STATE OF MONTANA
Thomas L. Judge, *Governor*

BUREAU OF MINES AND GEOLOGY
S. L. Groff, *Director*

Special Publication 74

September, 1976

ELEVENTH INDUSTRIAL MINERALS FORUM

Polished slab of rhodonite from Salt Spring Island (p. 160).
Specimen is about 4 x 6 inches.

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ELEVENTH INDUSTRIAL MINERALS FORUM

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PREFACE

This volume of the Proceedings of the Eleventh Forum on Geology of Industrial Minerals is, as were the Proceedings of the ten previous Forums, a masquerade dictated by convention, necessity, and mature judgment. The real proceedings were spoken words, less organized than these, and bright screens in a dark room—above all, flesh and blood. Ideas were broached. Concerns were shared. Friendships were bonded, often by liquids barred from our lexicon of cementitious materials. But the sights and sounds of June 18-20, 1975, in the Outlaw Inn of Kalispell, Montana, are gone, and just as well. That is why mature judgment endorses convention and necessity. In these papers are all that the speakers meant to say, if they had had time, the qualifications they would have made, and perhaps a few afterthoughts. The authors of these papers were the heart of the live proceedings. Their words deserve to be its final mask.

Other acknowledgments are due, however, and we are happy to make them. Part of the cost of printing these Proceedings was paid by a grant of five hundred dollars from the Society of Economic Geologists' Foundation. Mr. Ray Kajawa of the Zonalite Division of W. R. Grace Company conducted a field trip through the vermiculite mine near Libby, and Capt. Parker of the U.S. Army Corps of Engineers conducted a field trip to Libby Dam.

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WHAT HAPPENED ON THE WAY TO THE FORUM

Robert L. Bates*

This is a brief account of one man's infatuation with the industrial minerals, together with a few reflections on the field as a whole. When I came to Ohio State in 1951, my primary assignment was to teach petroleum geology, and this I have been doing ever since. Within a month of my arrival, however, a colleague in the department yielded to the siren song of administration and decided to forego any further teaching. Before departing for the dean's office, he asked me if I would take over his course in geology of nonmetallic mineral deposits. Though I knew scarcely anything about the subject, I accepted. It was love at first acquaintance; I haven't had a geologically dull moment since.

Let me comment on a few aspects of my good fortune. First, to have as a subject of study such a diverse and wide-ranging field is ideal for a person like myself, who has a short attention span. It is a matter of scientific life style. I happen to prefer to accumulate moderate learning about a wide range of subjects rather than to learn more and more about less and less. The industrial minerals are a "natural" to those of us who can think about more than one thing at a time. Second, teaching about this subject, as about any other, is a fine way in which to learn. It has prompted me to roam through a vast literature, to make the acquaintance of specialists in many fields, and to visit mines, pits, and quarries at every opportunity. Teaching has even granted me a license to write a book. Best of all, I can occupy an ivy-covered tower, above the tough daily grind of earning a living from a mineral deposit. I can assure you that it beats working.

Another attractive feature of the industrial minerals is their close relationship to the real world. This is no news to you, but remember, I'm speaking as a professor. Being involved with this practical field has spared me the necessity of doing only the useless research that occupies the time and efforts of so many of my academic brethren. To be related geologically to life as it really is, no matter at what a distance, is very satisfying. Finally, applied geology leads directly to extraction, processing, bulk handling, transportation, and the whole array of ultimate uses. As every one of these fields is fascinating in its own right, they constitute another aspect of the variety and diversity that I find irresistible.

On the other hand, I am not so enraptured with this field that I can think of nothing that I would like to see changed. It annoys me, for example, that we in the industrial minerals continue to be the victims of what a Canadian colleague has termed the "metallic mentality" -- the assumption, by people who ought to know better, that mineral deposits is synonymous with metallic ore deposits. A recent issue of Economic Geology, for example, is devoted to "Canadian mineral deposits", but these turn out to include only porphyry copper, massive sulfides, and the like. Our image, or rather our lack of one, is apparently one of those things that we just have to live with. At any rate, it gives us a chance to exercise saintly forbearance with our metallically minded friends. Another fact that makes me unhappy is the placement picture. Geology graduates who want to work in the industrial minerals do not at present have any ready means of learning about available openings. A third matter of concern is that, over the last 20 years or so, courses in mineral deposits have actually become fewer in our university departments, instead of more numerous. With the likelihood of mineral shortages staring us in the face, discontinuing courses in the geology and economics of mineral resources seems a myopic policy indeed.

