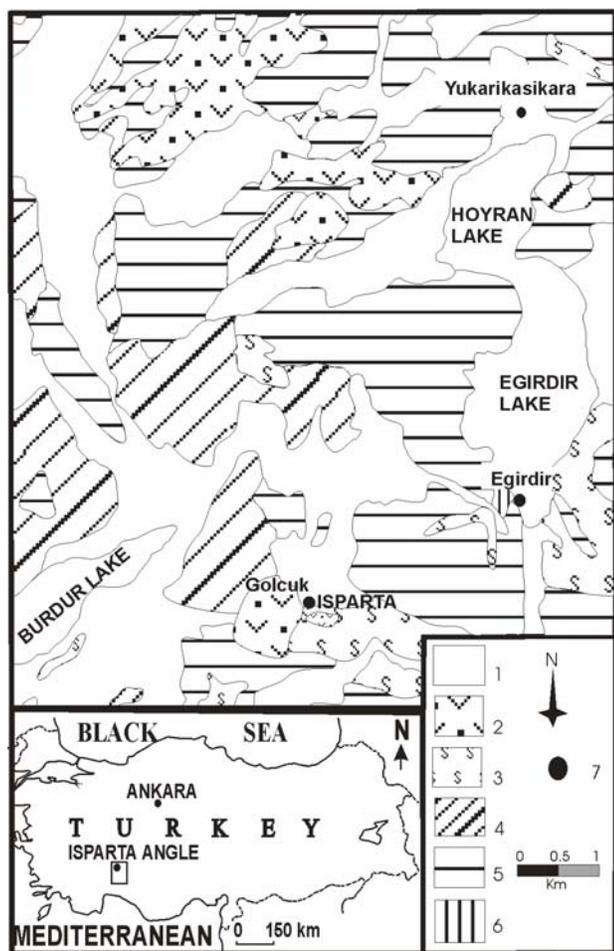


Figure 1. Geological map of the Isparta Angle (modified from Yağmurlu, 1997).

- 1- Plio-Quaternary sediments; 2- Neogene volcanics; 3- Mesozoic ophiolites; 4- Tertiary sediments; 5- Mesozoic carbonates; 6- Paleozoic metamorphics; 7- City centre

and zeolite. Commonly, clay minerals are interpreted to form during alteration or weathering of previously stable silicate minerals. The Yukarıkaşıkara clay-beds have white, blue-green and yellowish colours. They usually are compact and soapy to the touch; hardness varies from 1 to 2 and they expand when placed in contact with water. Most of the clays are residual, left behind when the argillaceous carbonate beds are dissolved. This is in accord with findings of Deconinck and Debrabant (1985), who argue that chlorite abundances increase in the calcareous beds as they dissolve.

The nature of smectite in bentonite deposits depends on both the initial glass composition and the characteristics of the groundwater (Chamley, 1989). Montmorillonite varieties of smectite are derived from silicic volcanic ash (Hein and Scholl, 1978). In the Gölçük area, montmorillonites formed during alteration and weathering of the dominant rhyolitic to dacitic volcanoclastites. Bilgin and Köseoglu (1991) also

reported montmorillonite from Gölçük volcanoclastites. Illite and halloysite are also abundant minerals in the Gölçük bentonites. Fischer and Schmincke (1984) noted that smectites tend to be replaced by illite-smectite and illite with increasing burial depth. However, Quantin *et al.* (1987) report that halloysite can constitute significant amounts of diagenetic alteration products of alkaline trachytic pumices in temperate regions, similar to Central Italy. Halloysite is evident on x-ray diagrams by peaks at 7.12 Å, 4.43 Å, 3.57 Å, 2.56 Å, 2.49 Å and 2.33 Å. When the mineral is heated from 0°C to 1300°C, endothermic peaks occur at 130°C and 580°C, and an exothermic peak at 980°C (Mackenzie, 1970). Zeolites are also common in alkali-rich volcanic environments confirming high-silica activity in the aqueous solutions at the time of silicate crystallization (Velde, 1995). Potassic feldspar-rich trachytic volcanism is widespread in Gölçük area, but no hydrothermal alteration was observed in the region. According to Velde (1995) zeolites in clay-stable environments are replaced by feldspar and quartz when chemical equilibrium is attained. Zeolites in the altered Gölçük volcanic rocks may be in-situ, open-system alteration products that are replacing the alkali feldspars. The mineralogical data demonstrate that smectite (montmorillonite) is the predominant clay mineral in both the lacustrinal (Yukarıkaşıkara) and volcanogenic (Gölçük) environments, whereas illite is more abundant in the volcanogenic environment.

Major and trace element data are presented in Table 1. Plots of K_2O versus Al_2O_3 , TiO_2 versus Al_2O_3 and SiO_2/Al_2O_3 versus TiO_2/Al_2O_3 clearly discriminate detrital beds and bentonites (Figure 2a, b, c). Yukarıkaşıkara detrital clays have relatively low K_2O/Al_2O_3 but high TiO_2/Al_2O_3 ratios relative to clays derived from the Gölçük volcanics. However, a far more effective separation is the enrichment of Ba, Sr, Zr, Nb and Y in bentonites relative to detrital rocks. Concentration of incompatible elements (Ba, Rb, Sr, Zr) within Gölçük bentonites exceed 100 ppm, and range up to 3500 ppm, while concentrations in Yukarıkaşıkara detrital clays vary from 11 to 30 ppm for Zr, 20 to 75 ppm for Ba, 8 to 27 ppm for Rb and 6 to 14 ppm for Sr (Table 1). Extreme enrichment of incompatible elements (like Ba, Sr, Zr) is also a characteristic aspect of the Isparta alkaline volcanism (Alıcı *et al.*, 1998). Pacey (1984) noted that high concentrations of immobile chemical elements such as Zr and Nb might indicate that the ancient volcanic layers were modified by diagenetic alteration. Volcanic rocks in the Gölçük area consist of flows, welded tuff and pumice, and their composition ranges from rhyolite to trachyandesite (Bilgin and Köseoglu, 1991). To test the correlation between volcanogenic clays and the host volcanic rocks, samples were plotted on the Zr- TiO_2 versus Nb-Y diagram (Figure 2d). All bentonites plotted fall well within the field of evolved silicic rocks signifying their host-rock origin.

TABLE 1. MAJOR OXIDE (WT %) AND SOME TRACE ELEMENT (PPM) CONTENTS OF THE CLAY SPECIES FROM THE YUKARIKASIKA (NB*) AND GÖLCÜK (G) AREA, ISPARTA, SOUTHWEST TURKEY

Sample	G1	G2	G3	G4	G5	G6	Nb5	Nb10	Nb9	Nb3	Nb11	Nb7
SiO ₂	63.70	59.50	75.30	67.90	75.00	54.00	62.10	60.70	64.50	54.50	72.60	60.70
TiO ₂	0.38	0.43	0.50	0.60	0.55	0.54	0.90	1.09	0.94	1.20	0.93	0.92
Al ₂ O ₃	17.50	17.80	15.10	14.70	14.00	30.30	15.60	24.90	15.40	31.30	16.30	16.00
Fe ₂ O ₃	2.72	3.58	2.09	7.32	3.00	2.00	14.80	5.96	12.50	4.25	4.81	12.20
MnO	0.07	0.10	0.10	0.12	0.14	0.10	0.32	0.01	0.04	0.01	0.03	0.07
MgO	0.76	0.73	0.90	1.05	1.45	2.00	1.70	2.34	4.92	1.07	1.24	4.79
CaO	2.86	3.00	1.00	0.75	1.00	1.00	1.85	0.70	1.49	0.65	0.30	3.25
Na ₂ O	5.21	5.30	0.25	0.36	0.50	0.20	0.29	0.52	0.02	0.62	0.33	0.01
K ₂ O	5.28	5.14	4.88	7.32	5.00	10.00	2.67	3.57	1.47	4.66	2.82	1.39
P ₂ O ₅	0.34	0.25	0.25	0.22	0.31	0.27	0.08	0.06	0.08	0.06	0.04	0.09
LOI	0.60	3.50	0.65	0.56	0.72	0.60	1.20	1.23	0.95	2.30	2.15	2.60
Total	99.41	99.25	101.00	100.90	101.70	100.90	101.50	101.10	102.30	100.60	101.50	101.90
Zr	381.00	417.00	355.00	287.00	356.00	443.00	30.60	15.30	12.00	15.90	30.60	11.80
Ba	1686.00	1548.00					48.00	50.80	19.50	74.60	49.00	19.90
Rb	191.00	144.00					13.10	23.10	9.30	26.40	14.30	8.60
Sr	2241.00	3318.00					6.10	14.10	12.60	13.60	5.80	13.10
Y	21.00	24.00	26.00	24.00			4.70	3.20	2.30	3.00	3.70	2.70
Nb	18.00	21.00	20.00	18.00			0.80	1.40	1.60	1.70	0.90	1.10

* from Bülbül (1993)

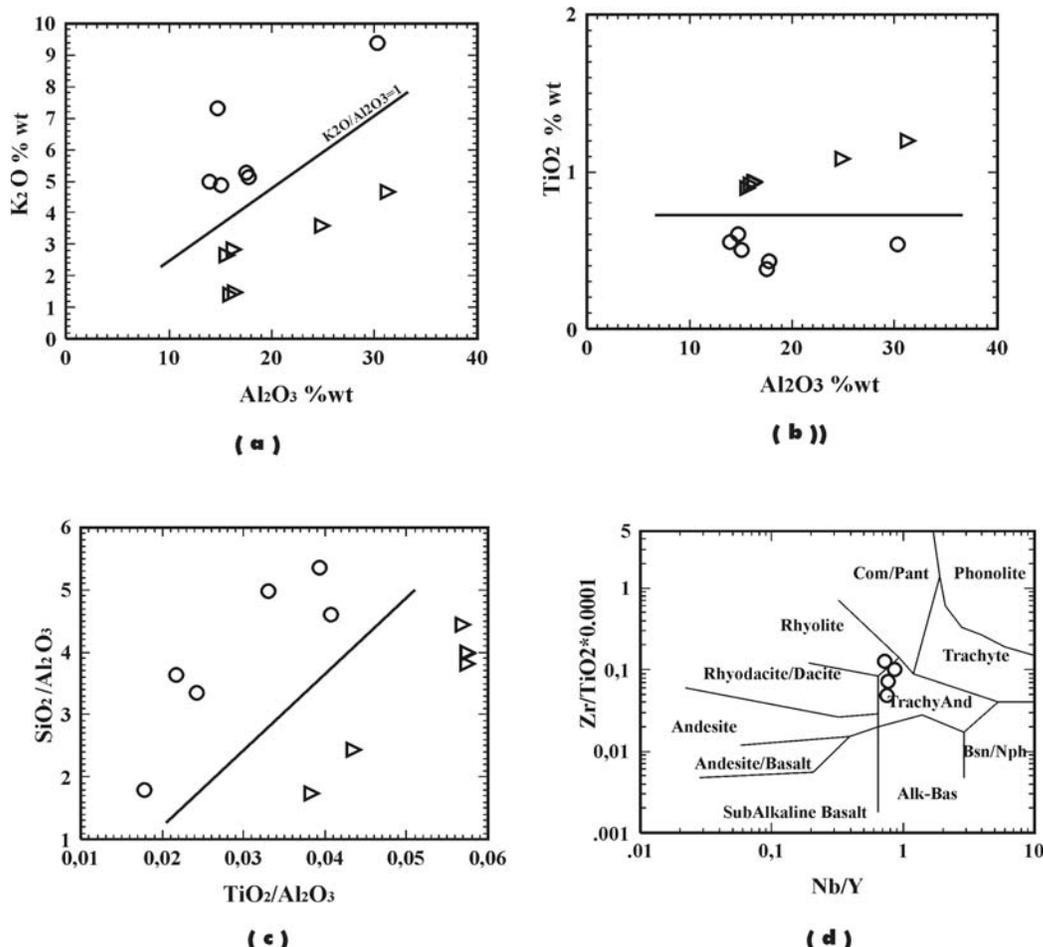


Figure 2. a) , b) and c) Plots of K₂O vs. Al₂O₃, TiO₂ vs. Al₂O₃, and SiO₂/Al₂O₃ vs. TiO₂/Al₂O₃, respectively. d) Plot (After Winchester and Floyd, 1977) of (Nb/Y) / (Zr/TiO₂) for Gölcük bentonites. Symbols: > - The lacustrine (detrital) Yukanskara clays, and O - volcanicogenic clays (bentonite) from Gölcük volcanics.

CONCLUSIONS

Using a combination of mineralogical and chemical data, we compared clay beds from the Neogene Yukarıkaşıkara detrital and Gölcük volcanic geological environments within the Isparta Angle, southwest Turkey. Clay beds derived from volcanic rocks are characterized by the presence of smectite (montmorillonite), illite, halloysite and zeolite. Those derived from lacustrine beds consist of smectite (montmorillonite), chlorite, kaolinite, illite, calcite, quartz and muscovite. Gölcük clay beds are interpreted to be bentonites derived from the volcanic tephra. Variations in K₂O/Al₂O₃, TiO₂/Al₂O₃ and SiO₂/Al₂O₃ ratios and in incompatible element abundances are useful in distinguishing and determining the genesis of these clays.

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MARILLA PERLITE - VOLCANIC GLASS OCCURRENCE, BRITISH COLUMBIA, CANADA

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ABSTRACT

Perlite is a natural hydrated volcanic glass that displays concentric 'onion-skin-like' fractures in hand sample or in thin section. It can occur as silicic lava domes, lava flows, welded ash-flow tuffs, glassy plugs, laccoliths and dikes. There are two main processes that cause hydration of perlite. Primary hydration occurs during formation of the rock before it has cooled; secondary hydration occurs after the rock has cooled and is the more important of the two processes. Perlite has a number of industrial and agricultural applications. There are at least 23 known occurrences in British Columbia, which are listed in MINFILE (a British Columbia computer-based mineral inventory system). There are currently no producing perlite mines in Canada.

The Marilla perlite occurrence is located approximately 170 kilometres west of Prince George, directly south of Cheslatta Lake, and outcrops for 65 metres along the eastern side of Marilla Road. It consists mainly of aphyric or porphyritic biotite-plagioclase-bearing rhyolite typical of the Ootsa Lake Group, which outcrops sporadically throughout the area. Geochemical analysis confirms that the six identified lithological units are rhyolite or rhyodacite in composition. Expansion tests, using a propane torch, showed at least some degree of expansion in each sample, with a boulder found near the occurrence expanding readily. This study confirms the exploration potential in the Prince George area for expanding perlite deposits, however the distance to the market should be taken into consideration during a conceptual study.

BACKGROUND INFORMATION

Definition

Petrographically, perlite is defined as a hydrated natural rhyolite glass with perlitic texture (Bates and Jackson, 1987). It consists of 2 to 5% total water held within the glass structure, which is considerably higher than average obsidian water content. Industry defines perlite as any hydrated felsic rock which through rapid thermal expansion increases in volume to form a white

porous lightweight cellular aggregate (McPhie *et al.*, 1993; Breese and Barker, 1994; Simandl *et al.*, 1996).

Expanded perlite is made by heating crushed perlite rock to the softening temperature of glass in a furnace. At temperatures ranging from 870 to 1100°C, the glass becomes soft enough for the water it contains to expand into steam resulting in a cellular structure and an increase in volume of up to 20 times. The result is a frothy particle with extremely low density, high surface area and light or white colour (Breese and Barker, 1994).

Origin of Perlite

The water content of obsidian is typically less than 1 weight percent and is considered to represent "primary" magmatic water. The water content of perlite ranges up to about 5%, which is attributed to the addition of "secondary" water from external sources, such as ground water or surface water (Ross and Smith, 1955; Friedman *et al.*, 1966; Lofgren, 1971). Primary hydration occurs during the formation of a volcanic rock or glass (Nasedkin, 1988). Secondary hydration occurs after emplacement and late in the cooling history of the glass, probably under zeolite facies conditions, or after complete cooling to surface temperatures (Nasedkin, 1988). Zeolite facies metamorphism and rock weathering typically occur below 2.5 kilbars and 300°C.

Perlite Applications / Uses

In the building and construction industry, expanded perlite is mixed in mortar, concrete and plaster to utilize its thermal, acoustic, lightweight and fire resistant properties. Its thermal insulation properties and low density make it highly effective in roof insulation board, pipe insulation, and refrigerator insulation. Its sonic insulation properties make it an ideal material for acoustical ceiling tile (Breese and Barker, 1994).

The ability of expanded perlite to retain water in its cellular structure makes it desirable in horticultural applications, and it is therefore used to condition soil. Expanded perlite adds loft, reduces compaction, and facilitates water drainage and moisture retention in soils (Simandl *et al.*, 1996). It is commonly used as a

propagating medium for seedlings and for the packaging and storage of bulbs and plants (Breese and Barker, 1994). Expanded perlite can also be used as a substrate in hydroponic farming, and as a fertilizer-carrying matrix (Lin, 1989).

The internal cellular structure of expanded perlite makes it useful as a filtration aid and oil absorbent. Expanded perlite offers high porosity and does not interfere chemically with the liquid filtered (Shackley and Allen, 1992).

Expanded perlite is used extensively in livestock applications for the absorption of nutrients, liquid chemicals such as pesticides, fertilizers, oils, and pharmaceuticals. It is used as an additive in animal feed mixtures to aid in digestion and for growth promotion (Lin, 1989), and also can be used as an absorbent in litter padding for chicken coops (Lin, 1989). Unexpanded perlite can be used in ceramics, glass, explosives and several other applications (Lin, 1998).

GENERALIZED CHARACTERISTICS OF PERLITE DEPOSITS

Perlite can occur in silicic lava domes and lava flows, welded ash-flow tuffs, glassy plugs, laccoliths, and dikes (Breese and Barker, 1994). Most commercial production comes from flows associated with thick accumulations of tuffs and lava flows, and from lava domes (Chesterman, 1966).

A single perlite flow can range in thickness from less than a metre to several metres and may be traced along strike for more than a kilometer. Silicic lava

flows commonly display internal textures and structures such as flow banding, aligned elongate phenocrysts, and stretched vesicles (McPhie *et al.*, 1993). Perlite domes can range from 100 metres to 2 kilometres in diameter, and can extend vertically more than 100 m from their base (Chesterman, 1966). Rhyolite domes are usually flat or gently sloping on the upper surfaces, with steep sides and flow fronts (Figure 1). Upper parts of the dome may exhibit steep flow foliations and ramp structures with ridges on the surface (McPhie *et al.*, 1993). These silicic lava flows and domes (Figure 1) typically consist of a texturally zoned exterior glass unit enclosing a partially devitrified and crystallized inner glass unit. This zonation is produced by rapid quenching of exterior surfaces and crystallization of the interior (Breese and Barker, 1994).

PERLITE MARKETS

There are no producing perlite mines in Canada, so sized and expanded perlite is imported mostly from the United States and Greece. Greece is by far the largest exporter of perlite, from its deposits on the island of Milos in the Aegean Sea (White, 2002). The United States exports about 10% of its production, mainly to Canada. Crushing and sizing is generally done at facilities located close to the pits. To reduce transportation costs, the unexpanded perlite is shipped directly from the pits to local markets where it is expanded and processed for distribution to end users (Breese and Barker, 1994).

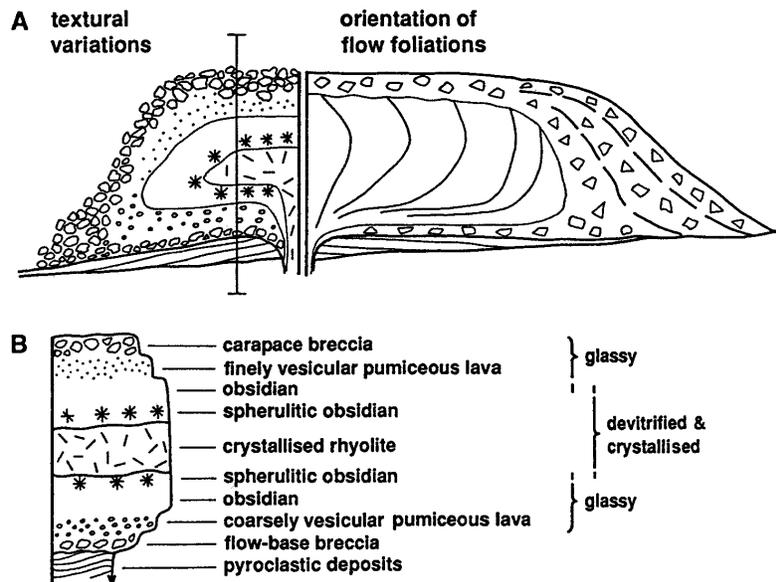


Figure 1. (A) Schematic cross-section through a subaerial silicic lava flow. The left side shows the internal textural variation arising from vesiculation, devitrification and flow fragmentation. The right side shows the orientations of internal flow foliations, and crude layering in flow margin talus breccia (B) Vertical section through the flow at the position indicated in (A), showing the major textural zones. Modified by McPhie *et al.*, (1993) from Fink and Manley (1987) and Duffield and Dalrymple (1990).

The total world production of perlite is over two million tonnes per year (Coope, 1999). The market value for high-quality raw perlite in British Columbia, Alberta, Washington, and northwest Oregon in 1994 was estimated at \$2.9 million Canadian dollars, and the total market for perlite in the same region in 1994 at 42 000 tonnes (Gunning and McNeil, 1994). Of this amount, 35 000 tonnes were sized ore and 7000 tonnes were expanded perlite. Coated perlite microspheres represented 2700 tonnes and \$2.5 million Canadian dollars (Gunning and McNeil, 1994).

PERLITE IN BRITISH COLUMBIA

There are 23 perlite occurrences in British Columbia described in MINFILE (a computer-based inventory system). The inventory can be accessed at: <www.em.gov.bc.ca/Mining/Geosurv/Minfile/search/>. Several of these occurrences are within the Ootsa Lake Group in the Prince George area, including the Marilla perlite occurrence (Figure 2). Other reports on perlite resources in British Columbia were prepared by White (1990), Morin and Lamothe (1991), Hora and Hancock (1995), Simandl *et al.* (1996) and White (2002). The Francois and Frenier deposits are two past producing perlite mines in British Columbia. From 1949-1953, Western Gypsum Products Ltd. mined 1589 tonnes from the Francois deposit. The Frenier deposit yielded 6000 tonnes of crude perlite from 1983 through 1985. The Frenier mine has been inactive since 1986, in part due to

a low-capacity bridge across the Fraser River.