In a field so varied and so geographically dispersed, communication is of the greatest importance. Here we have come a long way in the last couple of decades. A new and comprehensive

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*Ohio State University

edition of Industrial Minerals and Rocks is forthcoming. Annual reviews of the field appear in Mining Engineering and in Geotimes. We have salt symposia, clay conferences, and international congresses — all with volumes of authoritative proceedings. Since 1967 we have had the indispensable magazine Industrial Minerals. And ladies and gentlemen, we have the Forum.

I think we should count our blessings — first on being involved in this wonderful and dynamic field, and second on meeting in pine-scented Montana to hear papers on the industrial minerals of the Pacific Northwest of the United States and the Pacific Southwest of Canada. I am now pleased to yield the podium, so that our technical program can get under way.

MINING TRONA FOR SODA ASH IN WYOMING

Lawrence E. Mannion*

ABSTRACT

Wyoming trona has rapidly assumed a dominant role in the United States as raw material for soda ash. The Green River ancient lake deposits are economically unique among the known sodium carbonate concentrations in the world. Their size is huge. The tens of billions of tons of mineable Wyoming trona is greater than the stripping coal reserves of the state.

Favorable mining conditions that have aided mine developments include moderate depth, simple horizontal structure, and readily workable thickness. The individual trona beds are of high grade, notable uniformity, and great extent. Even the smaller ones contain hundreds of millions of tons.

Modified coal mining machinery and methods have proved economical and effective in trona mining. Expansion of the field appears certain to continue. Principal challenges are development of deeper trona beds, improvement of extraction and costs, and coping with waste materials.

INTRODUCTION

At a time when various minerals are or soon will be in short supply, it is pleasing to discuss a commodity that seems adequate to support any likely demands upon it. Wyoming trona is the world's largest resource of natural sodium carbonate and source of commercial soda ash. Other natural sodium carbonate deposits contain solid salts and brines and support soda ash operations but they are much smaller than the Wyoming sources. Such deposits include Searles Lake (Flint and Gale, 1958; Smith and Haines, 1964) in southern California, Lake Magadi (Baker, 1958) in Kenya, and alkaline lakes in northern China and southern Siberia.

SODA ASH PRODUCTION

Soda ash is a bulk chemical, which is sold as a very pure, uniform product containing 99.8 percent Na_2CO_3. It is a free-flowing, white, granular material and has a bulk density of 55 to 65 lb. per cu. ft. Its major use is in glass manufacture, where more than half the production is consumed. Much of the rest is used in detergent formulations, including soda ash itself, and phosphates and silicates derived from soda ash. Other uses spread over a wide spectrum of industrial and consumer products.

Soda ash has been long manufactured by the ammonia soda or solvay process, which uses limestone, salt, and ammonia. On a world scale, this process is still the principal method of production, but in the United States it has recently been surpassed by soda ash from naturally occurring sodium carbonate. In the last 40 years no new solvay plant has been built in this country. The age of solvay plants, deteriorating economics, and environmental considerations attendant on disposal of byproduct calcium chloride virtually assure the demise, in the United States, of ammonia soda production in favor of "natural" soda ash.

In the United States there are six ammonia soda plants, three Wyoming trona-based plants, and two Searles Lake brine-based plants; their total capacity is about 8.6 million tons of soda ash. In 1974, soda ash production in the United States was about 8 million tons, of which Wyoming trona accounted for more than 50 percent. Expansion of Wyoming trona-based soda ash facilities in the last fifteen years has been rapid, and more is to come. Additional Wyoming capacity announced and under construction amounts to approximately 2.75 million tons. Because soda ash demand increases at only about 3 percent per year, it is evident that much of the growth of Wyoming soda ash has come and will come at the expense of the older ammonia soda plants. A major soda ash expansion has also been announced for Searles Lake, California.

In Wyoming several other products are produced, including sodium bicarbonate in a plant operated by Church and Dwight. Some sodium tripolyphosphate is also produced in trona-related plants.

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*Stauffer Chemical Company, Richmond, California.

WYOMING TRONA DEPOSIT

Trona was discovered in 1938 (Lindeman, 1954) in southwest Wyoming in an oil and gas exploration hole, the John Hay No. 1, located about 20 miles west of Green River. A bed 10 ft. thick was identified by the U. S. Geological Survey in core from a depth of about 1,600 ft. Additional drilling confirmed the existence of a widespread workable layer, which was opened by Westvaco (FMC) in the 1940's and 1950's. Further exploration, which accelerated in the early 1960's, determined the existence of many trona beds over a wide area (Parker, R. B., ed., 1971).

Wyoming trona occurs in the central part of the Green River Basin as more than forty beds found at depths of 400 to 3,500 ft. (Figure 1-1). The beds are distributed through the Wilkins Peak Member of the Green River Formation. The Wilkins Peak consists predominantly of lake beds containing saline minerals. These lake beds are most recently believed to be derived in major part from carbonate playa lake muds associated with an alkaline saline lake. They contain almost ubiquitous shortite, which is a double carbonate of sodium and calcium. The trona layers were deposited in alkaline lakes and, of the more than forty beds known, at least twenty-five beds have a minimum thickness of 3 feet and reach a maximum of 40 feet. These twenty-five beds have been designated by Culbertson (1966) as major beds and numbered consecutively from oldest to youngest.

The Wilkins Peak Member is an extensive complex lens of saline lake beds overlain and underlain by oil-shale-bearing lake deposits, which are nonsaline. These are all enclosed by fluviatile deposits of the Wasatch and Bridger Formations. Most of the trona (more than half the beds) was deposited during the first half of Wilkins Peak time and confined to an area now bounded by the Uinta Mountains, U. S. Highway 80, the Green River, and the Uinta-Sweetwater County line. These early trona beds make up nearly half the vertical section of the lower part of the Wilkins Peak, are roughly coextensive, and underlie an area of 400 to 600 square miles. Many of these earlier beds also contain considerable halite (sodium chloride). Later, trona deposition shifted northward, and the last beds are notably smaller and more scattered although of good grade and thickness.

TRONA RESOURCES

The forty known beds contain perhaps a hundred billion tons of trona. Of this, perhaps a relatively small part would be regarded as potentially mineable under present conditions, but even that part would amount to tens of billions of tons. Current practice would seem to require a mining thickness of at least 6 feet for competitive extraction. All or parts of a dozen or more beds would qualify under this requirement.

Other important considerations involved in assessing a trona bed for mining include:

(1) The presence or absence of water-bearing strata closely adjacent to trona beds. Inadvertently breaking into water flows is obviously undesirable in mine workings in, and supported by, water-soluble material.

(2) The presence or absence of salt (sodium chloride). Sodium chloride is a significant hindrance to processing because there is at present no efficient or cheap method of separating it from the sodium carbonate.

(3) Finally, the depth to the trona. Strength limitations, not so much of trona but of the strata making up the roof and floor, are of great significance. Floor heaving and roof buckling can become serious in deep mines where overburden weight and minor structures give rise to significant problems.

Considering the above, it is not fortuitous that, so far, the operating mines are in the younger, salt-free trona beds in the northern part of the district and are less than 1,700 feet deep.

MINING CONDITIONS

Trona is mined underground in Wyoming at depths between 850 and 1,700 ft. below the surface. Mining conditions are generally good and adapted to large-scale, efficient, mechanized operations. The trona beds are generally nearly flat, of large extent, and uniform in grade, character, and thickness. Working heights in most places exceed 7 feet, and the grade is 88 to 92 percent trona over areas of tens of square miles. Waste matter consists of shortite, mudstone, and oil shale and lesser amounts of organic matter, iron sulfides, and rare mineral species. These have little or no effect on mining operations such as drilling, breaking, and transporting ore.