MARILLA PERLITE SHOWING

The Marilla perlite showing is located approximately 170 kilometres west of Prince George, directly south of Cheslatta Lake at N53° 42.588' and W125° 19.371' (Figures 2 and 3). It outcrops along the eastern side of Marilla Road for 65 metres. The showing was mapped and sampled in 2000 by the British Columbia Geological Survey. The deposit consists mainly of an aphyric or porphyritic biotite-plagioclase-bearing rhyolite. The unit is part of the Ootsa Lake Group as described by Duffell (1959), Tipper (1963), Diakow *et al.* (1997), and Grainger and Anderson (1999).

The Ootsa Lake Group consists of rhyolitic flows and domes, crystal and lithic-crystal tuffs, pyroclastic and autoclastic breccias, and minor dacite and andesite flows (Grainger and Anderson, 1999). The predominant rock type is a flow-laminated rhyolite that generally occurs as flows and less commonly as domes. Colour usually varies from red to white to grey, but is locally purple or green. Textures within the Ootsa Lake group can change within metres. Monolithic breccias containing flow-laminated clasts are found associated with rhyolite flows and domes. The rhyolites are aphyric or sparsely plagioclase-phyric. Biotite, alkali feldspar, quartz, and/or rare hornblende are minor phenocryst phases. Of interest here, the bases of several exposures of buff, flow-laminated rocks are black,



Figure 2. Location of perlite occurrences in BC listed in MINFILE, showing the area of Prince George deposits in Figure 3. 1-Prospect Creek; 2-Empire Valley; 3-Moore Lake; 4-Frenier; 5-French Bar Creek; 6-Terrace Mountain; 7-Anahim Peak; 8-Nazko; 9-Tasalit Mountain; 10-Denny Island; 11-Lagoon Bay; 12-Ironside Mountain; 13-Coates Creek; 14-Skelu Bay; 15-Blackwater Creek; 16-Canoe Creek; 17-Ship Keita Island; 18-Juskatla Inlet; 19-Florence Creek; 20-Cheslatta Lake; 21-Henson Hills; 22-Uncha Lake; 23-Francois; 24-Marilla. Modified from White (2002).

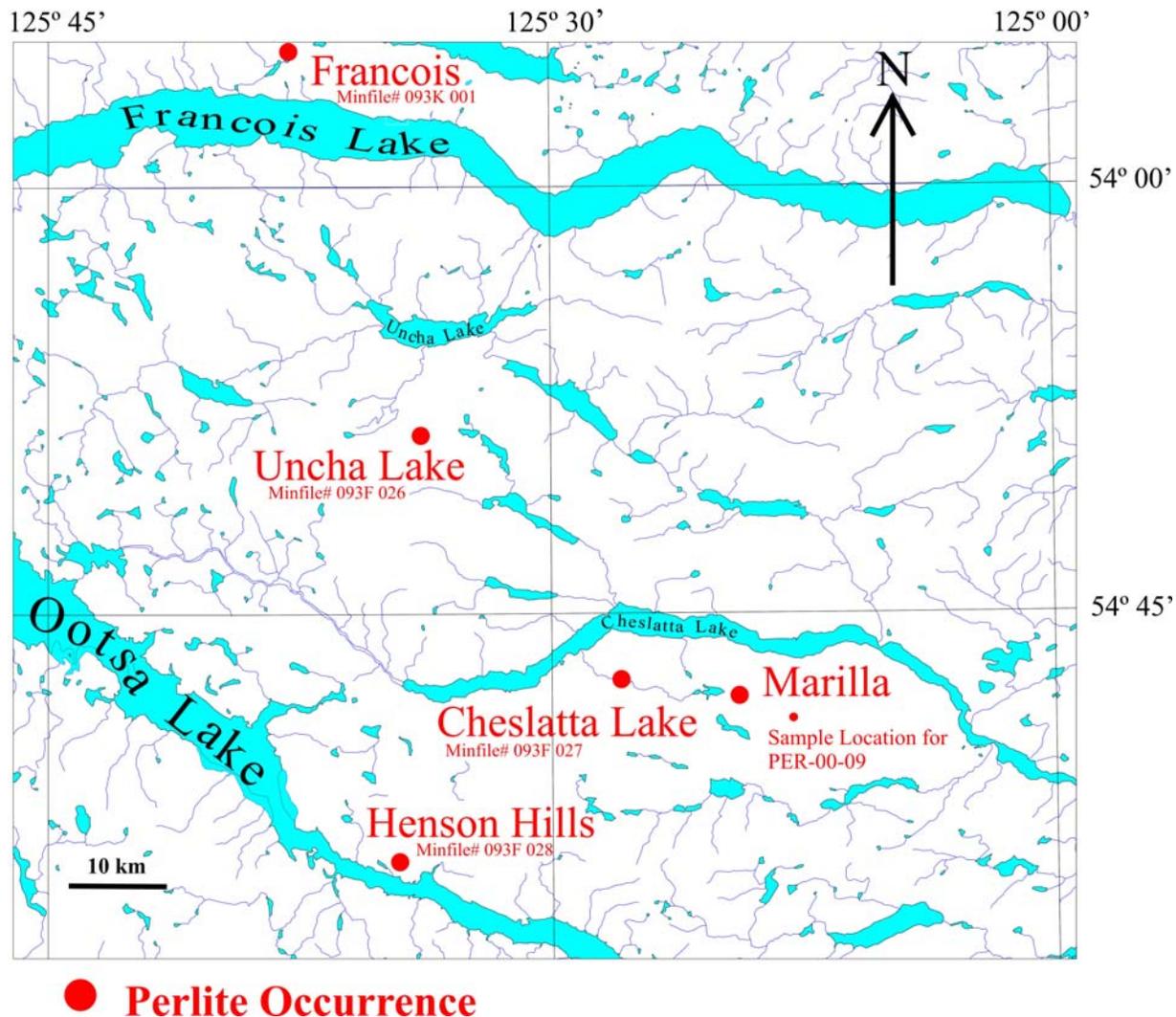


Figure 3. Perlite occurrences in the Prince George area. Ootsa Lake Group with location of the newly discovered Marilla perlite occurrence. See Figure 2 for location of map within BC.

glassy, and perlitic (Grainger and Anderson, 1999). As well as the Marilla occurrence, the Ootsa Lake Group hosts the Cheslatta Lake, Henson Hills, Uncha Lake and Francois occurrences (Figure 3).

Six lithologies that comprise the Marilla perlite showing were distinguished in the field (Figure 4). These are: Banded Spherulitic Rhyolite Breccia, Flow-Banded Perlite, Rhyolite with Biotite Phenocrysts, Spherulitic Amygdaloidal Perlite, Spherulitic Rhyolite, and a Grey Perlite Breccia. Sample MAR-00-09, was collected from a loose angular boulder of flow banded perlitic obsidian about one meter in diameter. This boulder was found on the roadside 200 metres west of the showing. Sample PER-00-01, from the Perlite with Amoeba-like Spherulite unit, was taken from a small flat outcrop in the ditch approximately 4 kilometres east of the Marilla perlite showing. The coordinates for this unit are N53° 42.211' and W125° 16.42'.

PERLITE ROCK UNITS

Banded Spherulitic Rhyolite Breccia (MAR-00-01)

This rock is layered grey and cream with maroon spherulites on a fresh surface. Altered surfaces are grey with 2 to 3 millimetre thick beige bleached zones. Common opal fills open spaces in the rock, with some opal forming veinlet swarms. Phenocrysts are subhedral partially dissolved plagioclase grains (5 to 10%) averaging 1 millimetre in diameter and biotite (2%), averaging 0.8 millimetres in longest dimension. Spherulites consisting of plagioclase microlites make up 40 to 45% of the rock and are up to 1 centimetre in diameter (Figure 5). The spherulite's brown colour is due to the presence of palagonite, which is a low temperature hydration and alteration mineral of sideromelane. Some spherulites are nucleated on plagioclase phenocrysts. Minor constituents are epidote (less than 1%, 0.25 millimetres in diameter) and iron oxides (2%). There are

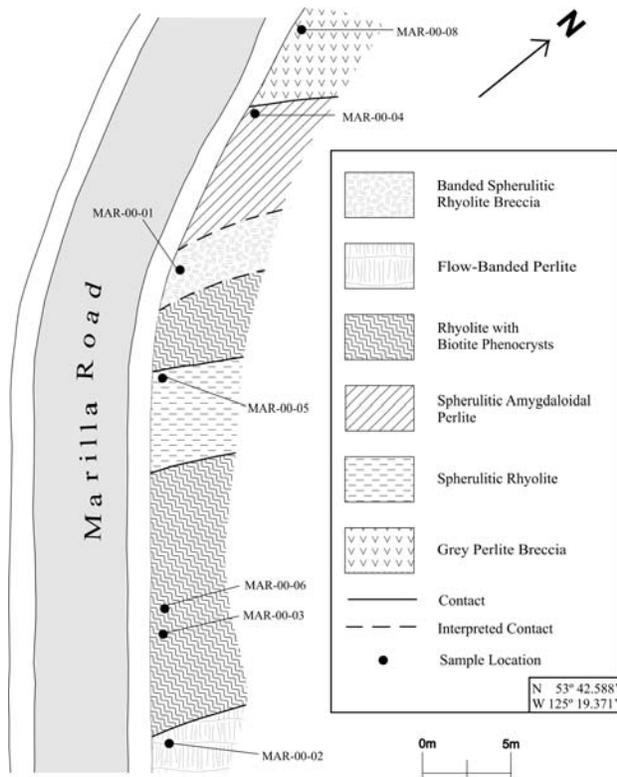


Figure 4. Outcrop at the Marilla perlite occurrence seen in plan view. It shows the six major lithological units.



Figure 5. Spherulite of sample MAR-00-01 (Banded Spherulitic Rhyolite Breccia) in plane-polarized light. The width of the field of view is 1.2 millimetres.

relatively few plagioclase microlites in the glass matrix but perlitic texture is common throughout the glass matrix. The rock expands by less than 30% when heated with a propane torch.

Flow-Banded Perlite (MAR-00-02)

This unit consists of dark grey and orange/red layers with maroon spherulites. Layers are up to 3 centimetres thick, with flow banding and spherulites following the flow banding. There is a pearly luster on the hackley glass

fractured surface. The major constituents are spherulites (40%) that are up to 1 centimetre in diameter. Also present are subhedral, partially dissolved plagioclase grains (5 to 10%) averaging 0.7 millimetres in diameter and biotite phenocrysts (2%) that average 0.3 millimetres in longest dimension but may reach up to 0.9 millimetres. Minor constituents are opaques (less than 1%) averaging 0.08 millimetres in diameter, epidote (less than 1%) averaging 0.1 millimetre in diameter, and amygdules of silica, agate and common opal (1 to 2%) that average 6 millimetres in longest dimension. Large areas of alteration displaying remnant perlitic texture are common. The rock made some popping noises when heated with a propane torch, but expansion was minimal at less than 5%.

Rhyolite with Biotite Phenocrysts (MAR-00-03)

This rhyolite is beige/pink/grey with black biotite phenocrysts of 2 millimetres in diameter that have a copper coloured reflection on a fresh surface. The altered surfaces appear lighter coloured than the fresh surfaces. Main phaneritic constituents are plagioclase and orthoclase phenocrysts (5%) averaging 0.5 millimetres in diameter with some up to 2 millimetres, and bright orange/red coloured biotite (2%) averaging 0.25 millimetres in longest dimension. Carbonate amygdules (2%) display fan textures are present and average 1.3 millimetres in longest dimension. Embayed feldspar grains are cemented with a glassy matrix, and fiamme texture is evident throughout the rock. No expansion was observed when heated with a propane torch.

Spherulitic Amygdaloidal Perlite (MAR-00-04)

This rock is dark grey/green with maroon spherulites averaging 0.5 centimetres in diameter on a fresh surface. Weathered surfaces are light brown and green with maroon spherulites. Spherulites (85%) are the major constituents, and are up to 0.75 centimetres in diameter. Partially dissolved embayed plagioclase phenocrysts (8%) are an average of 0.6 millimetres in diameter, and biotite (1%) averages 0.2 millimetres in longest dimension. Minor constituents are epidote (less than 1%) averaging 0.5 millimetres in diameter, opaques (less than 1%) averaging 0.1 millimetres in diameter, amygdules (1%) averaging 2 millimetres in diameter, and swallow-tails of plagioclase (less than 1%). Most of the perlitic textured glass is altered and has been overprinted by spherulitic texture. Most spherulites are round but some are fan or plumose shaped. The lighter coloured portion of the rock popped, but no obvious expansion occurred when heated with a propane torch.

Spherulitic Rhyolite (MAR-00-05)

This rock is light grey with abundant maroon spherulites on a fresh surface. It breaks apart easily on

altered surfaces due to fracture networking marked by beige bleaching and swarms of veinlets. No layering or banding is evident. The main constituents are spherulites (55%) up to 2.5 centimetres in diameter, partially dissolved plagioclase phenocrysts (7%) averaging 0.75 millimetres in diameter and biotite (2%) averaging 0.5 millimetres in longest dimension. Opaques (possibly hematite, magnetite or ilmenite) constitute 1% of the rock and are 0.1 millimetres in diameter. The spherulites are nucleated mainly on plagioclase or biotite phenocrysts, and some have reaction rims between them and the glass. The glass matrix displays perlitic texture in which microlites have grown in the perlitic fractures (Figure 6). The rock expanded by 35% when heated with a propane torch.

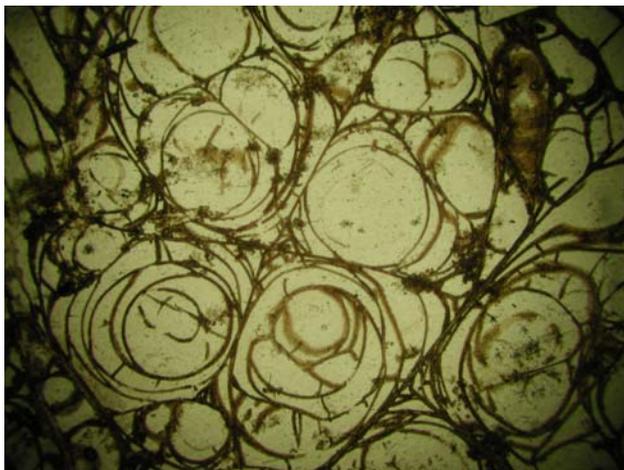


Figure 6. Perlitic fractures of sample MAR-00-05 (Spherulitic Rhyolite unit) in plane polarized light. The width of the field of view is 1.8 millimetres.

Rhyolite with Biotite Phenocrysts (MAR-00-06)

This sample was taken from the same lithological unit as sample MAR-00-03, the *Rhyolite with Biotite Phenocrysts* unit, and is similar in hand sample and thin section. The thin section has a slightly darker appearance in cross-polarized light than Mar-00-03, which may be the result of slightly more alteration, denser compaction, or a slightly thicker slide. Swallow-tails of plagioclase occur, and zoned feldspars are common. The rock expands by less than 3% when heated with a propane torch.

Grey Perlite Breccia (MAR-00-08)

On a fresh surface this rock has dark grey fragments averaging 2 centimetres in diameter, surrounded by cream coloured matrix and smaller brecciated pieces of light grey rock. The altered surface is beige/cream and light grey. Biotite phenocrysts, up to 1.5 millimetres in diameter, are present. The phenocrysts are partially dissolved plagioclase (3%) averaging 0.4 millimetres in diameter, and biotite (1%) averaging 0.5 millimetres in

longest dimension. Minor constituents are epidote (less than 1%) averaging 0.2 millimetres in diameter, and a feathery high birefringence fracture-filling mineral (possibly a chlorite/sericite mix). Brecciated unaltered glass constitutes 30% of the rock, clasts average 1.0 centimetre in diameter. They are enclosed by altered lighter-coloured glass. Perlitic texture is evident throughout the glass, but more alteration occurs in the darker-coloured areas. The rock expands by 40% when heated with a propane torch.

Flow Banded Perlite Obsidian (MAR-00-09)

This sample is from a boulder found on the roadside 200 metres west of the Marilla perlite showing. In hand sample, it is dark grey/green with black flow banding up to 3 millimetres in width. It has a pearly hackley/conchoidal fracture on a fresh surface and beige/brown coatings on altered surfaces. Constituents are partially dissolved feldspar phenocrysts (5%) averaging 1.0 millimetre in diameter, biotite (2%) averaging 0.1 millimetres in longest dimension, and amphibole (less than 1%), which is likely tremolite, averaging 0.1 millimetres in diameter. Minor constituents are opaques (less than 1%) averaging 0.2 millimetres in diameter, and veins of a yellow alteration material (possibly clays, zeolites, or a mineral of the silica group). The flow banding, which appears to be speckled in thin section with remnant perlitic texture, flows around plagioclase and other grains (Figure 7). The glass is relatively unaltered with abundant perlitic texture and makes up the majority of the rock (up to 90%). There are plagioclase hopper structures and swallow-tails, and some biotite hopper structures in the perlitic glass matrix. Small spherulites, in their first stages of growth, occur in 1% of the rock and average 0.4 millimetres in diameter. They radiate from plagioclase phenocrysts in fan and plumose structures. The rock expands several times its original volume when heated with a propane torch.

Perlite with Amoeba-like Spherulites (PER-00-01)

This sample was taken from a small flat outcrop in the ditch approximately 4 kilometres east on Marilla Road. Its fresh surface is black/grey with purple amoeba-like spherulites up to 0.5 centimetres in diameter. The altered surface has a peach, green or yellow coating. Spherulites occur in 60% of the rock and have amoeba-like branches that radiate from a central point (Figure 8). Some spherulites are nucleated on plagioclase grains. Relatively few phenocrysts occur in the surrounding altered glass, which displays some perlitic texture. Phenocrysts include 3% plagioclase up to 2 millimetres in diameter, 1% biotite and less than 1% epidote. Vesicles in the glass are common. The rock expands by less than 3% when heated with a propane torch.



Figure 7. Flow banding in sample MAR-00-09 (Flow Banded Perlitic Obsidian unit) in plane polarized light. The width of the field of view is 4.0 millimetres.

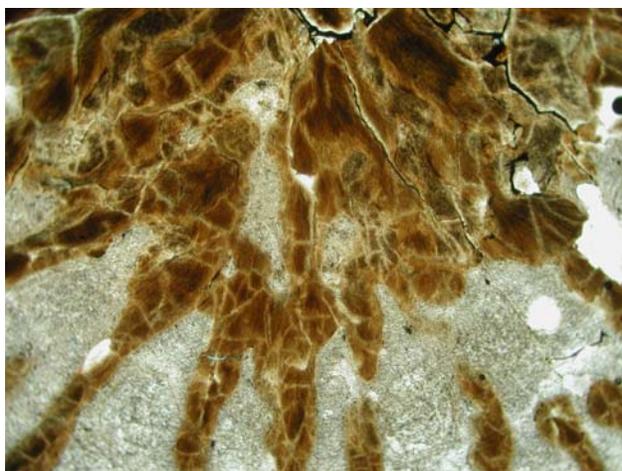


Figure 8. Spherulite in sample PER-00-01 (Perlite with amoeba-like spherulites unit) in plane polarized light. The width of the field of view is 1.2 millimetres.

GEOCHEMISTRY OF THE MARILLA PERLITE SHOWING

All units of the Marilla perlite showing were identified as rhyolites in the field based on textures and structures. The major and minor element geochemistry of representative samples was analyzed using x-ray fluorescence and results are given in Table 1. The SiO_2 content varies from 62.86% to 73.26% and the TiO_2 values are relatively low at 0.18% to 0.23%, which is normal for rhyolite. The LOI (lost on ignition) values range from 3.2% to 4.15%. The *Rhyolite with Biotite Phenocrysts* sample (MAR-00-03) has a high LOI (15.53%) and a high CaO content (2.21%), reflecting carbonate in the amygdules. LOI of the *Grey Perlite Breccia* sample (MAR-00-08) is 6.69%. It is assumed that a large portion of the LOI value represents water incorporated into the glass structure, although it was not analyzed for.

Typical chemical compositions of perlite ores around the world and the average compositions of perlite and rhyolite are given for comparison to the Marilla perlite values (Table 1). This data shows that the TiO_2 and Fe_2O_3 content of the Marilla perlite, averaging 0.23% and 1.2% respectively, are higher than other perlite ores around the world that average 0.07% and 0.8% respectively (Breese and Barker, 1994).

Major and minor elements are plotted on three different discrimination diagrams (Figures 9, 10, and 11). The $\% \text{SiO}_2 - (\% \text{Na}_2\text{O} + \% \text{K}_2\text{O})$ diagram shows that all, but the *Rhyolite with Biotite Phenocrysts* unit (sample MAR-00-03) plot in the rhyolite field. This unit contains carbonate amygdules that make classification by this means unreliable (Figure 9). Samples from the Marilla perlite showing are relatively pristine with no visible effects of hydrothermal alteration or weathering. Consequently, the major element plot of $\% \text{SiO}_2 - (\% \text{Na}_2\text{O} + \% \text{K}_2\text{O})$ is considered to be reliable, and most units are interpreted as rhyolite.

Four of the eight samples were sent for trace element analyses (Table 1). These samples are plotted on a $\text{Zr/TiO}_2 - \% \text{SiO}_2$ graph (Figure 10). Three of these samples plotted in the rhyodacite-dacite field with one sample falling in the trachyte field. The same four samples were also plotted on a $\text{Nb/Y} - \text{Zr/TiO}_2$ graph (Figure 11). Diagrams using immobile element ratios such as Nb/Y and Zr/TiO_2 are useful in determining the original composition of volcanic rocks affected by alteration. Elements such as Zr, Ti, Nb, and Y are relatively immobile and remain in the rock when alteration occurs. Figure 11 shows all the samples falling near the rhyolite, rhyodacite/dacite, and trachy-andesite boundaries.