Because the strata above all trona beds are particularly weak and subject to air slacking, mine practice involves leaving 2 or 3 feet of the upper part of the trona

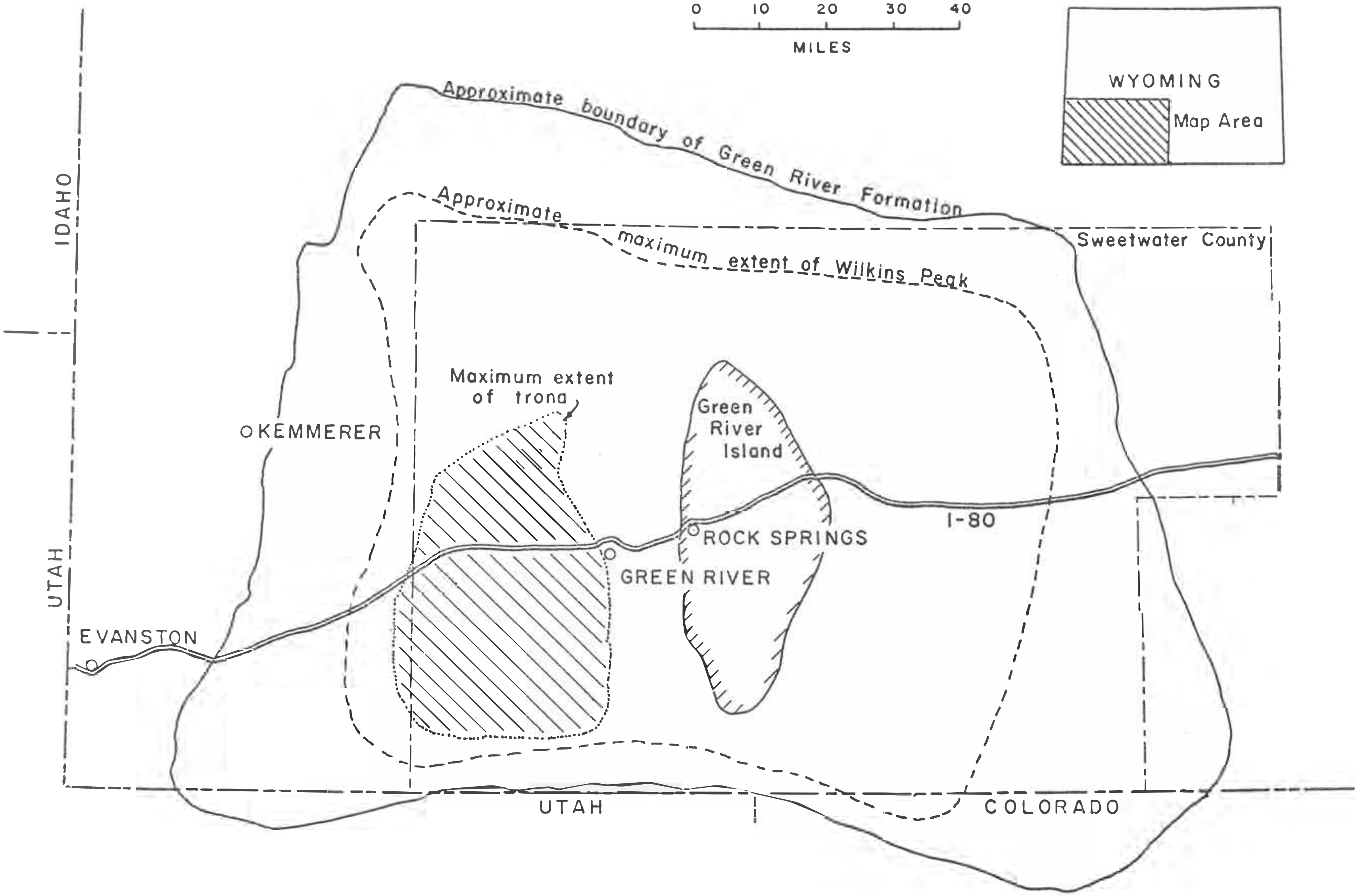

Figure 1-1.–Map of southwest Wyoming showing approximate maximum extent of the Green River Formation and the Wilkins Peak Member of the Green River Formation, and the area underlain by trona.