ECONOMIC POTENTIAL

When they were subjected to a torch flame, most samples displayed at least some degree of expansion. Rigorous testing using standard laboratory equipment is needed to confirm whether the occurrence or surrounding area could provide raw material for an expanding perlite plant. The *Flow Banded Perlitic Obsidian* unit (sample MAR-00-09 from the boulder found 200 metres west of the showing), expanded several times its original volume. The source of this expanding perlite may be found in the area covered by overburden. The direction of ice flow during the last glaciation was estimated at 66°NE (Plouffe, 1999), and the angularity of this boulder suggests a nearby source for the Flow Banded Perlitic Obsidian boulder (sample MAR-00-09) that would be southwest of the Marilla perlite showing. The Ootsa Lake Group is a favourable host for expandable perlite, so testing of known volcanic glass occurrences and further exploration in Prince George area is justified. Several of the volcanic glass and perlite localities in this area have

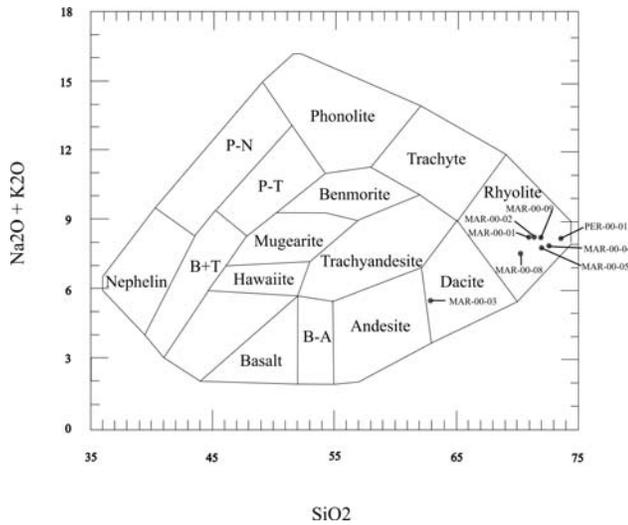


Figure 9. { %SiO₂ - (%Na₂O+%K₂O) } discrimination diagram for volcanic rocks, (Cox *et al.*, 1979).

been previously described by Tipper (1963), Duffel (1959), Grangier and Anderson (1999), White (1990) and White (2002). Distance of the deposit from perlite consumers should be taken into consideration before investing heavily into exploration of this geologically favourable area, however, production from the Francois occurrence (Figure 3), where Western Gypsum Products Ltd. mined 1589 tonnes from 1949 to 1953 proved that material from this area can satisfy industry specifications.

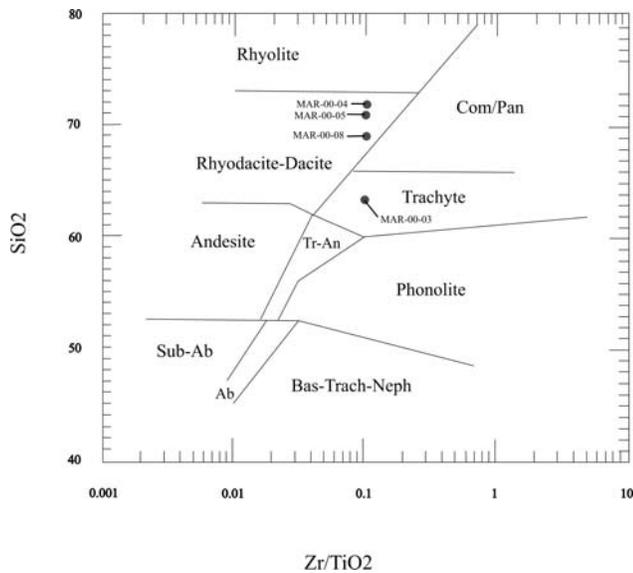


Figure 10. (Zr/TiO₂ - %SiO₂) discrimination diagram for volcanic rocks. Abbreviations: Com = comendite, Pan = pantellerite, TrAn = Trachy Andesite, Ab = andesite basalt, Bas-Trach-Neph = basalt/trachite/nephelinite (Winchester and Floyd, 1977).

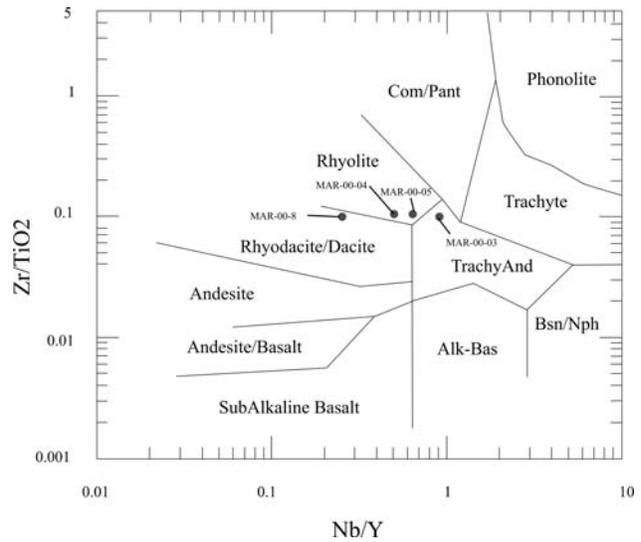


Figure 11. (Nb/Y - Zr/TiO₂) discrimination diagram for volcanic rocks. Abbreviations: Com = comendite, Pant = pantellerite, Bsn = basanite, Nph = nephelinite, Alk-Bas = alkali basalt (Winchester and Floyd, 1977).

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TABLE 1. GEOCHEMISTRY OF THE MARILLA PERLITE, CHEMICAL COMPOSITIONS OF PERLITE ORES AND AVERAGE COMPOSITIONS OF PERLITE AND RHYOLITE

Marilla Perlite		SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Y	Zr	Nb	Th	Ti	V	Ba	Hf	
		%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
MAR-00-01		71.62	0.23	12.78	1.15	0.01	0.14	0.87	3.13	5.3	0.01	4.15									
MAR-00-02		72.33	0.23	13.05	1.4	0.01	0.18	0.82	3.18	5.28	0.01	3.08									
MAR-00-03		62.86	0.21	12.09	1.37	0.03	0.55	2.21	0.93	3.69	0.01	15.53	26	205	21	11	1250	10	967	4	
MAR-00-04		72.23	0.23	12.86	1.38	0.02	0.18	0.93	2.9	5.3	0.01	3.2	35	214	19	31	1378	11	1051	5	
MAR-00-05		71.65	0.23	13.03	1.25	0.01	0.17	0.87	3.05	5.07	0.01	4.15	31	221	20	18	1370	8	1046	5	
MAR-00-08		69.83	0.21	12.6	1.15	0.02	0.25	1.1	2.47	5.13	0.01	6.69	35	207	20	19	1200	8	1050	5	
MAR-00-09*		71.51	0.23	12.75	1.34	0.02	0.18	0.77	3.06	5.36	0.01	4.13									
PER-00-01**		73.26	0.18	12.35	1.02	0.03	0.12	0.69	2.98	5.34	0.01	3.48									

*boulder found 200 metres west of the Marilla perlite showing

**sample from approximately 4 kilometres east along Marilla Road from a small flat outcrop in the ditch (N53°42.211' W125°16.42') see Figure 1b.

Perlite Ores		SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI
		%	%	%	%	%	%	%	%	%	%	%
No Agua, NM+		72.1	0.06	13.5	0.8		0.5	0.89	4.6	4.4		3
Superior, AZ+		73.6	0.1	12.7	0.7		0.2	0.6	3.2	5		3.8
Pioche, NV+		73.1	0.08	12.8	0.7		0.2	0.9	3	4.7		3.9
Big Pine, CA+		73.6	0.07	13.2	0.8		0.1	0.6	4.1	4.1		3.3
Milos, Greece+		74.2	0.08	12.3	0.95		0.13	0.85	4	4.4		2.8
Akita, Japan+		74.2	0.06	12.9	0.68		0.05	0.45	4.1	4		3.3
Bulgaria+		73.8	0.07	12.8	0.56		0.03	0.5	3	4.9		4
Argentina+		72.3	0.08	13.4	1		0.3	0.59	3.4	4.7		3.7
Hungary+		73.5	-	13	1.8		0.4	1.5	3.5	3.8		3
Average Chemical Composition of Perlite [^]		72.70	0.91	12.91	1.35	0.05	0.23	0.82	3.07	4.73	0.04	3.19
Average Chemical Composition of Rhyolite [^]		72.82	0.28	13.27	2.58	0.07	0.39	1.57	3.55	4.30	0.07	1.10

+Taken from Breese and Barker (1994), source Kadey Jr., (1983).

[^]from Shackley and Allen, (1992). Based on 50 perlite samples examined by Shackley (1989) and 60 rhyolite samples examined by Le Maitre (1976).

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KYANITE AND ANDALUSITE OCCURRENCES IN BRITISH COLUMBIA, CANADA

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BACKGROUND INFORMATION

Andalusite, kyanite and sillimanite are aluminosilicate polymorphs of metamorphic origin with the chemical formula Al_2SiO_5 . When calcined, these polymorphs convert to mullite, a highly refractory material. The conversion is accompanied by an irreversible volume expansion of 5%, 18% and 7% for andalusite, kyanite and sillimanite, respectively (Skillen, 1993). Worldwide, andalusite is the preferred of the three raw materials because it converts to mullite at lower temperatures (1380°C) than sillimanite (1550°C). Although kyanite converts to mullite at 1370°C, andalusite is favoured because the volume change during mullitization is negligible; therefore no calcination is required before manufacturing refractory shapes. Approximately 4.22×10^9 joules (4×10^6 BTU) are needed to mullitize one tonne of kyanite (Skillen, 1993). Despite this, kyanite is the most widely used polymorph in North America, because of its local abundance, proximity to markets, and availability of relatively inexpensive energy. As energy costs continue to increase, this may change.

In 1998, production of kyanite was probably less than 200 000 tonnes. Prices at the time of writing were US\$135 to US\$165 for raw kyanite and US\$238 to US\$268 for calcined kyanite; both contain 54 to 60% Al_2O_3 . The sizes of typical United States kyanite products are 28, 35, 100, 200 and 325 Tyler mesh. Concentrates are generally about 91% kyanite, less than 1% iron oxides, and the rest quartz.

South Africa is by far the world's largest andalusite producer. Other andalusite producing countries are France, the United States and China. Commercial andalusite concentrates from South Africa and France vary in composition from 53 to 60% Al_2O_3 and from 0.8 to 1.5% Fe_2O_3 . An andalusite-pyrophyllite-sericite mixture is mined in the United States for a captive market. In some cases, andalusite-pyrophyllite material has applications in ceramics. Iron is a detrimental impurity in most refractory applications.

Total world production of andalusite for 1998 was estimated to be 300 000 tonnes. The bulk of this production came from Africa. In July of 2000, andalusite prices varied from US\$171 to US\$200/tonne for a 2 000 tonne bulk shipment FOB South Africa.

Andalusite deposits are formed by low pressure, contact or regional thermal metamorphism of high-alumina, low-calcium pelitic rocks.

Formation of andalusite deposits depends on having a mineable thickness of pre-metamorphic protolith, its chemical composition, and low pressure thermal metamorphism. Grades of currently exploited 'hard rock' andalusite ores vary from 7 to 20% andalusite. Production capacities of existing mines vary from 25 000 to 65 000 tonnes/year. Generally, andalusite crystals are nearly inclusion free, and the coarser the crystals, the easier it is to upgrade the ore. Crystals from mined deposits vary from 1 millimetre to several centimetres. Ores are commonly crushed and then upgraded using heavy liquids; flotation is required for the treatment of fine-grained ores. Placer deposits account for a substantial proportion of the andalusite produced in South Africa. In these deposits, garnet and staurolite commonly coexist with andalusite and are recovered as byproducts.

There are more than 45 kyanite and 23 andalusite occurrences known in British Columbia (<http://www.em.gov.bc.ca/Mining/Geosurv/Minfile/search/>). Locations of these occurrences are presented on Figures 1 and 2. Selected occurrences are described below. Most of the occurrences have been described by Pell (1988), Simandl *et al.*, (1995), and Hancock and Simandl (1996).

KYANITE

The Tsimpsian Peninsula and Hawkesbury Island kyanite occurrences are considered to be representative of the more than 45 occurrences reported in British Columbia. The occurrences are restricted to high-alumina, high-grade metasedimentary rocks in the Coast and Omineca tectonic belts.

Dudevoir Passage and Trail Bay

At Dudevoir Passage and Trail Bay, the kyanite occurrences are probably within the same alumina-rich zone. It is possible that kyanite occurrences on the shore 13 and 29 kilometres southeast of Trail Bay (Hutchison, 1982) are part of this same zone. Where measured, the alumina-rich zone is 3 metres wide but it may thicken in fold hinges. The kyanite crystals are coarse, up to 2 centimetres long, with several coarse inclusions of quartz.

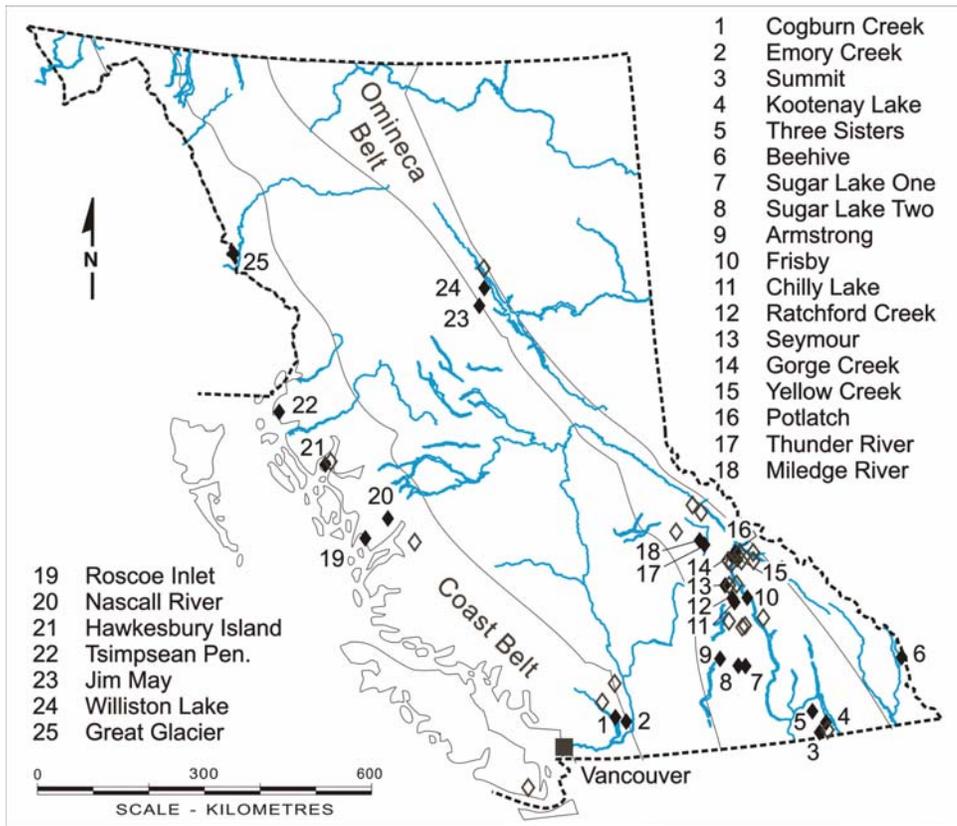


Figure 1. Location of significant kyanite occurrences in British Columbia. Major showings are named (Hancock and Simandl, 1996)

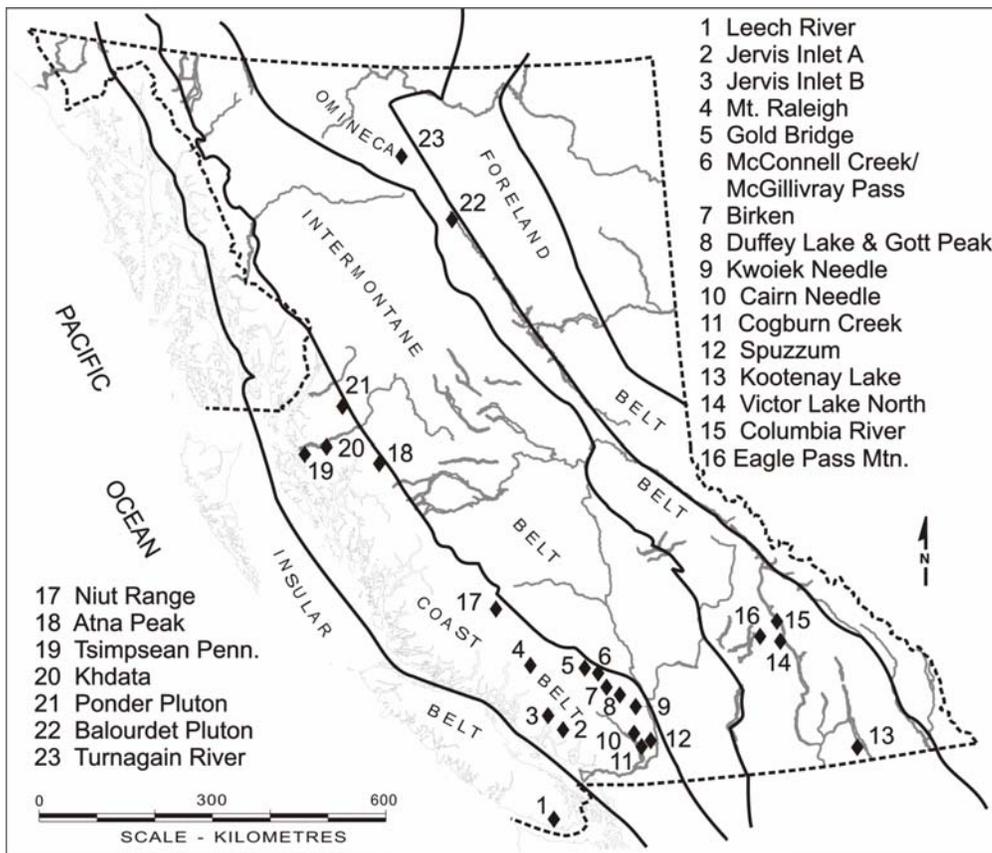


Figure 2. Andalusite occurrences in British Columbia (Simandl *et al.*, 1995)

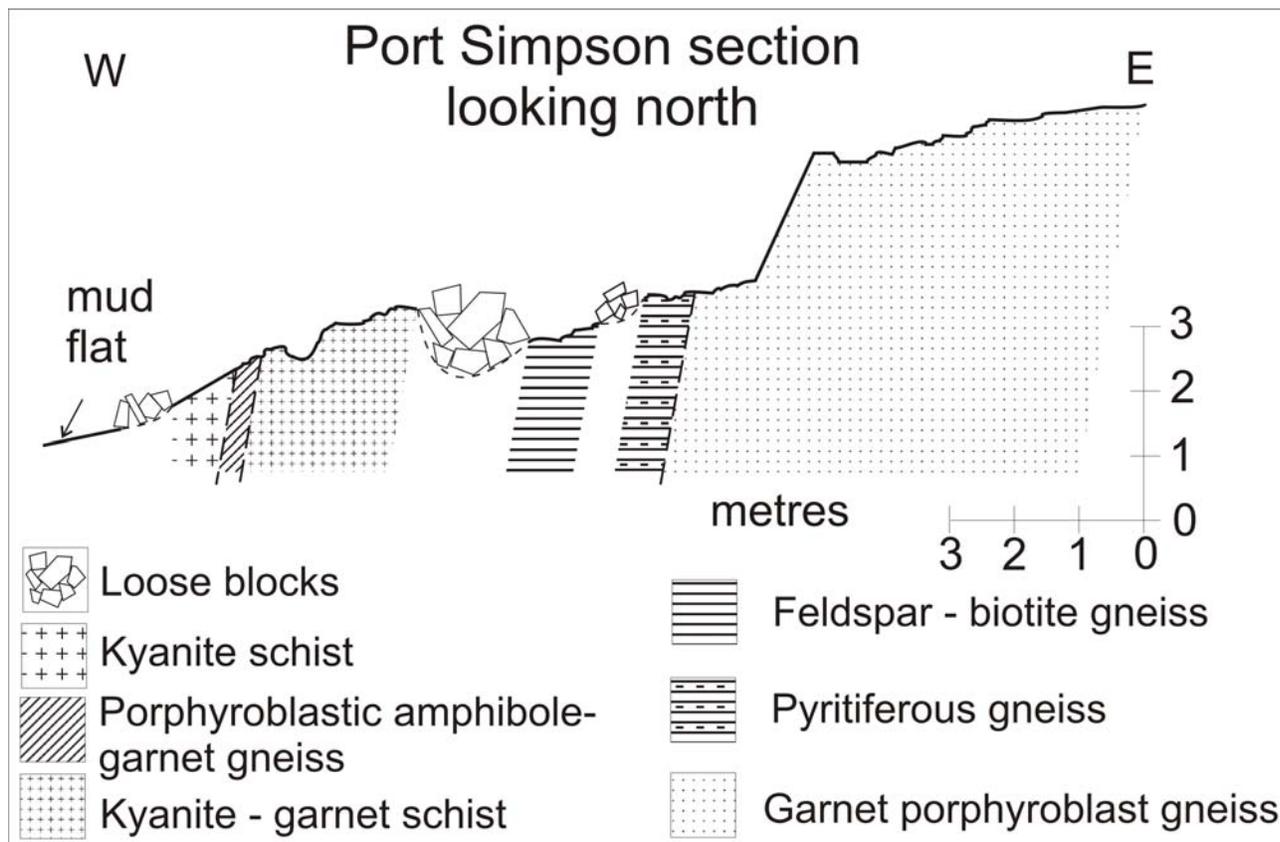


Figure 3. Section across the Dudevoir Passage kyanite showing (Hancock and Simandl, 1996)

Graphitic material within the kyanite layers could probably be removed by calcination.

At Dudevoir Passage, the kyanite outcrops form small bluffs 450 metres south of the western mouth of the passage. A vertical cross section of the Dudevoir Passage is shown on Figure 3. The section begins in medium to coarse-grained kyanite schist comprised of quartz and plagioclase with 10 to 15% each of biotite and muscovite flakes that are less than 3 millimetres across. Pyrite and magnetite are minor constituents (less than 1% each) and graphite is less than 0.5%. Kyanite content varies from 10 to 25%, and crystals measure from few millimetres to 2 centimetres in length. They contain microscopic quartz inclusions. Porphyroblastic amphibole-garnet gneiss (metabasite) is garnet-rich near the contacts and rich in feldspar and mafic minerals towards the centre of the unit. The mafic-rich center consists of amphibole and pyroxene.

At Trail Bay the kyanite-bearing gneiss contains 35 to 40% kyanite, 40% quartz, 10% biotite, which is less than 6 millimetres in size, 5% feldspar, less than 5% 1 to 2 millimetre staurolite, 2% garnet, which is less than 2 millimetres, and trace amounts of pyrite. Some kyanite crystals contain inclusions of iron oxides and graphitic material. A single kyanite zone is well exposed at the head of the bay but more than one zone may be present toward the southern limit of the exposures. The kyanite-bearing gneiss is 3 metres wide and is exposed for 50

metres along strike. It is bronze-grey on weathered surfaces. Coarse kyanite crystals, less than 5 centimetres long, generally form between 20 and 40% of the gneiss; locally, kyanite makes up 80% of the rock. Other minerals present are quartz ($\pm 40\%$), biotite ($\pm 10\%$), feldspar ($\pm 5\%$), staurolite (less than 1%) and trace amounts of graphite. Kyanite-bearing outcrops along the west side of the bay contain 5% of 2 to 5 centimetre long kyanite crystals; 1% garnet that is 2 to 5 millimetres in diameter, and less than 5% fine-grained graphite.

Hawkesbury Island

There are 7 kyanite zones known on Hawkesbury Island. They vary in size from a few meters to several tens of meters in width and have been traced intermittently for up to 5 kilometres. Individual zones contain 10 to 70% kyanite as 0.2 to 4 centimetres long crystals. It is unlikely that kyanite alone could be economically recovered, but the rock also contains garnet, staurolite and muscovite that could be byproducts. Kyanite occurs within a number of discrete zones of high-grade metapelitic gneiss that are part of Roddick's feldspar-hornblende schist unit (Money, 1959). Kyanite-bearing zone 1, which is within a quartz-feldspar-biotite gneiss, is 3 to 25 metres across and was

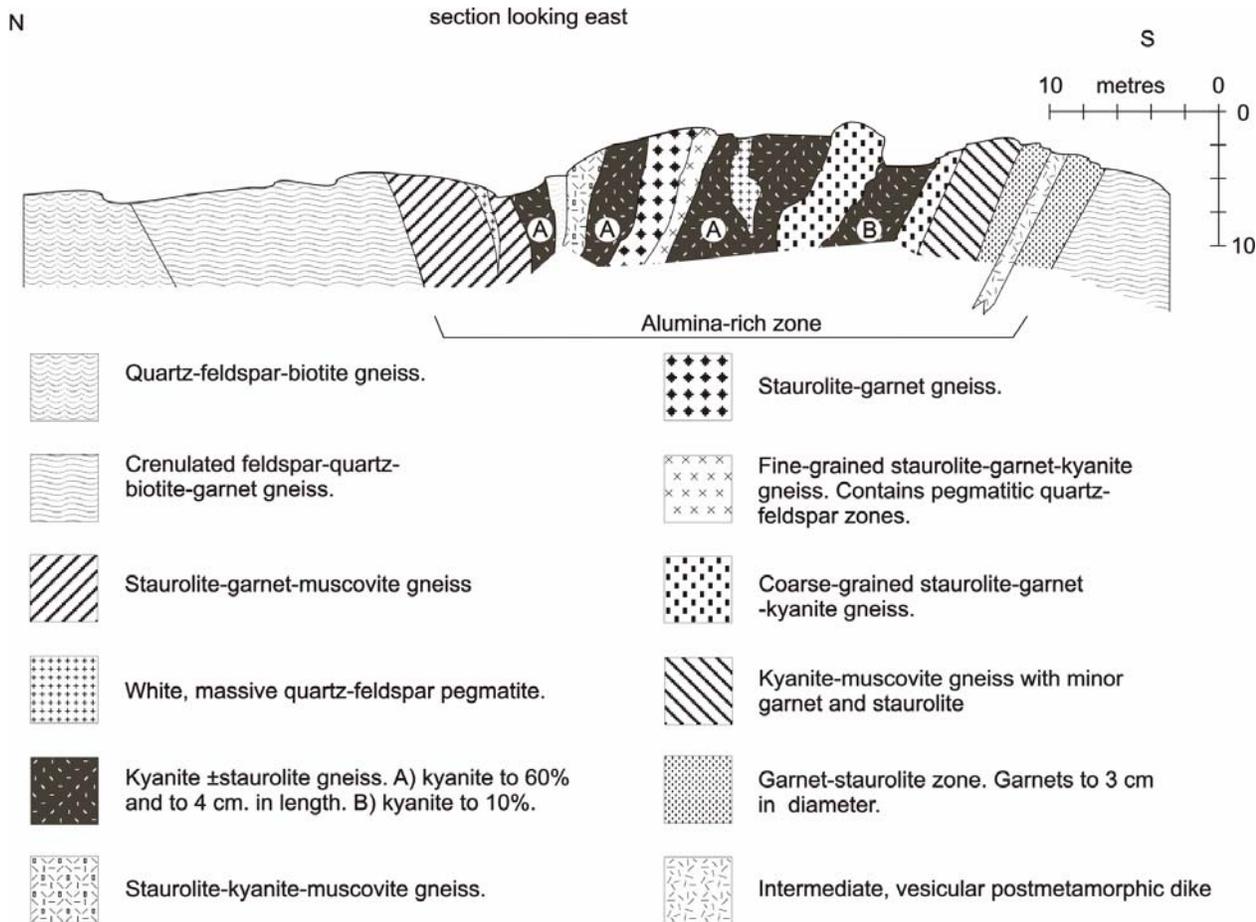


Figure 4. Section across the zone 1 kyanite showing on Hawkesbury Island (Hancock and Simandl, 1996).

traced for 900 metres along strike. Individual gneissic layers pinch and swell from 0.1 to 1 metre, and are folded. Quartz-feldspar pegmatite layers, veins and swells exhibit pygmatic folding. Significant mineral components include kyanite, garnet and staurolite. The mapped section (Figure 4) is 25 metres across. The kyanite zones exposed in the area may be part of a structurally repeated sequence. Selected units are described in Figure 4.

- Kyanite ± staurolite gneiss contains up to 60% kyanite crystals from 0.2 to 4 centimetres long enclosing inclusions of quartz. Staurolite is disseminated and forms 5% to 40% of the rock. Garnet may form massive lenses. The gneiss is muscovite-rich with a few percent of biotite. Remaining minerals are quartz and feldspar.
- Staurolite-kyanite-muscovite gneiss averages 7% staurolite and kyanite but locally these minerals make up to 65% of the rock. Staurolite and kyanite crystals are 2 to 10 millimetres wide and 5 to 20 millimetres long. Garnet grains are less than 1 centimetre in diameter but they comprise less than 5% of the rock.

- Staurolite-garnet gneiss contains 5% staurolite, 3% garnet and less than 10% biotite. The balance of the rock consists of feldspar and quartz.
- Fine-grained staurolite-garnet-kyanite gneiss has numerous feldspar-quartz pegmatite layers. It contains 10% staurolite, 5% garnet and 5% kyanite along with feldspar and quartz.
- Coarse-grained staurolite-garnet-kyanite gneiss is coarser than the previous unit. It contains 40% staurolite that is 4 to 20 millimetres in size, as well as 10% garnet that is from 5 to 30 millimetres in diameter and less than 10% kyanite.
- Kyanite-muscovite gneiss is distinguished by its 15% muscovite content. It also consists of 20% kyanite crystals, 1 to 5% garnet and 0 to 20% staurolite.
- Garnet-staurolite gneiss has 3 centimetre-sized garnets that form 30% of the rock. Staurolite is an accessory mineral.
- A post-metamorphic, fine-grained intermediate dike crosscuts the section.

Kyanite-bearing zone 2, which lies 450 metres south of zone 1, is 225 metres long and 10 metres wide.

It is very complexly folded. Kyanite occurs in concentrations of up to 10% in layers that are less than 25 centimetres thick. Kyanite grains are 1 to 2 centimetres long. Staurolite averages less than 5%. Grains are less than 2 centimetres long, nearly black and often form dense masses adjacent to coarse-grained quartz-feldspar lenses. Garnets occur as disseminated grains with concentrations in the 1 to 10% range. The crystals are 0.5 to 2 centimetres in diameter. In or immediately adjacent to quartz-feldspar lenses, garnets form 1 metre long masses comprised of 7 centimetre crystals (Hancock and Simandl, 1996).

ANDALUSITE

The areas of the Omineca, Coast and Insular belts affected by contact metamorphism or low-pressure, high-temperature regional metamorphism have good geological potential for andalusite deposits wherever aluminous protoliths are present. Unfortunately, in many cases andalusite was converted to sillimanite or kyanite by a later high-temperature metamorphic overprint or to low-temperature, hydrated minerals such as muscovite.

Omineca Belt

This belt (Figure 2) consists largely of metamorphic and intrusive rocks (Gabrielse *et al.*, 1991). Andalusite is related to low pressure, high temperature metamorphism that overprints an earlier higher pressure metamorphism. Several showings (Figure 2) are reported in the southern Omineca Belt on the west side of Kootenay Lake, near Victor Lake, near Eagle Pass Mountain, and north of Revelstoke along the Columbia River. Andalusite-bearing rocks are also known in the northern Omineca Belt, where they occur within basement gneiss near the Eocene Balourdet pluton in the Sifton Range, and in rocks 30 kilometres to the north (Evenchick, 1988). Another occurrence is near the confluence of the Turnagain and Cassiar rivers (Gabrielse, personal communication, 1994), where andalusite porphyroblasts, 3 to 4 centimetres long are partially retrograded to muscovite. This occurrence is hosted by metasediments along the contact of an Early Cretaceous pluton.

INSULAR BELT

Andalusite is present in rocks of the Leech River complex on southern Vancouver Island (Figure 2). These rocks were affected by Late Eocene low pressure metamorphism (Fairchild and Cowan, 1982).

Coast Belt

This belt is composed largely of granites, and greenschist to granulite facies metamorphic rocks. Andalusite occurs on the eastern edge of the Coast Belt

along a northwest trend where low pressure, high temperature metamorphic conditions prevailed during Mid to Late Cretaceous deformation and magmatism (Rushmore and Woodsworth, 1994). Peak metamorphic conditions were estimated at 3.5 kbars and 500 to 650°C. Examples within this belt include the Mount Raleigh, Nuit Range, Bridge River, Cogburn Creek, McConnell Creek, Birken, Duffey Lake, Gott Peak, Ratchford Creek, Kwoiek Needle, Cairn Needle and Spuzzum pluton occurrences (Figure 2).

Bridge River Area

In the Bridge River area, 180 kilometres north of Vancouver (Figure 5), several fine grained, andalusite occurrences are hosted by black argillite, formally referred to as the Noel Formation (Cairnes, 1937; Stevenson, 1958; Rushmore, 1985; Roddick and Hutchison, 1973; Journeay and Mahoney, 1994). Potential ore from these occurrences would be more difficult to upgrade than coarse South African ores. Showings such as CH-4 demonstrate that lithologies with favorable chemical composition have thicknesses of tens of meters. The Bridge River area is readily accessible and could be systematically prospected for andalusite.

The Noel lithofacies is a sequence of thinly bedded, fine-grained turbidites. Near the confluence of Cadwallader Creek and Noel Creek it is more than 350 metres thick and consists mainly of siltstones and black argillites. It is best developed in 2 belts near the Hurley River. Metamorphism of these argillites resulted in development of biotite, garnet, andalusite, cordierite and staurolite within a groundmass of quartz, biotite and pyrite. The andalusite-bearing rock is a hornfels with more than 12% andalusite. The andalusite is idiomorphic, relatively inclusion free and fine grained (1 to 7 millimetres) but the porphyroblasts are partly retrograded (Simandl *et al.*, 1995). Occurrence **CH-4** is an excellent example, located 8 kilometres west-southwest of Bralorne on an overgrown forestry road and about 200 metres from the Hurley River. The outcrop is 30 metres long and 14 metres high. Weathering produces exfoliated layers several centimetres thick. The prismatic andalusite crystals (5 to 12%) are 5 to 20 millimetres long and 0.5 to 3.0 millimetres across. The hornfels also contains more than 1% pyrite (Simandl *et al.*, 1995).

Lillooet Area

Occurrences known in the Lillooet area have many similarities to those of the Bridge River area but are strongly retrograded to muscovite. All known andalusite occurrences (Figure 6) are hosted by hornfels derived from black argillites and siltstones similar to those of the Noel lithofacies of the Bridge River area. Unfortunately, andalusite porphyroblasts from this area are almost entirely retrograded to mica. There are a few

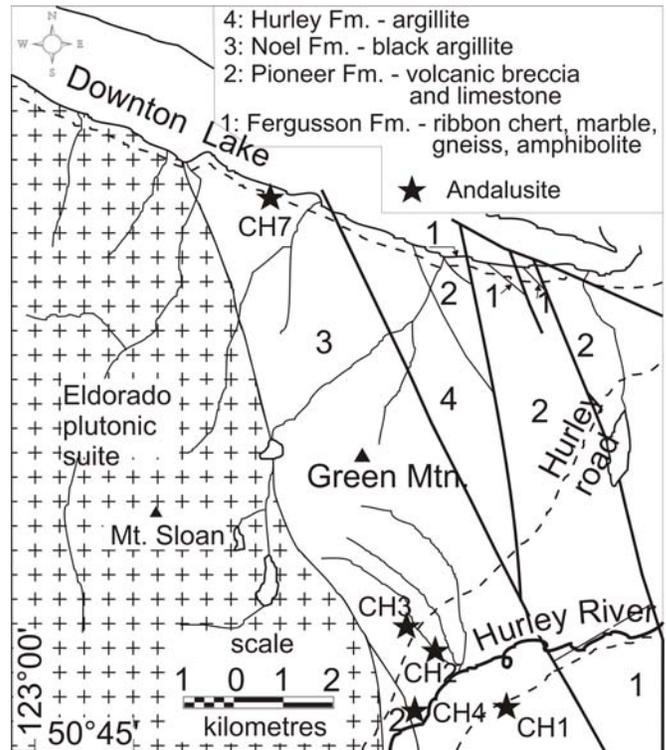


Figure 5. Andalusite occurrences in the Bridge River area (Simandl et al, 1995).

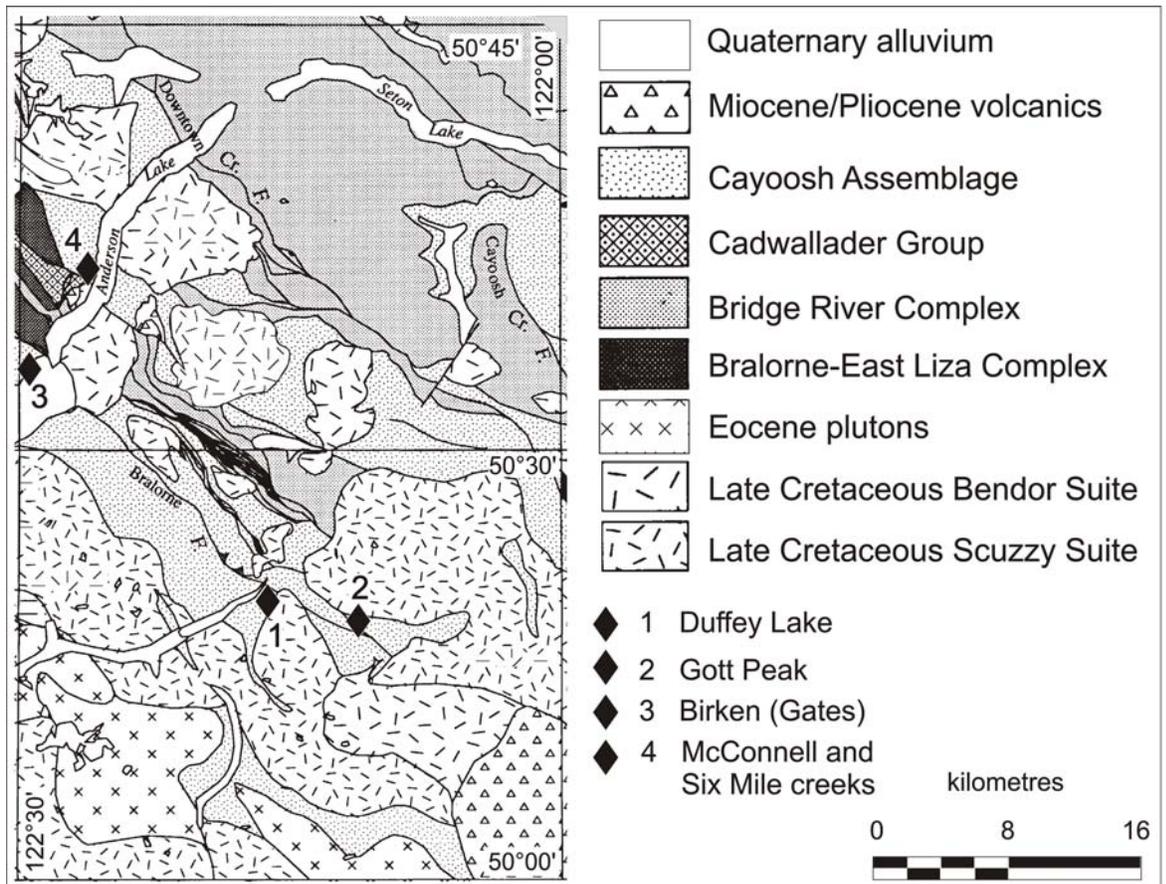


Figure 6. Andalusite occurrences in the Lillooet region (modified from Journey and Mahoney (1994)). 1 - Duffey Lake; 2 - Gott Peak; 3 - Birken (Gates); 4 - McConnell and Six Mile creeks. (Simandl et al., 1995, figure 3)

occurrences in the Duffey Lake area; the main one is west of Highway 99 near the northern tip of Duffey Lake (Figure 6). The andalusite horizon is a few meters thick and exposed over a 60 metres strike length. The groundmass is mainly biotite, quartz, possibly feldspar, pyrite (less than 1%), and garnets (less than 1 millimetre). Andalusite (2 to 15%) varies from 10 to 50 millimetres by 1 to 4 millimetres, and is retrograded to muscovite.

North of Gott Peak a raft of metasedimentary rocks (Journeay, personal communication, 1994) occurs within a granitic intrusion (Figure 6). Several fresh boulders (1 by 0.5 by 1 metres) were found south of that area. Mica pseudomorphs after andalusite, which are from 3 to 8 millimetres by several centimetres in length, comprise 20% of the rock.

The Birken (Gates) showing (Figure 6) is similar to Gott Peak but lies on the eastern margin of the Mount Rohr pluton (Journeay, personal communication, 1994). Blocks containing andalusite and staurolite in a groundmass of quartz, biotite, iron oxide (less than 1%) and millimetre-size garnets were found near the contact of sedimentary rock with the granite pluton near Birken. The largest block was 20 x 5 x 25 centimetres. Andalusite is largely retrograded to muscovite.

Hornfels boulders containing up to 15% high-alumina silicates were found in the bed of nearby Six Mile Creek (Figure 6). They contain 3 to 10% andalusite. The crystals are less than 6 millimetres in cross section and are enclosed in a quartz-biotite-feldspar groundmass.

Leech River Area

Andalusite occurrences are numerous in the Leech River area. The andalusite porphyroblasts vary from a few to 30 centimetres in length. Most of the occurrences are of no economic interest because of low grades, narrow widths, or the effects of intense retrograde metamorphism. Retrograde metamorphism decreases westward, so the area of greatest potential is adjacent to and west of the Jordan River. (Simandl *et al.*, 1995)

The Leech River Complex is fault bounded and consists of sedimentary and volcanic rocks intruded by igneous rocks and affected by low-P metamorphism. At the Late Eocene metamorphic peak, pressure is estimated to have been 1.5 to 3.5 kbar, and temperature between and 500 to 600°C. To the east, andalusite is strongly retrograded to either mica and staurolite or mica and chlorite; the degree of alteration diminishes westward from Valentine Mountain.

This study indicates that rocks in the western two-thirds of the area (Figure 7) contain abundant staurolite porphyroblasts. They are less than 1.5 centimetres long.

Andalusite is limited to specific outcrops where it is partially or entirely replaced by muscovite and chlorite. Individual andalusite occurrences are described by Simandl *et al.*, (1995); most are retrograded.

Other Andalusite Occurrences in the Coast Belt

Examination of hand specimens collected by the Geological Survey of Canada from the Raleigh Mountain area, and descriptions of occurrences in the Terrace region, indicate that some of the areas not covered by our reconnaissance study are prospective: In the Kwoiek area, andalusite pseudomorphs are replaced by sillimanite, (Hollister, 1969a, b).

At Mt. Raleigh, occurrences are in a roof pendant of volcanic and sedimentary rocks. Metamorphic grade increases to the southwest. Andalusite is confined to beds of graphitic, pelitic schist. The main andalusite-bearing unit, the Styx Formation, is 400 metres thick (Woodsworth, 1979). Porphyroblasts are less than 2 centimetres in cross section and 15 centimetres long. They form less than 10% of the rock. The Formation is exposed over a ten square kilometre area. Quartz and graphite inclusions occur in the porphyroblasts and the andalusite is partially retrograded to muscovite and quartz. Where metamorphism is highest, the andalusite is intergrown with fibrolite.

Andalusite-bearing rocks along the east side of the Coast Range (Nuit Range) are described by Rushmore and Woodsworth (1993, 1994). Metamorphic grade increases from northeast to southwest. Andalusite, garnet, staurolite and sillimanite are found only in pelitic rocks of the Cloud Drifter Formation where retrograded andalusite forms 'spots' and porphyroblasts less than 10 millimetres across. Andalusite content ranges from 5 to 10%.

Andalusite and biotite-bearing metasedimentary rocks are reported near the head of Jervis Inlet and at Phantom Lake (Greenwood *et al.*, 1991).

Although andalusite-bearing veins of Eocene age are reported to crosscut sillimanite-cordierite gneisses within the Khdata Lake Metamorphic Complex (Hollister, 1982) in the Prince Rupert and Terrace area, they are not of economic interest. North of Terrace, andalusite is found within the contact aureole of the Ponder pluton. It is very abundant within several 100 metres of the contact of the pluton on Mount Kenney. In Maroon Creek, at the head of Kitsumkalum Lake, boulders containing chiastolite prisms 2 centimetres in diameter are common. Andalusite occurrences at Atna Peak (Evenchick, 1979) are characterized by crystals with chiastolite cross-sections that occur in metagreywacke and argillite over several square kilometres.