to ensure the best possible roof. This trona is commonly somewhat lower in grade than the main body of the bed and is thus suited to the purpose. In the Big Island beds, the trona below the mineable unit is interbedded with layers of oil shale and marlstone, and the floor is placed at the top of the first substantial bed of waste rock. Present economics do not permit recovery of these thin trona layers below the floor, which thicken and thin irregularly and include much waste. Trona beds tend to undulate somewhat, so marker beds consisting of thin shale seams within the main trona unit are helpful in maintaining the development and mining openings within the high-grade section.

Because the overlying oil shales commonly contain methane gas, the trona mines are classified as gassy. "Permissible" underground equipment must be used, and ventilation is of prime concern.

MINING METHOD

Circular, concrete-lined shafts have become standard as access to trona beds, and modified coal-mining techniques are extensively employed. Most trona is mined by the room-and-pillar method; a seven-entry system has been designed to permit production units to be employed in driving accessways with no loss in trona production.

In the past, solution mining through wells has been attempted, although without success. Also utilized has been nearly complete extraction through robbing of pillars after mining the rooms. More recently, longwall mining has been introduced with a view toward more nearly complete extraction and more effective methods of roof control.

At the Big Island Mine, large coal-mining machinery, adapted to the heavier, tougher, and more abrasive trona, is employed. A production unit consists of about ten men who advance several parallel entries and connecting cross cuts. The typical mining sequence involves:

(1) Top cutting to produce a flat, unshattered roof, using specially modified heavy-duty cutting machines.

(2) Drilling the face with auger drills to a depth of 10 feet, with as many as 17 holes per face.

(3) Loading and shooting the face with an ammonium nitrate—fuel oil—coal dust mixture.

(4) Moving the ore from the face with modified coal loaders into shuttle cars, which may be electric or diesel.

(5) Roof bolting to ensure integrity of the roof.

After leaving the face, the ore is

(1) discharged to crusher-feeders that supply minus-12 inch ore to a belt conveyor system to the hoisting station, then

(2) crushed to minus-6 inches at the hoist and hoisted to surface.

The Big Island Mine operates around the clock, seven days a week. Maintenance is, of course, a prime requisite for effective continuous operation. Each production shift has a crew of maintenance mechanics assigned to production maintenance. Once a week a shift is set aside for routine checks and major maintenance items. Adequate spare parts permit major maintenance to be carried on Monday through Friday.

THE FUTURE

Wyoming trona provides a very large, high-grade raw material for manufacturing soda ash. The deposits lend themselves to safe and efficient extraction in large-scale operations, and multimillion ton mines are the rule. The southwest Wyoming district seems destined to dominate the soda ash production in the United States for many years to come. Among the challenges are (1) coping with large quantities of waste water and waste solids, (2) improving mine and plant recoveries and holding down costs as the mines become older, and (3) developing for the future the deeper trona beds economically and safely so as to make use of the vast resources that lie at those greater depths.

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SODIUM SULPHATE DEPOSITS OF SASKATCHEWAN AND ALBERTA

Paul L. Broughton*

ABSTRACT

Commercial deposits of sodium sulphate and associated salts are harvested from alkaline lakes, which are widespread throughout semiarid southern Saskatchewan and adjacent southeastern Alberta. This sodium sulphate chemical, commercially known as salt cake, is extracted from several of the larger lakes and prepared for industrial markets. It ranks second only to potash in central-western Canada's nonmetallic mineral production. This salt is recovered directly from surface brines, from intermittent salt beds, and by solution mining from the shallow subsurface. At present sodium sulphate chemical is extracted from eight alkaline lakes and salt flats in Saskatchewan and one in Alberta. Commercial reserves are estimated at 30 to 40 million tons, and annual production is approximately a half million tons. The manufacture of kraft paper is the most significant market for salt cake, but additional quantities are used in the glass and detergent manufacturing industries.