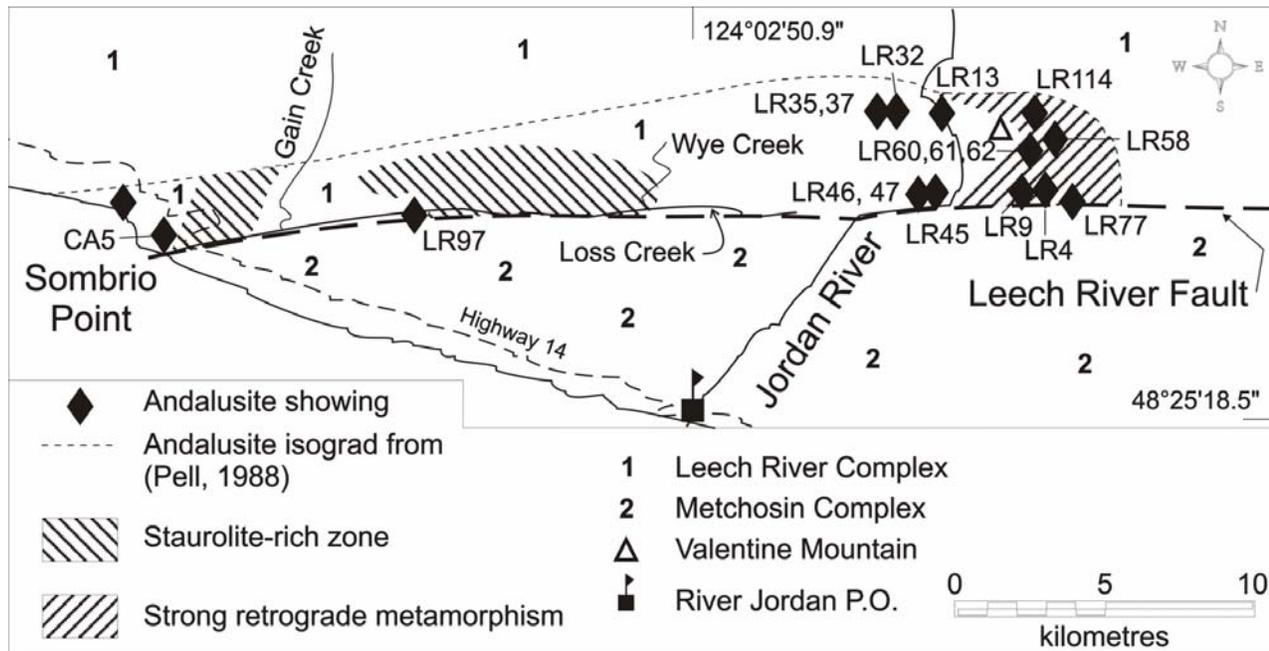


Figure 7. Andalusite occurrences in the Leech River area.

SUMMARY

British Columbia has good geological potential to host economic kyanite and andalusite deposits. Overall, most andalusite occurrences in the province appear to be affected by metamorphism. Thus andalusite is either partially or completely replaced by sillimanite or kyanite during later, high-temperature metamorphic overprint or to hydrated minerals, such as muscovite, during a later low-temperature (retrograde) event. Kyanite is less affected by later metamorphic events than andalusite, but the need for calcination of kyanite before use, makes it less attractive exploration target. The distance of the occurrences from infrastructure and the coast must be considered in preliminary selection of exploration targets.

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ORDOVICIAN UPTON CARBONATE-HOSTED BA-ZN-PB DEPOSIT, SOUTHERN QUEBEC APPALACHIANS: GEOLOGY AND GEOCHEMISTRY

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Lower Ordovician carbonates of the Upton Group, in the southern Quebec Appalachians (Figure 1), host stratabound Ba-Zn-Pb mineralization and vein- and breccia-type Cu deposits (Paradis *et al.*, 1990). The largest

deposit, Upton, consists of several stratabound lenses containing 950 000 tonnes of ore grading 46.5% BaSO₄, 1.9% Zn, 0.6% Pb, 0.15% Cu, 0.11% Cd, and 13.5 g/t Ag (Robex Resources Inc., 1988).

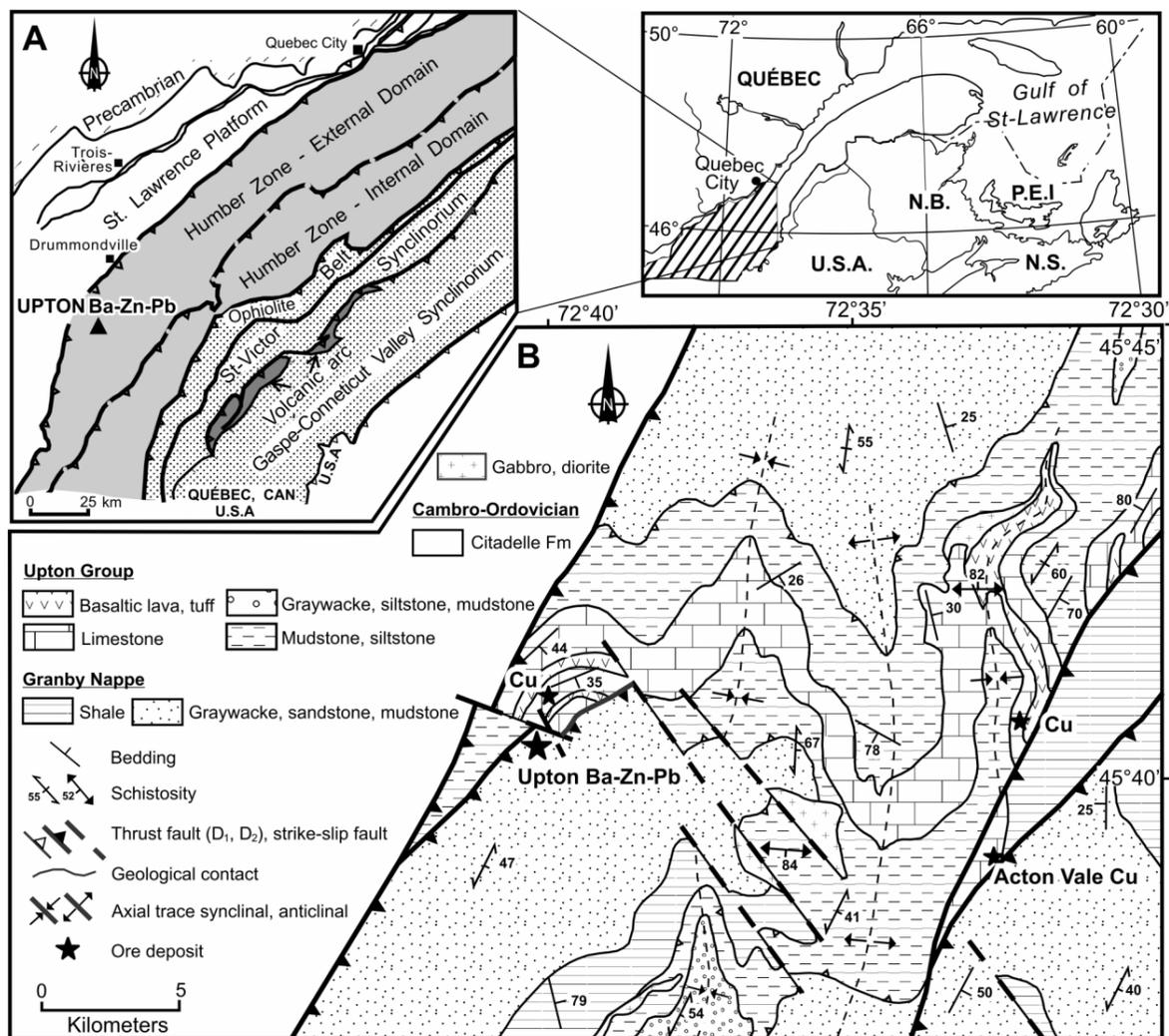


Figure 1. A. Location of the Upton Ba-Zn-Pb deposit within the Taconian external nappe domain of the southern Quebec Appalachians (modified from St-Julien and Hubert, 1975). B. Geological map of the Upton-Acton Vale area and location of the Upton Ba-Zn-Pb deposit (after Paradis and Lavoie, 1996).

Robex Resources Inc. is trying to proceed with the development of its Upton deposit. Known reserves could sustain production for more than 13 years at a projected exploitation rate of 26 500 tonnes of concentrated barium sulphate annually (Industrial Minerals, August 2000). Barite is used mainly in drill muds; other potential uses are as heavy aggregate, marine ballast, chemicals, and filler in industrial products (Paradis *et al.*, 1999). Mineralization at the Upton Ba-Zn-Pb deposit consists mostly of barite with minor amounts of sphalerite, pyrite, galena, and chalcopyrite, in addition to calcite, quartz, and bitumen cements. Barite occurs as clusters of subhedral and bladed crystals and rosettes replacing cement in the rock, and as fracture-filling material. Sulphides are disseminated through the limestone and form trains of aggregates concentrated along stylolites and crystal boundaries.

The deposit is hosted by bioclastic limestone of the Upton Group. The Upton Group consists of a mixed platform carbonate - siliciclastic - volcanic succession with two limestone intervals that are exposed as windows within the tectonically overlying Cambrian shale-feldspathic sandstone of the Granby Nappe. The deposit is hosted within the upper limestone interval. The mineralized limestone consists of well-sorted, cross-laminated crinoidal grainstone of shallow subtidal origin (Lavoie, 1992; Paradis and Lavoie, 1996). It is interbedded with, and capped by, a black calcareous shale, and underlain by a mudstone - siltstone - volcanic succession and a lower, poorly fossiliferous limestone of intertidal origin.

The lower, non-mineralized limestone recorded extensive early dolomitization followed by meteoric alteration and burial diagenesis. In contrast, the mineralized limestone, which underwent significant post-

depositional recrystallization and hydrothermal alteration, has abundant early to late diagenetic features, fracture-filling cements, and barite and sulphide mineralization. The main mineralization events coincide with two phases of barite mineralization (Figure 2).

The hydrothermal events are marked by: (1) development of secondary porosity and precipitation of a subhedral barite cement, (2) precipitation of a minor calcite fracture-filling phase, (3) precipitation of bladed barite cement and fracture-filling barite, (4) filling of fractures and remaining voids of the sediment by a sparry calcite cement, and (5) precipitation of sulphides, quartz, organic matter, and bitumen in remaining voids or fractures, and along stylolites (Paradis and Lavoie, 1996). Pre-barite syntaxial calcite overgrowths on crinoids yield $\delta^{13}\text{C}_{\text{PDB}}$ values of -3.9 to -15.0 per mil and $\delta^{18}\text{O}_{\text{PDB}}$ values of -13.7 to -14.8 per mil. Post-barite sparry calcite cement and fracture-filling calcite have $\delta^{13}\text{C}_{\text{PDB}}$ values of -2.6 to -13.0 per mil and -2.4 to -17.9 per mil, respectively, and $\delta^{18}\text{O}_{\text{PDB}}$ values of -13.6 to -14.2 per mil and -14.0 to -15.8 per mil, respectively.

Fluid inclusions in subhedral and bladed barite cement have homogenisation temperatures of 42.1°C to 96.9°C (Figure 3A). In fracture-filling barite, the inclusions have homogenization temperatures of 101.4°C to 142°C. Salinity varies between 4.7 and 8.1 wt percent NaCl equivalent, and is slightly higher in subhedral barite than in bladed barite (Figure 3B). Post-barite fracture-filling calcite and sparry calcite cement have homogenization temperatures of 80° to 130°C.

Sphalerite has homogenization temperatures and salinities of 82.4°C to 132.2°C and 18.3 to 19.7 wt% NaCl equivalent, respectively. Quartz has

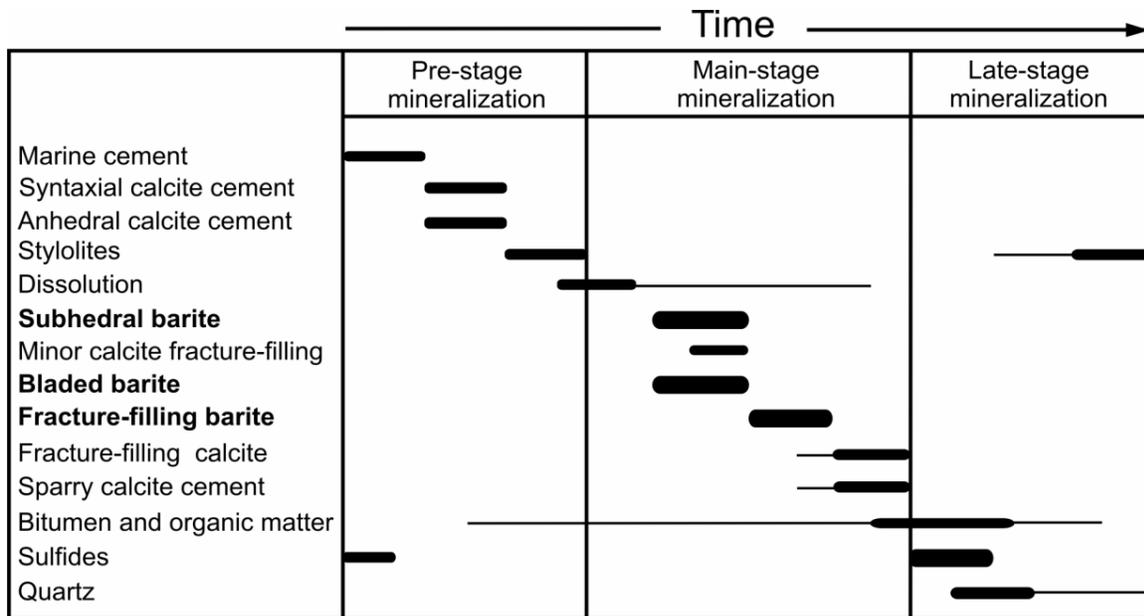


Figure 2. Paragenesis of the diagenetic features within the Upton Ba-Zn-Pb deposit (modified from Paradis and Lavoie, 1996).

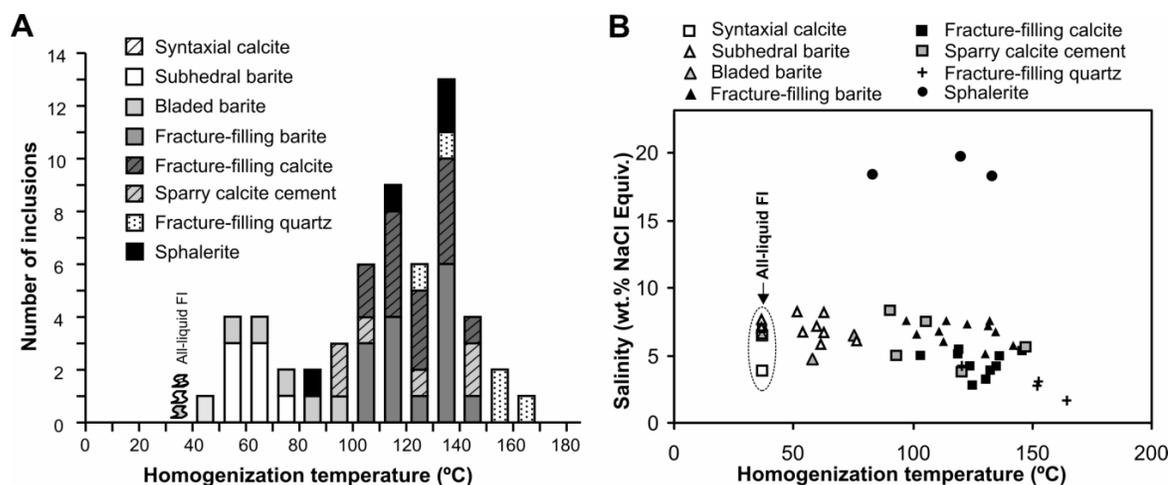


Figure 3. A. Histogram of homogenization temperatures of fluid inclusions from the Upton Ba-Zn-Pb deposit. The homogenization temperatures of the single-phase liquid inclusions cannot be determined but are probably about 50°C (broken bars). (B) Homogenization temperature versus salinity diagram for fluid inclusions from the Upton Ba-Zn-Pb deposit.

homogenization temperatures of 121.8°C to 164.2°C and salinities of 1.7 to 4.2 wt percent NaCl equivalent. Fluid temperature increased with time between precipitation of subhedral to bladed barite, and precipitation of post-barite fracture-filling calcite, sparry calcite cement, sphalerite, and quartz. Bitumen is present throughout the paragenesis, but primary CH₄ inclusions only occur in quartz. H₂S- and CH₄-enriched gases were detected in barite and calcite by quadrupole mass spectrometry (QMS) analysis, occurring as secondary fluid inclusions. The ⁸⁷Sr/⁸⁶Sr ratios of the barite range from 0.70654 to 0.70781, lower than Early Ordovician seawater.

Mineral paragenesis and geochemical data suggest that the deposit formed by mixing of marine water-dominated, SO₄²⁻-rich fluid with an ¹⁸O-enriched and ⁸⁷Sr-depleted basinal brine that carried Ba, Zn, and Pb. The basinal brine could have been expelled from the siliciclastic-volcanic succession of the Upton Group during the Taconian orogeny. It is postulated that the brine migrated upward into, and interacted with, the bioclastic limestone to create secondary dissolution porosity where barite and sulphides precipitated. Mixing of hot basinal brine with colder sulphate-rich seawater-derived fluid is the most likely cause of barite precipitation. The reduced sulphur required for the precipitation of sulphides was derived from thermochemical reduction of sulphate by hydrocarbons. The late precipitation of sulphides relative to barite is explained by the sluggishness of the reaction between the hydrocarbons and SO₄²⁻ to produce H₂S and ¹³C-depleted calcite.

In summary, the Upton Ba-Zn-Pb deposit has an epigenetic origin involving the focused discharge of hydrothermal solutions along faults into a porous crinoidal limestone aquifer. Precipitation of the mineralization took

place within open spaces of the limestone, and subsequently replaced the limestone. The physico-chemical conditions suitable for barite and sulphide precipitation probably occurred during the Middle to Late Ordovician Taconian orogeny when tectonic burial and compression is thought to have initiated the circulation of fluids.

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JADE (NEPHRITE) IN BRITISH COLUMBIA, CANADA

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DEFINITION:

Jade is a commercial term encompassing green, white, black or yellow-brown material that consists either of Na-rich pyroxene (jadeite) or prismatic to acicular amphiboles of the tremolite-actinolite series that form bundles that are randomly oriented and interlocked (nephrite).

Nephrite is tougher (harder to break) than jadeite material. Its fracture strength is about 200 MN/m² whereas that of jadeite is about 100 MN/m². On the other hand, jadeite material is harder (7 compared to 6.5 on the Mohs scale).

JADE IN BRITISH COLUMBIA

There are over fifty known nephrite occurrences in British Columbia. These are located in the Cassiar, Cry and Dease Lake, and Mount Ogden areas, as well as in Southern British Columbia (Simandl, *et al.* 2001). 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 contacts of ultramafic/mafic rocks (mainly serpentinites) with cherts, and other metasedimentary or igneous felsic rocks of oceanic terranes such as the Cache Creek (Mississippian to Jurassic) and Slide Mountain (Devonian to Permian) terranes. These contacts are commonly interpreted as shear/fault related. In general, it is believed that the British Columbia nephrite formed by metasomatic exchange between ultramafic and silica-bearing rocks. Impurities in the nephrite are spinel group minerals (chromite, magnetite, picolite), diopside, uvarovite, titanite, chlorite and talc (Leaming, 1978; Simandl *et al.*, 2000).

MINING THE NEPHRITE DEPOSITS

Mining a gemstone that is accurately described as the “toughest natural stone on earth” presents a challenge to any miner. As with any gemstone, explosive devices must be avoided to prevent unnecessary damage to the jade. However, traditional, non-explosive rock splitting methods are virtually useless on jade because its tightly locking fibres make reducing the jade into manageable pieces difficult. As some glacial boulders weigh in excess

of 100 tonnes and all in situ deposits have complex shapes and the need to reduce the jade into manageable sized pieces is the main task of a mining operation.



Figure 1. Nephrite in British Columbia

Two metre diameter circular diamond saws and diamond wire saws are used to reduce the size of the jade blocks and provide a visible cut surface for quality evaluation purposes (Figure 1). Modern extreme high pressure hydraulic splitters are helpful when existing fractures can be found.

The mining, or perhaps more accurately, quarrying, method used for the nephrite jade is determined by the type of deposit.

Jade boulders, formed by glacial erosion, represent the simplest occurrences to mine. These boulders are tested by diamond drilling or sawing, and only the commercial grade material is removed from the mine site for sale.

Today, in situ jade deposits have overtaken alluvial mining as the main source of jade production in Canada. The Northern British Columbia nephrite deposits are large but due to the difficulty in extracting the material and the current world demand favouring high and gem grade jade, only a small percentage of deposits are in production.

The northern jade deposits are remote and winter conditions are harsh, so mining typically occurs during

the very short summer season, which lasts from mid June to late September.

MARKETING JADE

For the past 100 years, British Columbia nephrite has been used in local jewelry and ornamental applications. It is the best quality nephrite jade that is available in the world today. Exports of approximately 200 tonnes per year over the past 25 years represent more jade produced than at any other time in the history of man. This has resulted in new uses for a stone once reserved for the Emperors of China.

The bulk of Canada's jade production is used for traditional jade carvings and jewelry. Products are exported to the historical jade nations of China, Taiwan and New Zealand. Canada's relatively small domestic consumption of at 4 to 5 tonnes per year supplies a few successful jade artists of world renown.

The famous gem-grade discovery at the Polar Mine secured Canadian Jade's fame as a world class gemstone producer. Polar Jade™ is now exclusively used for jewelry and museum quality carvings, but there are other very well-known high-quality nephrite deposits in British Columbia.

As the availability of Canadian jade has become better known, non-traditional uses of the stone have also increased. From massive Buddha statues, to fireplaces in the Getty Mansion, to translucent window panels in the Smithsonian Museum, Canadian nephrite is becoming world famous as a stone of wide versatility.

Its aesthetic appeal, strength, and toughness, coupled with the massive deposits of relatively low cost raw material, could lead to the use of jade as a dimension stone for interior and exterior tiles. This will probably be the next step in the evolution of the Canadian jade industry.

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THE CLEVELAND SOUTH 30 × 60 MINUTE QUADRANGLE SURFICIAL-GEOLOGY MAP: ITS USE FOR PRELIMINARY EVALUATION OF INDUSTRIAL MINERAL AVAILABILITY

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The combined value of all nonfuel industrial minerals (limestone and dolomite, sand and gravel, sandstone and conglomerate, clay and shale, salt, gypsum, and peat) sold in Ohio in 1999 was more than US\$786 million. This represents an 81% increase in value since 1990 (Weisgarber, 1991; Wolfe, 2000). This increase in industrial-mineral production was led by clay and shale (+141%); other commodities that also increased significantly are: sandstone and conglomerate (+59%), limestone and dolomite (+51%), and sand and gravel (+36%). Ohio is a national leader in industrial-mineral production (United States Geological Survey, 2000). In 1999, Ohio ranked 4th in the production of lime (1.8 million tonnes), 4th in the production of salt (4.1 million tonnes), 5th in the production of construction sand and gravel (53.5 million tonnes), 5th in the production of clay and shale (6.4 million tonnes), and 7th in the production of crushed stone (73.2 million tonnes).

The rapidly expanding production of industrial minerals in Ohio must compete with many other land uses in the heavily populated state. In a recent urban-sprawl analysis, the Cincinnati metropolitan area was ranked 11th worst in the United States, and Columbus 17th worst for cities with populations greater than 1 million. Similarly, Lima ranked 6th worst in the less than 250 000 population category (USA Today, 2001). Planning for sequential land use that includes development of industrial mineral resources in these growing areas is vital to the sustainability of urban and suburban centers.