INTRODUCTION

Sodium and magnesium sulphates are the principal deposits in the widespread alkaline lakes of southern Saskatchewan (Fig. 2-1) and adjacent southeastern Alberta. These sulphates form permanent to intermittent crystalline beds along lake margin mud flats and are the major salt constituents of the lake brine. The salts from several of the larger alkaline lakes are commercially harvested for sodium sulphate chemical, and this industry ranks second only to potash in central-western Canada's nonmetallic mineral industry. Most of the sodium sulphate chemical is utilized in the manufacture of kraft paper, the coarse brown paper of paper bags and cardboard.

Sodium sulphate occurs naturally in the alkaline lakes of southern Saskatchewan and southeastern Alberta as the mineral mirabilite, $Na_2SO_4 \cdot 10H_2O$, commonly known as Glauber's salt. When kiln dried for commercial shipping, this hydrated sodium sulphate is converted to the mineral thenardite, Na_2SO_4, a white, dry, free-flowing crystalline material referred to as salt cake.

THE PRAIRIE SODIUM SULPHATE DEPOSITS

Surficial sodium sulphate deposits are distributed throughout southeastern Alberta and southern Saskatchewan and in adjacent semiarid regions of northeastern Montana and northwestern North Dakota. This broad district is more than 400 miles long and 100 to 300 miles wide. These northern Great Plains deposits are lacustrine and lie within areas covered by Pleistocene glacial drift. Most of the commercial production is limited to southern Saskatchewan, where the deposits occupy dissected river valley basins that have impervious clay bottoms and little or no drainage. Spring water and runoff water containing as much as 1,000 ppm dissolved salts contribute to the brine in the closed basins, and when the evaporation rate sufficiently exceeds the rate of water influx, the salts precipitate to form crystalline beds.

One of the largest known deposits contains more than nine million tons of sodium sulphate, computed on a water-free basis, and more than a dozen other deposits are estimated to contain more than a million tons each. The thickness of the salt bed deposits ranges from a foot or less to a hundred feet and shows great lateral variation.

The genesis of the sodium sulphate deposits in the northern Great Plains has been investigated for more than a half century. Grabau (1920) attributed some of the southern Saskatchewan deposits to decomposed igneous rocks and to connate salts from older buried salt beds. One of the more generally accepted theories (Cole, 1926) suggests that the deposits were generated by cation exchange reactions between gypsum and alkali silicates in bentonite, which is common in the glacial till of the region. Many of the springs around southern Saskatchewan's alkaline lakes contain more than 1,000 ppm dissolved salts, which would be sufficient to generate the deposits since the Pleistocene. The genesis of the sodium sulphate is also attributed to recycling of the deeply buried Prairie Evaporite (Devonian), which underlies a

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large part of the northern Great Plains (Grossman, 1968). Regional ground water from the Rocky Mountain area presumably circulated eastward into the large structural basin, the Williston Basin, underlying southern Saskatchewan, eastern Alberta, western North Dakota, and eastern Montana, dissolving the Prairie Evaporite strata at depth from late Devonian time onward.

This solution process was persistent from the late Paleozoic through the Tertiary and produced much of the subsurface structural relief of southern Saskatchewan, superimposed upon the regional structure of the Williston Basin. The surficial sodium sulphate deposits lie almost entirely within the area underlain by this Devonian formation. It is proposed that in the late Pleistocene ascending mineralized ground water discharged into melt-water channels in the stratified drift overlying buried bedrock valleys (Fig. 2-2). Meromictic conditions (chemical stratification and poor circulation) developed in the deeper lakes in valley troughs protected from the mixing action of winds. The persistence of such a stagnant layer of lake water at depth would permit the accumulation of crystalline salts and permanent salt layers on the lake bottom, particularly with the onset of aridity in the post-Pleistocene. The low-saline supernatant drainage systems subsequently disintegrated, and brine was concentrated by evaporation. Freezing conditions that prevail throughout a large part of the year impel the mirabilite to crystallize (Fig. 2-3), precipitate, and concentrate on the lake bottom. Spring floods flushed some of the lakes, but more importantly, deposited silt layers that protected the established salt beds from solution during the next inundation.