Three-dimensional surficial materials mapping is an indispensable tool for informed land-use planning. For example, the reconnaissance-scale surficial geology map of the Cleveland South 30 × 60 minute quadrangle (Pavey and others, in prep.) is a recent digital product of the Ohio Division of Geological Survey (DGS). It was completed as part of the DGS participation in the United States Geological Survey (USGS)-funded National Cooperative Geologic Mapping Program. The Cleveland South 30 × 60 minute surficial-geology map can be used both for regional land-use planning, and for preliminary evaluation of industrial-mineral availability in the heavily populated Cleveland-Akron metropolitan area.

There are four primary features depicted on the Cleveland South map: (1) major lithologies; (2) lithology thickness; (3) lateral extent; and (4) vertical sequences that are shown by stack symbols. Each stack represents a

generalized cross-section for each area. Data were obtained from county soil maps that were modified by interpretation of local geomorphic settings; from other government sources, such as the Ohio Department of Natural Resources, Ohio Division of Water water-well logs, Ohio Department of Transportation test-boring logs; and from theses, and published or unpublished geologic reports and maps. Total thickness was calculated from DGS 7.5-minute open-file bedrock-topography maps. Bedrock units are based on DGS open-file bedrock-geology maps.

Map units of primary interest for industrial-mineral evaluation include: Wisconsinan-age interbedded sand and gravel commonly containing thin, discontinuous layers of silt and clay (**SG**); Wisconsinan-age ice-contact deposits (**IC**): highly variable, poorly sorted sand and gravel with common inclusions of silt, clay, and till, which were deposited from stagnant ice as kames or esker landforms; and Wisconsinan-age sand containing minor amounts of gravel, silt, or organics (**S**). These units are in colours from yellow orange (**SG**), to dark red (**IC**), to yellow (**S**) on the map and are easily discernible (Pavey and others, in preparation). Wolfe (2000) reported that most sand and gravel production (approximately 5 million tonnes in 1999) came from these units in the Cleveland South 30 × 60 minute quadrangle.

Bedrock map units of secondary interest for evaluation of industrial mineral potential occur principally in areas of thin till. These include the Pennsylvanian-age Sharon sandstone in the eastern portion of the map area (**Ss**), and Mississippian-age Berea Sandstone in the northwestern portion of the map area (Pavey and others, in prep.). The Sharon is a greater than 90% silica sandstone used primarily by the glass industry. Production of Sharon sandstone in the map area was approximately 900 000 tonnes in 1999 (Wolfe, 2000). The Berea is generally a medium- to coarse-grained blue-grey to buff sandstone. The Berea was quarried in the late 1800s and early 1900s in the map area and was used extensively as a dimension stone throughout Ohio, the eastern United States, and eastern Canada (Bownocker, 1915). West of the map area, in Lorain County, the well-known Cleveland Quarries have been producing Berea Sandstone dimension stone for more than 100 years. The **Ss** unit is light pink on the map and is easily recognized.

After initially identifying areas of interest, the three-dimensional database for the Cleveland South map can be

used to determine potential mineable resources. For example, areas delineated as **SG** with 20 feet or less of till and greater than 20 feet of sand and gravel may warrant further examination. Stack units delineating areas of organics (**O**, *), clay, silt, till and silty clay (**C**, **L**, **T** or **LC**) help to determine the boundaries of potentially mineable sand and gravel deposits. General transportation networks, mined areas, and possible markets are depicted on the map; these are also factors that determine whether a more detailed evaluation is justified.

SUMMARY

The Cleveland South 30 × 60 minute surficial-geology map can be used as a “quick-look” reconnaissance tool to help evaluate the availability of potentially mineable industrial-mineral resources for an urban area of nearly 3 million people. The map is digital, and future plans of DGS include production of easy-to-update GIS products. This state-federal collaborative mapping effort was a precedent. Subsequently, the state geological surveys of Ohio, Michigan, Indiana, and Illinois collaborated with the USGS to establish the Central Great Lakes Geologic Mapping Coalition (Berg and others, 2000). The purpose of the Coalition is to standardize mapping techniques and stratigraphic nomenclature and to provide three-dimensional maps of glacial and related deposits (Central Great Lakes Mapping Coalition, 2000). The more detailed mapping to be done under the auspices of the Central Great Lakes

Geologic Mapping Coalition would be invaluable in transforming surficial-geology information into a much more important tool for industry to evaluate the availability of potentially economic industrial-mineral deposits.

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A LONG TERM SUCCESS STORY BASED ON SIMPLE CLAYS AND SHALES

By Don Harris, Clayburn Industries, Abbotsford, BC, Canada

The company known today as Clayburn Industries Ltd. was first incorporated in 1905 when John McClure, an engineer from Scotland, discovered what he recognized to be a fireclay deposit on the north face of Sumas Mountain, a few kilometres from what was then the village of Abbotsford. Since that time, the company has changed hands several times, gone through many ups and downs financially, and changed manufacturing locations twice. Despite these dramatic events in its history, Clayburn survives today and is, after 96 years, still a vital force in the refractory industry on a worldwide scale.

The basis of the extended success of the company is a deposit found on Sumas Mountain. As set out in the "Capsule Geology" on the Government of British Columbia Ministry of Energy and Mines website, as follows:

A series of shales, including a true fireclay deposit, occurs in the sedimentary rocks that cap the southwestern end of Sumas Mountain. This sedimentary sequence comprises more than 366 meters of interbedded shales, sandstones and conglomerates.

A zone of highly kaolinized material between the Tertiary sediments and underlying rocks suggests that a period of intense weathering of the basement material preceded the deposition of the sedimentary series. The thickness of the kaolinized zone varies, and is known to range up to 21 meters (in depth). The fireclay seam was deposited in an arc-shaped basin that averages about 500 meters east and west.

The lower part of the Tertiary series consists of alternating beds of shale and sandstone with a few lignite seams. The shales are thought to be of the Eocene-Oligocene Huntingdon Formation.

From the kaolinized fireclay and higher temperature shales, Clayburn Industries Ltd. has manufactured a range of firebrick, refractory monolithic products and face brick. Face brick is used in the construction of buildings of all types. The original plant was located in Clayburn Village, now part of Abbotsford, but moved in the 1920s to the village of Kilgard on the south face of Sumas Mountain. Following a fire at the Kilgard plant in 1948, the operation moved to its present location in downtown Abbotsford.

Today the company employs approximately 45 production workers including supervision, has an administrative staff of 7, and has an executive team that oversees the efforts of the company worldwide. In

addition to the manufacturing operation in Abbotsford, the company is heavily involved in refractory construction throughout western Canada. These markets are served from offices and warehouse facilities in Edmonton and Calgary as well as that in Abbotsford. An office in Washington State serves as the headquarters for our worldwide aluminum marketing efforts. At times the company has been best known for its building products, however, its worldwide success is based upon production and sale of refractory products, firebrick and associated materials.

To put the company's position in perspective, worldwide there are about 2000 companies that produce close to 40 million tonnes of refractories per year. A major problem facing the industry is that the capacity to produce such products far outstrips the demand.

At 25 000 tonnes per year, Clayburn's production is small, but its products are used around the world. The company markets product throughout western Canada, but also in such far-flung spots as Mozambique, Australia and India. Success is based upon an ability to serve niche markets with products made mostly from the clays and shales found on Sumas Mountain. The company starts with clays and shales that cost less than \$10.00 per tonne delivered to the plant and manufacture products that sell for prices as high as \$500.00 per tonne. To be successful, the company produces a range of brick products that range from low heat duty firebrick through to 75% alumina brick. It also produces a complete line of refractory concretes, mortars and gun mixes that are manufactured both from calcined clays produced from our own deposit as well as from higher purity materials imported from the United States and China. Additionally, the company complements production of refractory products with face brick used in the construction of homes, as well as institutional, commercial and industrial buildings.

There is no large heavy industry or smelting base to British Columbia's economy, with the exception of Cominco's lead and zinc operation at Trail. Consequently, the company looks to the pulp and paper industry for local markets. Production of Kraft pulp is dependent upon the availability of caustic lime. In rotary kilns at mills throughout the province, lime is recovered and sent back to the process for re-use. Clayburn enjoys the bulk of this business in British Columbia, routinely supplying not only the high alumina and clay brick and refractory monolithic products used in the lining of such kilns, but also the expert crews needed to install the products. Of

the 16 rotary kilns that exist in the province, Clayburn supplies products and installation services to 12.

Clayburn supplies the Cominco smelter, which is a strong consumer of clay brick to line their roaster. This also creates opportunities for the company's construction crews to install both products manufactured by Clayburn and those from other sources.

Likewise, the ALCAN aluminum smelter at Kitimat uses Clayburn's products. On the reduction side of this large smelter, the company supplies brick as well as dry vibratable bottom materials used in the reduction cells. Clayburn has enjoyed a preferred position because the supply is relatively close to the smelter, and based on the quality and economic competitiveness of the company's products.

From our Abbotsford location, we also cover the consuming industries in the Pacific Northwest of the United States. Up until the early 1990s, Clayburn was the largest refractory installer in Washington and Oregon. A company upheaval in the early 1990s, combined with the growing litigation pattern in the American market led the company to abandon the construction market there. Today, the company works closely with end users as well as independent installers to offer Clayburn-made products to this market.

On the Prairies as well as locally, Clayburn supplies both manufactured products and installation services. The company focus in this geographic region is energy-related applications but the lime and cement companies also provide some business opportunities. Our business there is largely driven by industries that produce petroleum products, either from traditional oil refineries such as those in Edmonton and Regina, or by using newer technology, like the tar sands plants in the Fort McMurray area. The largest single market involves companies that use natural gas to produce methanol, fertilizers, carbon black and ethylene. Their plants consume large quantities of refractories, mainly in the form of monolithic products.

What truly differentiates Clayburn from other refractory producers is its focus on the primary aluminum industry. Over the past 15 years the company has become recognized around the world as the leading supplier of barrier materials to the reduction side of the aluminum smelting market.

In these smelters, primary aluminum is made from almost pure aluminum oxide, more commonly called alumina, which in turn comes from bauxite. The fluxing agent cryolite is mixed with alumina and charged to an electrolytic cell. Large quantities of electricity are used. The graphite cathode blocks that conduct this electricity sit on several layers of refractory in the bottom of the pot. The upper layer that supports the cathode block is known as the barrier layer, and it serves two purposes. Firstly, it provides structural support for the heavy cathode block in a relatively hot 950°C environment. Secondly, and of equal importance, it must be able to resist attack from the

corrosive cryolite constituents, fluorine and sodium, that are present largely as vapour at temperatures ranging from 850 to 950°C. Barrier materials take two forms: brick and dry vibratable materials.

The chemical inertness of brick is an important property that contributes to the long life of such cells. Inertness is associated with favourable chemistry and low porosity of the brick. Further, tight joints when the bricks are installed aid in resisting penetration of the lower layers that are insulating in nature. To achieve tight joints, close tolerances are required. Efforts to minimize porosity require development of glassy phases during the firing portion of the manufacturing process. However, glass formation will also lead to deformation as the brick softens at high temperature and cause variation in sizing. Clayburn has been able to achieve minimal porosity and also hold tolerances to about plus or minus one millimeter from a nominal dimension. Few producers worldwide are able to achieve such results. Based upon this technology, Pechiney approved Clayburn brick (Kilgard brand) for use in its state of the art 300 kA reduction cells around the world. Clayburn is one of two suppliers approved worldwide to provide this type of product. Of the ten such smelters presently in operation, Clayburn was the original supplier on all but two, and currently has brick in use in smelters using this technology in such far-flung locations as Australia, New Zealand, South Africa and Mozambique, as well as in four smelters in Quebec.

As stated above, the joints are one of the weak links in the barrier layer. If the joints in the brickwork could be eliminated, so could this source of penetration and cell or pot life would be extended. In the late 1980s, Intalco Aluminum, located just south of our plant at Ferndale, Washington, approached Clayburn with a challenge: "Can a monolithic material be developed to replace brick in this application that does not require water in the installation process?"

Avoiding water was important in the installation process to avoid lengthy dry-out periods that curtail production and decrease the risk of steam explosions that could result if not all the moisture was removed. Without water, refractory concretes that do not employ either conventional cement or those using the more evolutionary ultra low cement bonds were acceptable.

Working together, the two companies cooperatively developed Clayburn® Dri Barrier Mix™. This product, which employs proprietary technology, is a material that is vibrated into place without the aid of water or cement binders. By closely controlling the particle size distribution, the product is capable of being installed to density levels on the order 2 metric tonnes per cubic meter. Apart from a 1.5 centimetre layer on the surface, the material is compacted to a state where a harp pointed tool cannot penetrate the consolidated mass.

Once it is in place, a mineralizer is added to the mix that promotes creation of a glassy layer. The glass is

produced by reactions between the product constituents and the sodium and fluorine components of the cryolitic bath. Its chemical composition corresponds to albite or nepheline. The depth of this layer is controlled by the design of the pot bottom. The whole bottom package that includes the insulation as well as the working or barrier layer is designed so that the 850° isotherm at which this glass freezes, is in the middle of the barrier layer. With the isotherm so positioned, penetration is halted and the insulation is protected from impurities that would otherwise destroy its insulating properties.

At Intalco, performance of the material exceeded expectations. Not only did it perform as well as brick, but also pots using this new technology had increased lifespans on the order of 35%. Other savings resulted because fewer hours were required to install the product (one hour versus two to three shifts), and both power and cryolite consumption were reduced.

Thanks to its success at Intalco, we were able to take this product around the world. Today, it is used in Canada, the eastern and western United States, France, Brazil, Venezuela, Russia and the People's Republic of China. The success of Clayburn® Dri Barrier Mix™ contributed to establishment of the Xianyang Clayburn Refractory Co. Ltd., a wholly foreign owned venture with production facilities in Xianyang, Shaanxi Province, and sales and administrative offices in Nanning, Guangxi Province.

Clayburn entered the Chinese market in 1995 and formed a joint venture with a Chinese partner in 1996. While this company grew rapidly, Clayburn bought out those interests in 1999 due to problems attributable to the Chinese partner and re-incorporated the company as a 100% Clayburn owned venture. We now have a medium sized facility in the middle of China and 27 full time employees. This year, the company expects to exceed \$3 million in sales at profit levels that we could only hope to achieve here in North America.

Over and above our wholly owned businesses in Canada and China, Clayburn shares equal ownership with Lafarge Canada in Sumas Shale. This company mines shale and sandstone for sale as a cement kiln feed to Portland cement producers along the west coast of Canada and the United States. This company has no employees, leases the deposit from which it extracts the stone, and contracts its stripping, drilling, blasting, crushing, grinding, loading and hauling. Even the management and financial controls are done under contract.

Over the years, Clayburn has survived by adapting to changing market conditions and demands. Today, this statement is as true as it has been throughout the history of the company. Our success is based upon serving market niches that are literally worldwide. It is our goal and objective to continue to grow and prosper, not by being the biggest at what we do, just the best.

WEATHERING AND PROVENANCE OF MUSCOVITE -- A NEW APPROACH TO UNDERSTANDING THE SEDIMENTARY KAOLIN PROBLEM

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The origin of the Cretaceous and Tertiary kaolin deposits of central Georgia and South Carolina is controversial. Detailed studies over the past century have produced a number of hypotheses ranging from in situ weathering to a variety of sedimentary processes. A knowledge of the provenance of the sediments is necessary to test these hypotheses, and thus to understand the genesis of both the Cretaceous and Tertiary kaolin deposits (see for example Kogel. *et al.*, 2000; Pickering and Hurst, 1989).

Kaolin mining is a billion dollar industry in central Georgia and South Carolina. The intent of this research is to lead to improved models of kaolin genesis, and these may aid in future kaolin deposit exploration both in the United States and abroad. Aside from their economic importance, the deposits themselves are very interesting to the research community. A thorough study of the ages of the muscovite micas within the deposits will yield a better understanding of their provenance, the degree of weathering of the sediments, and the role of mica weathering in the formation of kaolin. Knowledge of both the source area for the sediments that host the deposits and the degree of weathering they have undergone since deposition will help us understand the processes that produced the kaolin deposits in the Coastal Plain and shed light on the genesis of other sedimentary kaolin deposits around the world.

Muscovite is a plentiful component of the mined Cretaceous and Tertiary kaolin deposits, and crystals up to 5 millimetres in diameter are common in the sandy layers. K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of muscovite micas from both the sand layers and the kaolin lenses of the deposits will enable comparisons to radiometric ages from crystalline rocks of the Georgia Piedmont. Additionally, potassium and argon contents in the weathered muscovite as compared to accepted values in pristine muscovite may provide clues as to the provenance of the sediments in the deposits, and improve understanding of chemical weathering that has affected the source rocks. Hassanipak (1980) measured K-Ar ages of the weathered muscovite in 15 samples from one locale in the area; the reported ages range from 343 Ma to 191 Ma. His results also show the average K-Ar ages of muscovites from sediments deposited during the Late Cretaceous, Paleocene, and Eocene are 257, 295, and 281 Ma, respectively. The

average age reported is similar to ages of muscovite from crystalline Piedmont rocks to the north, like the Stone Mountain and Palmetto Granites, (Dallmeyer, 1978, McConnell and Abrams, 1984). Laser $^{40}\text{Ar}/^{39}\text{Ar}$ spot analyses of individual muscovite grains (Hames and Hodges, 1993; Hames and Andresen, 1996) should yield a range of ages. The oldest age, which is usually near the centre of the crystal, is expected to provide the closest estimate of the time of original cooling through the Ar retention temperature by the source rock. K-Ar ages of muscovite separated from the same sedimentary units should yield age minimums. By combining results from the K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ methods it is possible to constrain the source of these micas and to assess the magnitude of the losses of K and radiogenic argon due to weathering.

For some time it has been assumed that the kaolin deposits of central Georgia and South Carolina were derived from the weathering products of the Piedmont crystalline rocks. At this time, only Hassanipak (1980) has attempted to correlate the two using radiometric age techniques. Although his data support this theory, Hassanipak did not study or take into account the severely weathered nature of the muscovite separates he dated. Muscovite, like most sheet phyllosilicates, tends to separate, or splay, at the crystal margins perpendicular to their 001 axes during weathering. It also tends to gradually transform to kaolinite or other clay minerals. This weathering trend undoubtedly releases interlayer K and Ar, and due to its gaseous character, interlayer Ar may be released preferentially relative to interlayer K, which would decrease apparent K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

Recently, laser $^{40}\text{Ar}/^{39}\text{Ar}$ spot analyses of individual muscovite grains from detrital sediments have been used to determine provenance (Copeland and Harrison, 1990; Kelley and Bluck, 1992). As mentioned, muscovite tends to weather preferentially along the exposed edges leaving the centers relatively unaltered and similar tendency is seen in muscovite elsewhere that has undergone low temperature metamorphism (Hames and Cheney, 1997). The result of both processes is to produce an age gradient across the mineral surfaces perpendicular to the 001 axis, with the youngest ages near the edges and around fractures, and the oldest near the centres. This is entirely due to preferential loss of radiogenic Ar during weathering and metamorphism. In both cases, ages from

the centres of the mineral grains would more closely approximate those from muscovite in the unaltered parent material. A more accurate and precise estimation of the provenance of the detrital mineral grains could be determined if muscovite ages from all possible sources were available. Unfortunately, relatively large mineral grains are necessary to use the $^{40}\text{Ar}/^{39}\text{Ar}$ spot analysis technique, so data are limited. Muscovite grains smaller than 200 microns cannot be analyzed, and even those large enough to analyze may be too weathered to produce reliable data, so the number of stratigraphic units from Georgia kaolin deposits that could be dated using this technique is also limited.

Although the muscovites are severely weathered, traditional K-Ar analyses of separates from the deposits may still yield significant data. Ideally, the K-Ar ages would show a trend throughout the deposits.

First, a normal chronology in the muscovite ages, with the oldest micas at the base of the deposits, and the youngest near the top, which would indicate that a single weathering and deposition history caused the stratigraphy now seen in the deposits. If, as in Hassanipak's study, the ages are similar to those of dated muscovites from the crystalline rocks of the Georgia Piedmont, and $^{40}\text{Ar}/^{39}\text{Ar}$ ages do not differ significantly from the K-Ar ages, then a straightforward weathering-transportation-deposition model will be supported. However, if a normal chronology is not seen, then a more complex history will be supported. Even if the $^{40}\text{Ar}/^{39}\text{Ar}$ ages differ significantly from the K-Ar ages, the trends seen in the K-Ar ages should still be valid. In any set of muscovite crystals derived from the same source, each crystal should show similar histories of weathering, and Ar and K loss would be expected to be consistent from one mineral grain to the next. This assumes that mica grains in a given deposit that survived transport have all suffered similar degrees of weathering.

This study will focus on dating the muscovite found in sand and accompanying kaolin lenses in Cretaceous and Tertiary deposits along the Georgia Fall Line and on studying their weathering characteristics through traditional light microscopy, scanning electron microscopy (SEM), and the laser $^{40}\text{Ar}/^{39}\text{Ar}$ technique. It should be noted here that the terms "Cretaceous" and "Tertiary" imply the ages of deposition of the deposits, and not the age of the minerals within the deposits.

Samples have been collected throughout the region and cover most of the stratigraphic units. A set of samples have already been prepared for K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ analysis by disaggregation, washing, and sieving. Samples prepared thus far from both the sandy layers and the kaolin lenses have yielded separates where muscovite and quartz tend to concentrate in various sieves. To prepare muscovite concentrates for K-Ar analysis, these muscovite and quartz-rich portions were placed in a heavy fluid solution for density separation. Unfortunately,

it appears that the muscovite grains used in this study are weathered to the point where their density approaches that of quartz, so separation with heavy liquids was impossible. Even if the sample was placed in a vacuum to remove any air trapped along the splayed edges of the muscovite heavy liquid separation was unsuccessful. It is possible that alteration products formed from the muscovite within individual grains could produce this effect. Another possibility is that potassium was leached from the muscovite during the extended weathering of the deposits, which may have reduced the density of the mineral grains. Detailed examination of the muscovite grains using SEM and the $^{40}\text{Ar}/^{39}\text{Ar}$ laser will be necessary to understand this behavior. This illustrates another possible application of the $^{40}\text{Ar}/^{39}\text{Ar}$ laser technique to the study of the weathering characteristics of detrital micas.

Hassanipak's early work indicated that the muscovite in the kaolin belt of Georgia came from the Piedmont. It is possible that more detailed information obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ ages and new K-Ar ages will be sufficient to pinpoint particular source areas within the Georgia Piedmont. Even if this is not the case, we hope that age trends relating to the weathering-transportation-deposition system and the $^{40}\text{Ar}/^{39}\text{Ar}$ age distribution within individual muscovite grains will provide a clearer understanding of the weathering history of the deposits.

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CABIN CREEK PHOSPHATE PROJECT

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Phosphorous is essential to all forms of animal life and together with nitrogen and potassium, is necessary for plant growth. Phosphate rock is the most suitable source of raw material in the manufacture of chemical phosphate fertilizers. This industry consumes approximately 95% of the world's phosphate production. Phosphate rock, in its natural state, is also used for fertilizer applications.

Phosphate is produced from three sources: marine sedimentary rocks, igneous apatite (carbonatites), and guano-derived deposits. Approximately 80% of phosphate production is from bedded sedimentary rocks, such as those located within the Jurassic Fernie Formation of southeastern British Columbia.

Earth Riches Resources Inc. is interested in the area that covers the southern limit of the Fernie Basin and includes the southernmost exposures of phosphate rock in the Basin. It is located 76 kilometres by road southerly from the town of Fernie. Imperial Oil Ltd. began exploration for phosphate in this region in 1978. Further investigation was done by First Nuclear Corporation in 1982. Exploration by individuals and other companies has continued sporadically to the present. Earth Riches Resources became interested in this area in 2000.

The Cabin Creek phosphorite bed occurs at the base of the Jurassic Fernie Formation. The phosphatic layer is 1.51 to 3.51 metres thick, and has been traced along a strike length of approximately 1700 metres. It consists of compact to semicompact pellets. The pellets are typically subrounded to subangular, structureless, well sorted and 0.1 to 0.3

millimetres in diameter. The matrix consists of quartz, calcite, minor potassic feldspar, and trace amounts of albite, dolomite and illite. The geological resource for the Cabin Creek area, as calculated by Earth Riches Resources staff, is estimated at 1.5 million tonnes averaging 19 to 20% P₂O₅ to a depth of 25 metres.

Although the total phosphate content of the Cabin Creek phosphorite is lower than that of material imported from the western United States, available phosphate compares favourably. Available phosphate is defined as the amount of phosphate that dissolves in a weak citric acid solution, which is believed to imitate conditions near plant roots. As well, phosphate rock from the Fernie Formation, and particularly from the Cabin Creek area, generally contains lower levels of the toxic metals cadmium, arsenic, uranium, selenium and lead (Table 1) than phosphate from other locations.

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TABLE 1: GEOCHEMISTRY OF SELECTED PHOSPHATE DEPOSITS.

Location	As	Pb	H ppm	U	C	P ₂ O ₅	F %	Organic Carbon
Montana Gray	53	66	1	121	1	31	2	0.24
Phosphoria Fm.								
Soda Springs Id.	10	47	0.05	70	23	28	*N/A	*N/A
Phosphoria Fm.								
Cabin Creek Fernie Fm	16	18	1	40	1	21	2	2.6
Phosphoria Fm.(average)	40	10	N/A	90	50	30.5	3.1	2.1
Fernie Fm.(average)	30	13	N/A	33	0.9	20.5	1.43	1.63
	*not available							

REPORT ON THE 1999 GROUND-PENTRATING RADAR INVESTIGATION: MT. MEAGER PUMICE DEPOSIT

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This report presents a summary of a geophysical investigation conducted by Golder Associates Ltd. (Golder) between September 16 and 19, 1999 on behalf of the owner, Great Pacific Pumice Inc. at the Mt. Meager Pumice Project site. The site is an operating open pit pumice mine located approximately 65 kilometres northwest of Pemberton on the North Slope of Plinth Peak at Mt. Meager. The main pumice deposit lies south of the Lillooet River, which over time has cut a 90 metre high, and 250 metre long bank at the bottom of the deposit. Ground Penetrating Radar (GPR) survey profiles were completed in the area of a planned new quarry on the west slope of the estimated 25 million cubic metre deposit.

The purpose of the investigation was to determine the minimum thickness of pumice across the proposed new quarry. The conventional approach used to evaluate the location and minimum depths of the pumice was an expensive drilling program. The purpose of the GPR survey was to provide an economical two-dimensional indication of the pumice distribution.

The survey area was mostly overgrown with thick vegetation; therefore survey lines were limited to road surfaces cut through the forest. Experience indicated that the pumice overlies a colluvial paleosol that developed during the Holocene, before the pumice eruption, approximately 2 350 years ago. The airfall pumice was deposited as a thick mantle on the existing topography, which in this area was a rock avalanche. Much of the pumice was deposited on the surface of the avalanche. Subsequent creep and sliding have resulted in development of small-scale lamination within the pumice. Overburden that developed on top of the pumice varies in thickness from a few decimetres to over a metre, depending on the surface slope and gravity driven accumulation/depletion.

The GPR method was selected for this investigation because dry, porous pumice would be relatively transparent to GPR whereas the underlying paleosol would be relatively reflective. In addition, GPR provides good vertical and lateral resolution of subsurface reflectors relative to most other techniques. Earlier, Dr. J.K. Russell from the University of British Columbia obtained trial GPR profiles at a nearby site with good results.

No boreholes have been drilled on the pumice fan, so calibration of the GPR traces against known stratigraphy was limited to exposures cut by the Lillooet River and

those in the existing quarry. The main limitation to GPR in this environment is the possibility of clay-rich materials in the surface soils that could limit GPR penetration into the pumice deposit.

A total of 2410 line-metres of GPR data were collected, and the following general comments can be made about the acquired data and their interpretation:

- In essence, the GPR data quality is controlled less by depth of penetration than by clutter from within the pumice deposits, which is usually in the form of discontinuous reflections;
- The multiple reflections and scattering seen within the pumice deposit can be used to typify these materials, and to distinguish them from the underlying glacially-derived paleosols and local bedrock;
- The maximum penetration through the surface soils and pumice deposit was approximately 28 metres, as seen on lines immediately upslope from the pumice cut bank on the Lillooet River;
- The surficial soils layer limited penetration on portions of some lines;
- The paleosol surface underlying the pumice is generally apparent in most of the GPR profiles as a contiguous reflector layer. Above it there is a characteristic scatter of discontinuous reflectors that is identified as the pumice deposit.
- Interpretation of the GPR survey profiles was based on geophysical principles and experience, combined with stratigraphic exposures in the pit wall and riverbank, and the general geomorphology of the pumice deposit.

SUMMARY

GPR profiles revealed a series of undulating paleosurfaces with pumice thicknesses of up to 28 metres, perpendicular to the paleosurface slope. The overburden was variable in thickness (up to 2 metres) and moisture content in places was significant enough to block penetration of the GPR signal. The survey objective was met. Results were considered reliable by the owner, and their engineer used them to calculate a resource that exceeds 3.2 million cubic metres within the study area. From this data, the company completed a 20-year mine plan.

INVESTIGATING THE POTENTIAL OF INDUSTRIAL MINERALS IN SAUDI ARABIA

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ABSTRACT

The Kingdom of Saudi Arabia has existed as a nation state since 1932. The discovery of oil in the 1930s and the fact that its oil reserves now represent 13% of the world's known oil resources, combined with a stable centralized government, has led to an extraordinary leap forward in terms of economic growth. The country is today a major and flourishing economic power with a GDP of around \$130 billion. A period of very rapid expansion has occurred since 1973; however periods of slow-down seen in the last decade have sparked a determined drive toward economic diversification. The role of minerals in general and industrial minerals in particular has been important, with the construction industry sector, notably cement and aggregates, leading at the outset of expansion. However, other industrial mineral sectors have expanded dramatically in the last 15 years, notably glass, ceramics, ground calcium carbonate (GCC), and titanium dioxide.

An intensive period of mineral exploration has taken place over the last four decades under the auspices of the Deputy Ministry for Minerals Resources (DMMR). The Ministry produced more than 600 technical documents, and created a mineral resource database. As a natural maturation of this process, the government created Ma'aden (Saudi Arabian Mining Company) and the Saudi Geological Survey (SGS) at the end of the 1990s.

Whilst the SGS will henceforth assume the role of a public service custodian of the national geological information database, involving upstream exploration and integrated research projects, Ma'aden's role is solidly based in the downstream development of mineral exploitation projects. The company is already heavily involved in gold production, and is presently working on several major industrial mineral projects. The main ones are the Az Zabirah bauxite, Zarghat magnesite, and the Al Jalamid phosphate projects; each will require investment of several hundred of million of dollars.

In parallel to opening up Saudi Arabia's commercial sector to private investment, and within the framework of the move towards entering the World Trade Organization (WTO), Ma'aden is set to become, over the medium term, a wholly privately owned organization, with equity on the Saudi stock market planned for 2003. Streamlining the mining code and the possibility of 100 % foreign ownership are seen as the keys to expansion in the minerals sector. In a move to supply the ever-growing Saudi industry with local minerals, and open up new opportunities for manufacturing development, Ma'aden recently sponsored a major industrial minerals market research program. Indications are clear that sectors that are currently heavily dependent on imports are set to expand and use indigenous raw materials.

INTRODUCTION

Saudi Arabia, an overview

The Kingdom of Saudi Arabia (KSA) conjures up vivid visions of desert sands, oil-wells, and OPEC meetings. The country sits on more than a quarter of total proven world oil reserves - some 263.5 billion barrels - that would last about 90 years at current production levels. With a production rate of 7.8 million barrels a day (MBD) or 13% of the world total in 1999, it is the world's leading oil producer as well as the largest exporter and holder of spare oil production capacity. Overall, the petroleum sector accounts for roughly 75% of the KSA's budget revenues, 35 to 40% of its GDP, and 80 to 85% of its export earnings, which totaled \$43.6 billion in 1999.

All this activity -- research, exploration, production, refining and export of petroleum and its derivatives such as crude oil, natural gas, liquefied gas, asphalt, and sulphur - is controlled by Saudi Aramco.

In an effort to reduce dependence on crude oil exports, there has been a concerted effort to diversify the economy. Thus in 1976 the Saudi Basic Industries Corporation (SABIC) was formed with US\$3 billion in capital to establish and operate basic industries that depend on local hydrocarbon and mineral resources. Owned 70% by the Saudi Government and 30% by private investors, SABIC currently maintains 15 production companies in Saudi Arabia, 3 production joint-venture companies in Bahrain, and several marketing subsidiaries worldwide.

Another diversification effort has been to develop the country's mining and value-adding industries in order to service the needs of the country's growing population and rapidly expanding infrastructure. Half of the country's native population of 15 million is less than 18 years old, and the population continues to grow at an average annual rate of 3%. As a consequence, Saudi Arabia has emerged as a regional manufacturing center based on imported as well as domestic mineral and chemical feedstocks.

The Saudi cement industry ranks third after petrochemicals and banking in terms of annual yield. The eight companies in the sector produced 13.6 million tonnes of cement in 1998. Cement factories in the Kingdom are reported to have a capacity of 22 million tonnes per year and are now turning to export markets to augment their sales. In late 1999, the major Saudi cement companies established a joint firm, the United National Exports Company, to market their products.

Other established industries include the Saudi Iron and Steel Co.'s 4 million tonnes per year steel plant and the neighboring 85 000 tonnes per year Gulf Ferro Alloys Company ferroalloy plant; five container glass, two fiberglass, and one flat glass plant; and a state-of-the-art chloride-route titanium dioxide pigment plant.

LOOKING TO THE FUTURE

The Saudi Arabian Mining Company (Ma'aden) was established in 1997 by Royal Decree to carry out mining and mineral development across the Kingdom. The company was capitalized with some US\$1 billion in funds and assets, and according to Dr. Abdullah Dabbagh, President and CEO, one of Ma'aden's key objectives is to act as a catalyst for private investment in the Kingdom. The concept is to work in conjunction with current and future private-sector projects to hasten development of the nation's mineral resources. Although Ma'aden's equity shares are held by the state, there are plans to progressively privatize the company and place it on the Saudi stock market after 2003.

The company is already in gold mining business through Mahd Ad Dhahab mine near the center of the Arabian Shield, and the nearby Sukhaybarat gold mine which is 100% owned by a Ma'aden subsidiary, the Saudi Company for Precious Metals (SCPM). At this time, the nearby proposed open pit gold project at Bulgah is entering the final feasibility stage. Production is planned for the Al Hajar deposit in the southwest of the Kingdom in 2001, and further north (just west of Riyadh), the Al Amar gold deposit is being assessed as a possible underground mine and other gold prospects are under evaluation. In addition to precious metals, deposits of copper and zinc, including the large Jabal Sayid copper-zinc ore body near Mahd Ad Dhahab and the smaller Khnaiguiyah zinc deposit near Al Amar, are being evaluated.

Through considerable investments in the mining sector, the Saudi government has paved the way for private sector investment. By mid-1997, government investment in mineral resource development and throughout the mining sector reached US\$6.67 billion.

THE HISTORY OF INDUSTRIAL MINERALS EXPLORATION IN SAUDI ARABIA

In 1962, the Saudi Arabian Ministry of Petroleum, (at that time called the Directorate General for Petroleum and Mineral affairs) in an attempt to expand programs of Mineral Exploration, formed the Deputy Ministry for Mineral Resources, or DMMR (initially a sub-unit termed Directorate General for Mineral Resources or DGMR). The proximity to the Hijaz Mountains and the Precambrian basement terrain of western Arabia meant that DMMR's location in Jeddah, on the Red Sea Coast, was ideal. However, the chronic lack of qualified workers meant that it had to lean heavily on expertise from overseas.

In the early 1960s the DMMR/USGS mission first undertook 1:500 000 scale geological mapping of the country. The results were published by the United States Geological Survey (USGS), under the name "Miscellaneous Geological Investigations I-200 series" and formed the basis of 35 years of intensive exploration.

By 1966 DMMR had built a strong relationship with the USGS and invited other outside agencies, notably France's BRGM, to conduct exploration in the country. In the 1970s, WGM of Toronto and Riofinex, the exploration subsidiary of RTZ, Seltrust Engineering, British Steel Corporation, and Minatom all began exploration in Saudi Arabia.

In 1966 BRGM proposed a program of systematic prospecting for industrial minerals and rocks in the shield of western Arabia. Interest focused initially on ornamental granites, with a pilot plant being established (Figure 1). Priority was given to finding construction materials, and over the next 25 years, prospecting operations were centred on the main towns. This work facilitated establishment of numerous cement, aggregate, and clay brick plants as well as ornamental granite dressing factories, to supply local demand. With the discovery of magnesite, phosphorite and bauxite deposits, the first major targeted exploration drilling programs were launched under contract to BRGM and Riofinex.

Geological mapping at 1:250 000 scale by DMMR, USGS and BRGM teams in the 1960s, and general prospecting programs revealed other industrial mineral resources of interest, such as silica sand, gypsum, white carbonates, nepheline syenite, bentonite, kyanite, wollastonite, and kaolinitic clays.

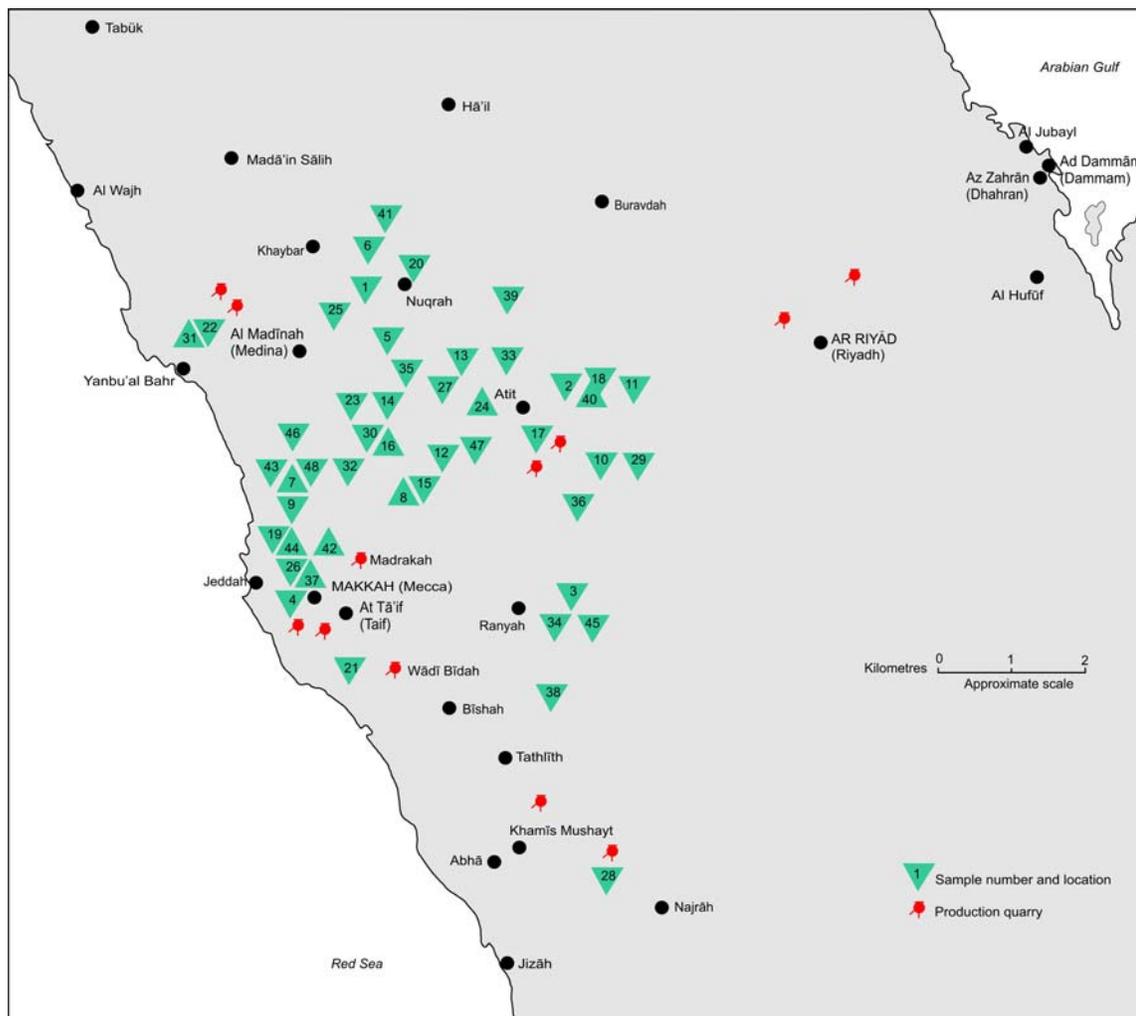


Figure 1. Catalogue of Ornamental Stone deposit locations published by the DMMR in 1974

In the 1970s, 1980s and early 1990s industrial minerals' prospecting was divided into 4 main operational types:

First, at the end of the 1970s and into the 1980s, the objective was to establish an inventory of potential resources within a 100 kilometre radius of the Kingdom's main towns. This program was independent of the 1:250 000 scale geological mapping and principally targeted resources for the construction industry.

Second, within the framework of the 1:250 000 scale geological mapping program, draft field maps were followed up by industrial minerals geologists who sampled targets of potential interest and evaluated the overall potential of the map area.

Third, specific targets based on priorities emanating from within the Ministry were investigated, such as locating raw materials for cement, and pozzolanic raw material.

Fourth, the Ministry initiated the 1:100 000 scale Industrial Minerals Resource Maps program in 1981 that

was completed in 1992. This involved the production of simplified geological maps for areas around each of the Kingdom's seven major cities at a scale of 1:100,000. These maps also contained all information pertaining to prospecting operations for industrial and construction minerals represented in a symbolic form with a circle diagram.

The large number of samples that were collected through the 1970s and 1980s required development of extensive laboratory facilities that were sited in Jeddah. The laboratories, now part of SGS, enabled chemical characterization and certain preliminary identification tests to take place. More specialized testing was sub-contracted to other laboratories in Europe and North America.

The exploration programs of this period were reported in DMMR Open File reports. By 1993, there were approximately 600 of these reports. The seven Industrial Mineral Resource Maps are classified as Technical Reports. Conceived in 1976 and operational in 1978, a database on mineral occurrences was set up and

called MODS (Mineral Occurrence Documentation System). Over the years some 5 200 entries were made, and the system became the Integrated Geoscience Information System that is now an integral part of the Saudi Geological Survey. Laurent completed the “Atlas of Industrial Mineral Resources”, and it was published in 1993 by the DMMR (Figures 2 and 3). Most of the more than 600 references cited in the Atlas are DMMR/SGS Technical reports that are available in the SGS library in Jeddah. In parallel and overlapping to a certain extent, the DMMR published “Mineral Resources of Saudi Arabia” in 1994 (Collenette and Granger, 1994). This document includes metallic minerals and focuses on large accumulations of minerals, rather than occurrences. This publication has 28 chapters covering industrial minerals, and presents details on reserve estimates and calculations, industrial tests and results, and other data.

THE SAUDI GEOLOGICAL SURVEY (SGS) AND MA’ADEN – DISTINCT AND COMPLEMENTARY ROLES

In November 1999, after four decades in which foreign agencies played a major role in mapping and producing mineral inventories of the country, the Saudi Geological Survey was created as a new and separate part of the DMMR. The highly qualified, young Saudi workforce is trained both in the Kingdom and abroad. The role of the SGS is to gather, store and make available geological data for the Government and citizens of the land. This also involves undertaking research programs to enhance the information base to improve management of the Kingdom’s natural resources and to provide information and advice in the formulation of land use plans to preserve the natural environment.

MOVING INTO INDUSTRIAL MINERALS

Ma’aden has a number of industrial minerals projects that it inherited from the period when the DMMR largely sub-contracted to overseas agencies. Phosphate, bauxite, and magnesite deposits are at various stages of evaluation. In the northern region of the country Ma’aden holds 20 000 square kilometres of phosphate exploration concessions and a 30 000 metre-drilling program is ongoing. The Al Jalamid deposit is slated for development with plans to use the phosphate rock as a feedstock for the production of di-ammonium phosphate and other phosphate products for export markets. This will require capital investment, including infrastructure, of about US\$2 billion and will involve an experienced partner or partners to help penetrate the market.

South of the phosphate region, Ma’aden continues to evaluate the mainly boehmite non-refractory grade bauxite deposit at Az Zabirah. Although the alumina content is high, the location is remote, infrastructure is a problem, and the ore requires Bayer Process digestion.

The third of Ma’aden’s ongoing industrial mineral projects is the Zarghat magnesite deposit some 160 kilometres southwest of Hail. This 4 million tonne resource could provide feed to a proposed processing plant that would produce high-grade deadburned magnesia and possibly fused magnesia for the export market. The projected budget for these facilities is US\$30 million. Joint venture possibilities are being reviewed.

Ma’aden began an industrial minerals exploration program early in 2000. The project started with a review of all known resources in the Kingdom housed in the Integrated Geoscience Information System. Based on the extensive data available, Ma’aden decided to focus on resources most likely to evolve into viable operations. The resulting list of more than 50 industrial mineral targets was screened to identify those most likely to be of commercial interest in the KSA.

The selection criteria used included the following:

- **Deposits identified in the Kingdom.** Priority was given to those minerals with known deposits in the Kingdom. Information on the location, size, and quality of these deposits further determined the attractiveness of the mineral for development. Minerals with an attractive market but no known occurrence in the Kingdom could form the basis for a future exploration program.
- **Inadequate local supply.** Ma’aden’s objective is to develop the industrial mineral resources of the KSA without competing with existing successful private-sector producers. Opportunities may arise that fill gaps in the current supply position – for example, supplying additional or superior grades, production in a different geographical area, etc. – and so eventually Ma’aden’s production may compete in the national market place with established producers. This competition would be healthy by providing the consumer with a choice, which in turn may stabilize prices and may improve the quality and service standards of the existing producers.
- **Markets identified.** A priority is to identify the size and type of markets for the various minerals divided according to distance from the point of production.
- **Domestic KSA market; Gulf Cooperation Council member countries; regional markets in the Middle East** where a demand and a competitive freight rate may allow market penetration from the KSA such as Jordan, Lebanon, Iran, Iraq, or Syria; more distant markets accessible to ocean transportation and with significant mineral demand, for example North Africa and southern Europe.

Clearly, certain minerals fit certain markets. Low-priced commodities such as construction materials and silica sand require minimum transportation costs and therefore a strong local market with little or no prospects for export. Mid-priced minerals may be able to compete in domestic and/or regional markets if they exist, whilst

higher priced minerals, or upgraded versions of mid-priced minerals, can compete in more distant markets such as North Africa, Europe, or elsewhere. At the same time, areas with larger and affluent populations that have a medium to high GDP per capita have a greater demand for minerals.

The work began with a detailed market survey of industrial mineral consumption in the Kingdom. Mineral consumers such as manufactures of paint, steel, ferroalloys, and glass were visited and their mineral needs discussed. Data was gathered on what minerals were used, the volumes, whether they are domestic or imported, critical specifications, packaging requirements, transportation options, and prices. The study was not comprehensive but the main consumers were contacted and an overall picture of the market in the KSA developed. Volumes and values were calculated and the main areas of consumption pinpointed. Supply problems were identified which might be translated into marketing opportunities. A similar exercise was performed in the other Gulf Cooperation Council member countries, including Kuwait, Bahrain, Qatar, the United Arab Emirates, and Oman, as well as (in less detail) other regional consumers in the Middle East. Some additional work identified potential markets in Europe where cheap maritime transport could reach the market competitively. The concept was to identify a handful of minerals that could be commercially developed together with a list of secondary minerals that could be attractive under certain circumstances.

The primary prospects selected by the analysis, are materials used mainly as fillers for paint and plastics, to produce glass, drilling mud, and refractories. The paint industry dominates the demand for white filler minerals like calcium carbonate, talc, and kaolin in the GCC, while container glass is the largest consumer of calcium carbonate, nepheline syenite, and soda ash. In the Middle East, the petroleum industry is a significant consumer of barite and refractories may be based on magnesite, alumina, kaolin, or dolomite.

The reasons for categorizing certain minerals as marginal candidates for development include:

- Lack of a domestic and regional market
- Inability to penetrate markets in North Africa and Europe.
- Small and/or declining world markets.
- Overwhelming competition from low-cost/exceptional quality producers.
- Highly complex technology/marketing.
- Possible environmental and/or occupational health and safety concerns.

The reasons for rejecting certain minerals as possible candidates for development in the KSA include:

- Lack of a domestic and regional market.

- Inability to penetrate broader markets in North Africa and Europe.
- Lack of known resources in the Kingdom.
- Overwhelming competition from producers with extremely low production costs and/or exceptional quality
- Highly complex technology/marketing.
- Small and/or declining markets.
- Environmental and/or occupational health and safety concerns.

CURRENT PRODUCTION OF INDUSTRIAL MINERALS

The recent article by Habib *et al.*, 2001 provides abundant statistical evidence of the production levels of industrial minerals in Saudi Arabia today. Table 1 summarizes some of this data.

THE INVESTMENT CLIMATE

Direct Investment Opportunities

Even when capital is in place, suitable deposits have been located and potential markets identified, most mineral resource development in the KSA will require foreign participation. It is generally accepted that there is a need to reduce state involvement and increase private sector, including foreign, participation and investment in the economy to support the growing population. Suggested changes include reduced government subsidies, financial sector reform, and increased privatization, as well as changes to the country's tax code on foreign business profits and foreign ownership rules. Traditionally, foreigners are limited to a 49% ownership of any joint venture, must have a Saudi sponsor, and may not own property.

Since October 1999, international investors have been permitted to invest in local shares through established open-ended mutual funds. In April 2000, Saudi Arabia's Council of Ministers approved a new Foreign Investment Law that allows foreigners 100% ownership of the projects, as well as ownership of the property required for the project itself or for housing company personnel, and allows them access to the same incentives given to national companies. For example, projects that are 100% foreign-owned will be eligible for loans from the Saudi Industrial Development Fund. The year-old Saudi Arabian General Investment Authority claims that more than 200 foreign entities have won licenses for US\$8 billion in projects so far, although few have progressed beyond the planning stage. However, more than twenty areas of business, ranging from oil

production to the retail trade, have been ruled out for foreigners.

The administration also reduced the corporate tax rate from 45% to 30% for foreign companies with profits over SR100000 a year. The new regulations also allow companies to carry forward corporate losses for an unspecified number of years. In May 2001 import duties were cut from 12% to 5%, and there are no taxes on personal income or sales. One factor driving these changes is the desire to become a member of the World Trade Organization (WTO). Current ownership and labour laws are incompatible with WTO standards and are being modified by the Saudi government. Saudi Arabia has "observer status" within the WTO, indicating that negotiations are in progress.

Attention is now being given to the mining industry as a means of providing a growing population with raw materials, downstream products, and employment.

An Attractive Mining Code

The highest authorities are currently approving a draft of a new mineral policy, in the Kingdom, prepared by the DMMR and reviewed by the Multilateral Investment Guarantee Agency and the World Bank's Mining Unit.

The mining code has extended a number of incentives to investors. Exploration licenses guarantee the exclusive right to explore within the license area, and the exclusive right to obtain a mining lease. The area granted could be as large as 10 000 square kilometres. Exploration

TABLE 1 MINERAL-BASED INDUSTRIES IN SAUDI ARABIA (DATA FOR 1998)

Industry	Raw Material	No of plants	Production (tonnes)
Aggregates	Hard rock, gravel, sand	584	120 000 000
Bentonite	Smectite rich clay	1	500
Caustic Soda	Salt and limestone	2	600 000
Cement	Limestone and clay	10	16 000 000
Ceramics	Kaolin, clay, feldspar, silica sand	3	200 000
Dimension Stone	Granite, marble	8	200 000
Drilling Mud	Barite	1	150 000
Fibreglass	Silica sand, kaolin, limestone	3	10 000
Glass	Silica sand, limestone,	6	530 000
GCC	Pure limestone or marble	3	230 000
Lime and lime products	Limestone	3	340 000
Terrazzo or mosaic tiles	Marble chips, white cement	60	250 000
Gypsum plaster	Gypsum	2	380 000
Pozzolanic material	Scoria, volcanic ash	3	2 000 000
Fired clay bricks	Clay	13	5 000 000
Rock wool	Basalt, limestone	2	80 000
Salt	Rock salt, brines	7	200 000
Sodium Silicate	Silica sand, salt	1	30 000
Total		712	146 200 500

leases are initially for five years, but they are renewable for another four years. Mining leases guarantee the exclusive right to produce and exploit specific minerals in a mining area as large as 50 square kilometers. Mining leases are initially for 30 years, but they are renewable for another 20 years. Mining leases come with a five-year tax exempt period. Furthermore, all imported mining equipment is exempt from import and export duties.

Foreign investors in the mining sector may repatriate their profits and capital with no restrictions.

The creation of Ma'aden, along with upcoming revisions to the mining code, promises more streamlined administrative processes. To date, over 920 licenses have been given to companies for exploration of mineral resources.

Indirect Investment Opportunities

According to the Ministry of Petroleum and Mineral Resources, the Kingdom is "not just intent on finding mineral resources, but also on developing them and integrating them into the Saudi economy." Plans to develop integrated downstream industries in the mining sector are starting to materialize. In 1996, a 160-tonne design capacity refinery for gold, silver, and other products was set up at the Jeddah industrial estate. The plant's output is expected to meet the Saudi market requirements for these products. Dahab, a Saudi-French Offset company, owns the project. The Saudi private sector holds 51 percent of the company, while the French concern, Thomson CSF, holds the remaining 49 percent.

Opportunities abound in the fields of industrial mineral extraction and processing. For extraction, there is a need for machinery such as crushers, drills, loaders, boring machinery, pumps, ventilation equipment, trucks, rock saws, crushers, conveyor belts, jack hammers, graders, cranes, and bulldozers. Processing can involve hoppers, screening equipment, silos, bagging facilities, high gradient magnetic separators, flotation cells, cyclones, ball and jet mills, kilns of a variety of types to mention but a few. Exclusive distribution for the Kingdom is not required.

In addition, the new railways extension project will generate demand for hardware and related items. Saudi Arabian Railways Organization is looking for a strategic partner with expertise in construction for three projects, worth US\$4.5 billion, to enhance the railway network. The projects are for a comprehensive package to include both land and sea freight. The first project is to construct a railroad to transport phosphates from the Al-Jalamid area in the north and from Az Zabirah in the Central Province of Saudi Arabia to Jubail Industrial City. The railway connection is expected to extend 1 200 kilometres, serving Al-Basim and the Central Province areas. The second project will connect Jubail Industrial City to the present railway system, which extends from Dammam to Riyadh. The railway connection is expected to be 130 kilometres long, and transport 25 000 tonnes of material. The final project will provide a link from King Abdulaziz Port on the Arabian Gulf to the Islamic Port in Jeddah on the Red Sea.

Opportunities are also available in consulting services and technical knowledge, as the mining sector is being developed. The most significant opportunities in this area include exploration, design and exploitation engineering services, as well as construction, commissioning, and training services. Consulting firms can access the Saudi market through one of two channels: either by establishing a joint venture, or by appointing an agent or agents in Riyadh, Jeddah and Dammam, the three major cities in the Kingdom.

CONCLUSION

In a determined drive to diversify the economy, Saudi Arabia is opening up its commercial sectors to foreign investors. In the Industrial Minerals sector, a market study sponsored by Ma'aden demonstrates that numerous opportunities exist.

Four decades of exploration have created a resource knowledge base that is on a par with that of any developed country, and the processes for upstream and downstream development are firmly established.

According to Ma'aden's President, Dr. Abdallah Dabbagh, Ma'aden "recognizes the importance of having transparent laws and regulations, and the need to attract international mining expertise." Given that mineral ores in remote areas lack the infrastructure needed to mine them, Ma'aden will also contribute to the development of water, electricity, and telecommunications.

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MINING IN AN URBAN ENVIRONMENT – AN EXERCISE IN COMMUNITY RELATIONS

By Barry Irvine, Lehigh Northwest Materials Ltd., Delta, BC, Canada

Tilbury Cement Ltd., through its aggregate companies, Construction Aggregates, Steelhead Aggregates, and Cadman, operates a number of aggregate mines varying in size from 100 000 tonnes per year to what will later in 2001 become a 6 000 000 tonne per year mine in Sechelt, BC. Tilbury also operates a cement plant in an industrial park in Greater Vancouver and as ready-mix plants in various locations throughout Vancouver and Seattle. All operations are in close proximity to urban areas and thus require community relations programs to ensure continued operation.

Community relations have become an increasingly important part of the life of any heavy industrial operation, whether near an urban area or not. Provincial and state governments are downloading responsibility for mining and industrial operations to municipal governments, having tired of complaints from voters. Operating rules are becoming increasingly limiting with noise, dust, and operating hours being the target of very restrictive rules. The success of future operations and permitting of new reserves relies increasingly on a record of satisfying local and external environmental concerns.

Construction Aggregate's (CAL) Sechelt operation overlooks the town of Sechelt. The closest structure to the mine is the town hospital. Noise generated at the mine carries across Porpoise Bay to higher-priced residential areas. The mine, still in its early stages of development, has a high visual impact on the town. With a large retired population in the community, increasing local jobs is not a universal need.

The days of hiding behind a fence and keeping a low profile in the hopes that neighbours will go away are long gone. Left to their imaginations, what people conjure up is without exception far worse than anything the plant is doing.

CAL has taken an active approach to community relations. As well as ensuring the town receives financial benefits through local purchasing and support of local charities and events, CAL has built a relationship with the local schools and residents. Students and teachers tour the mine regularly to see geology in action. The mine provides an opportunity to see a cross-section of geological history. Residents of the community are also encouraged to tour the mine either during the mine's annual community open house or as groups at any time during the year.

INDUSTRIAL ROCKS IN EUROPE

By Manuel Regueiro y González-Barros and Manuel Lombardero Barceló
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A review of production of the main European industrial rocks is made in the framework of the world situation and with a detailed analysis of its current outlook and future trends. Shortage of raw materials today is becoming a severe problem in European countries where the construction industry continues to flourish in many areas. National and European policy makers and mining organizations should develop legislation and conduct media campaigns to increase public awareness of the need to exploit such resources rationally and coherently while recognizing environmental concerns. Exploitation must be done in

accordance with the principle of sustainable development that a Union of all European countries requires; otherwise the European construction industry will face a raw materials shortage and increasing production costs in the medium term. In this age of globalization, producers of aggregates, gypsum, clay and other industrial minerals will follow the lead of the dimension stone industry in exploring other continents for raw materials. Consequently, the trend toward ever-increasing dependence on foreign sources of materials to service the European economy will continue, with the risks this trend entails.

UNITED STATES INDUSTRIAL MINERALS IN A GLOBAL CONTEXT

By David E. Morse, United States Geological Survey, Reston, Virginia, USA

The United States is the world's largest consumer of goods and materials. The Nation's aerial extent, geologic diversity, and level of technological development, allow it to produce a wide variety of industrial minerals for domestic use, and in some cases to be a major world supplier. For many industrial minerals, however, imports are required to meet demand, and the United States relies primarily on its neighbours, Canada and Mexico, to supply most of these needs.

A few industrial minerals that are not readily available from those trading partners are imported from other areas of the world.

In the coming decades, domestic resources will continue to supply the bulk of the industrial minerals consumed. However, it is probable that industrial mineral imports will increase, and most of those imports will come from Canada and Mexico.

OPPORTUNITIES FOR VALUE-ADDED BY-PRODUCT OR CO-PRODUCT MATERIALS FROM INDUSTRIAL WASTE STREAMS

By Todd Harris, Kline & Company, Little Falls, New Jersey, USA

This paper examines factors that are contributing to an increased level of activity among industrial mineral producers and consumers in developing profitable solutions to industrial waste manufacturing problems. In addition to the regulatory drivers that are forcing many companies to minimize or recycle their waste products, a number of companies are examining opportunities for developing saleable co-products from these waste streams. Although the technological challenges and investments required can be formidable,

so are the potential rewards. Unfortunately, most companies lack the market contacts or expertise to capitalize on an opportunity, even when they have overcome the technological hurdles of producing a saleable product from a waste stream. Despite the obstacles, these challenges are being met by industrial mineral producers and consumers in such varied industry sectors as titanium dioxide processing, lead-acid battery recycling, and flue-gas desulphurization.

BARGING OF BULK COMMODITIES ON THE PACIFIC NORTHWEST COAST

By W. Wayne Poole, Seaspan International Ltd., Vancouver, BC, Canada

This paper reviews the transportation of bulk commodities by tug and barge in the Pacific Northwest of North America, and outlines the broad range of cargoes that are carried locally. These cargoes include sand and gravel; rip rap, gypsum, limestone, coal and salt.

Two classes of barges are considered – those used in local treaty waters, which range from 3000 to 8000

short tons, and those that require an international load line, which must follow the convention limiting the draught to which a ship may be loaded. These ships travel between British Columbia and Oregon, California and Alaska, and range in size from 8000 to 16 000 short tons. Barge design is important, particularly from the point of view of containment of cargo and unloading methods. The majority of bulk cargo barges are flat

decks with cargo boxes; however, other types of barges also are important, particularly the hopper self-unloaders.

The economics of tug and barge transportation must consider typical tug and barge operating costs, the drop barge concept, and multiple tows. Costing must also take into account some of the regulatory issues, which govern the operation of equipment in coastal waters.

The marine industry is not without risks. The design of loading and unloading facilities can help tug and barge operators reduce the elements of risk. Future developments of water transportation will have a huge impact on industrial mineral deposits along North America's west coast.

KLINKER, PRECIOUS OPAL DEPOSIT, OKANAGAN AREA, BRITISH COLUMBIA, CANADA.

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Opal deposits can be classified into two major categories: "Volcanic-hosted" and "Sediment-hosted" (Paradis *et al.*, 1999a,b). The Klinker, a volcanic-hosted deposit, owned by Okanagan Opal, is located approximately 10 kilometres from Vernon within a paleo-basin that extends 150 kilometres from the west side of Okanagan Lake to East of Kamloops. Clast- and matrix-supported lahars and tuffs of Eocene or Miocene age host the deposit. The precious opal coexists with jelly opal, common opal and agate that occur as vesicle and fracture fillings over a 280 by 110 metre area. Other fracture filling and alteration minerals spatially associated with precious opal are celadonite, amorphous manganese oxides, zeolites, jarosite, bentonite and other clays (Simandl *et al.*, 1997). Doublets, triplets, solid, and boulder opal produced from the deposit are sold within British Columbia, and the market is steadily improving.

Although hydrothermal activity is commonly believed to be responsible for the formation of precious opal in volcanic rocks, the origin of this deposit is still not well understood. It is possible that the Klinker deposit is instead genetically related to weathering and the unconformity that lies between the opal-bearing sediments and overlying mid-Miocene tuffaceous rocks.

If this is true, Klinker would be analogous to the sediment-hosted precious opal deposit described by Paradis *et al.* (1999a).

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METALS CONTAMINATION IN A LIMESTONE QUARRY

By Richard Munroe, Lafarge Canada Inc., Surrey, BC, Canada

To satisfy chemical and cement grade specifications, limestone deposits must consist of high purity calcium carbonate. Although impurities such as silica and alumina can be incorporated in the industrial feed, metal contaminants are of major concern. During excavation of limestone deposits, great care must be

taken to avoid resources with high metal content. This results in production of significant amounts of waste material. A variety of methods may be applied to isolate and remove areas of metal contamination in chemical and cement grade limestone quarries.

THE EFFECT OF THE INTERNET ON INDUSTRIAL MINERALS

By Joseph Z. Keating, Polar Minerals, Lawrenceville, Georgia, USA

The Internet is a major new force in global commerce that will significantly affect most businesses within the next five years.

The speed and global presence of the Internet is rapidly expanding, and several new business models are being employed to shake up the traditional ways of doing business. The phenomena of Dot Com Startups have had a major effect on consumer and business markets; it will be even more important in future and

could have major effects on the Industrial Mineral markets. It is important for the Industrial Minerals producer to understand the Internet and learn from the experiences of the retail sector in order to implement an effective Internet strategy. The eventual impact of the Internet is not now known, but producers must be actively engaged as the Internet profoundly changes business practices.

WOOD COVE MARBLE

By Raul Vicencio, Techsol, North Vancouver, BC, Canada
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LOCATION

The Wood Cove marble deposit (MINFILE Number 092L 187) is located 35 kilometres northwest of Zeballos, British Columbia. The marble beds are situated on the west shore of Kashutl Inlet within Kyuquot Sound. Elevations on the claim group range from 0 to 350 metres above sea level. Slopes are moderate and get steeper to the west portion of the claims where some cliffs are exposed between 175 to 350 metres of elevation. The property is accessed by driving from Zeballos to Fair Harbour and taking a 12 kilometre boat ride to Kashutl Inlet (Fischl, 1992).

REGIONAL GEOLOGY

Lower Jurassic Bonanza Formation andesite-rhyodacite flows and tuffs underlie the southern portion of Kashutl Inlet, which includes the Wood Cove marble prospect. The marble beds are within the Bonanza Group sequence. There are massive 300 metre thick outcroppings of Upper Triassic Quatsino limestone in Brooks Bay and Quatsino Inlet (to the north), but this limestone has not proven to be favourable for quarries because of high Fe₂O₃ and Al₂O₃ content.

The high calcium limestone deposit consists of two marble beds, 50 to 67 metres thick, separated by 30 to 45 metres of argillite. The deposit is located below amygdaloidal andesite/dacite of the Lower Jurassic Bonanza Formation (Campbell, 1973). This sequence has been subjected to low grade epidote-pyrite-chlorite metamorphism during emplacement of a lower middle Jurassic 4 by 8 kilometre, elliptical granite/quartz diorite

/granodiorite intrusive complex (Muller, 1974). The marble beds strike northeast and dip 30 to 60 degrees southeast. The upper and lower beds are approximately 46 metres and 61 metres wide, respectively. The carbonate beds consist of massive, pearl grey to white, medium to coarse-grained recrystallized limestone (that is, marble).

Proven reserves were estimated at 16 250 tonnes (Black, 1973). The material is potentially suitable for cement or pulp-grade lime (Campbell, 1973). The deposit is estimated to contain a possible resource of 30 million tonnes (Campbell, 1973).

SUMMARY

The marble beds consist of two 40 to 60 metre wide traceable units separated by the 30 to 50 metres wide argillaceous siltstone. The apparent trend of the marble-volcanic contact is northeast with a moderate southeast dip. Marble can be used for cement and pulp-grade lime.

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FORUM 2002, ST. LOUIS, MISSOURI

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Missouri is an important mining state and has a long history of mining beginning with the earliest French exploration. In 1720, Father James Gravier, a French-Canadian priest, reported a very rich lead deposit along what is now known as the Meramec River. In 1721, two Frenchmen, Phillipe Renault and M. Lamotte, began lead mining in Madison County about 70 miles south of St. Louis and mining has been almost continuous ever since.

In 1999, the value of mineral production in Missouri exceeded US\$1.5 billion; of this more than \$1 billion was from industrial minerals. Since 1907, the state has been the domestic leader in lead production in the United States; the only exception was 1962 when there was a lengthy strike. More importantly, Missouri ranks high in

the production of cement, lime, and crushed stone; the commodities, along with transportation, are the themes of Forum 2002.

The Forum will be held in St. Louis and organized by the Missouri Department of Natural Resources, Division of Geology and Land Survey. Tentative dates are May 5th through 10th, 2002. Planned sessions include cement and lime resources and production, underground mining of stone, later reuse of mined space, and transportation of industrial minerals. Field trips are planned for aggregate operations in the St. Louis area, cement and lime operations in eastern Missouri, and underground quarries with developed mined-out space. Guest programs are also being planned.