The natural sodium sulphate reserves occur in three forms: in solution as brine; as intermittent crystalline beds, which deposit from the brine or go back into solution depending upon climatic conditions; and as permanent beds of mirabilite intermixed with other salts and contaminated with clay and silt laminae. Some lakes include all three forms, but in most lakes the total reserve is in the form of brine.

Figure 2-1.—Alkaline lakes in southern Saskatchewan having commercial deposits of sodium sulphate.

COMMERCIAL DEPOSITS IN SASKATCHEWAN AND ALBERTA

During the First World War, efforts expanded to locate a new source of potash, as German imports had ceased. An erroneous report of potash concentrations in southern Saskatchewan lakes led to a 1918 claim-staking rush at several alkali flats. Failure to find potassium minerals, however, resulted in the lapse of the claims and in loss of general interest in the area. Nevertheless, the lakes were found to contain large quantities of Epsom and Glauber's salts, the hydrated forms of magnesium and sodium sulphate. The first salts were produced from the alkali lakes late in 1918 by the Canadian Salts and Potash Company of Canada, Ltd., at Muskiki Lake.

Most estimates of total reserves of sodium sulphate in Saskatchewan alkali lakes range between 60 and 200 million tons (Bartley, 1966; DeWolf, 1960; Tomkins, 1954). A more recent evaluation (Anonymous, 1967) places the total anhydrous sodium sulphate reserve at 60 to 70 million tons and evaluated commercial reserves at 30 to 40 million tons.

Sodium sulphate is being produced commercially from eight alkaline lakes in Saskatchewan (Fig. 2-1 and Table 2-1) and one in adjacent Alberta. The major Saskatchewan reserves are: Whiteshore Lake, 6.5 million tons; Horseshoe Lake, 3.7 million tons; Frederick Lake, 2.4 million tons; Chaplin Lake, 3.0 million tons; Ingebright Lake, 9.0 million tons; Alsask Lake, 2.6 million tons; Sybouts Lake, 3.5 million tons; and Snakehole Lake, 1.7 million tons. Five additional Saskatchewan lakes have

Table 2-1.—Saskatchewan alkaline lakes from which sodium sulphate is being produced.

Lake	Company	Initial production	Initial reserves (millions of tons)	Maximum capacity (tons per year)
1. Alsask Lake	Francana Minerals	1967	2.6	50,000
2. Chaplin Lake	Saskatchewan Minerals	1948	3.0	150,000
3. Frederick Lake	Saskatchewan Minerals	1921	2.4	50,000
4. Horseshoe Lake	Ormiston Mining and Smelting	1930	3.7	100,000
5. Ingebright Lake	Saskatchewan Minerals	1967	9.0	150,000
6. Snakehole Lake	Francana Minerals	1967	1.7	100,000
7. Sybouts Lake	Sybouts Sodium Sulphate Company	1941	3.5	50,000
8. Whiteshore Lake	Midwest Chemicals	1934	6.5	100,000

Previous commercial production at Muskiki Lake, 1918-1938, Fusilier Lake (North), 1920-1938, Oban Lake, 1935-1937, Regina Beach (South), 1933-1934, Ceylon Lake, 1935-1954.

had relatively minor production in the past: Muskiki Lake, Fusilier Lake, Oban Lake, Regina Lake South, and Ceylon Lake. The largest single reserve of sodium sulphate, 11 million tons, occurs as brine in Big Quill Lake, but is not sufficiently concentrated to permit commercial recovery by existing technology. Tomkins (1954) noted that the salinity of Big Quill Lake increased by natural evaporation between 1939 and 1952, but there is no certainty that concentration will eventually be sufficient to permit commercial exploitation. Metiskow Lake is the single site of present commercial production for Alberta.

RECOVERY OF THE SODIUM SULPHATE

The traditional method of recovering sodium sulphate in Saskatchewan consists of pumping surface brine from the lake into storage reservoirs during the summer for the onset of winter freezing (Fig. 2-4). The steep decline of daily temperatures in late autumn and early winter cools the brine reservoirs sufficiently for the mirabilite to precipitate and form a crust on the bottom. The remaining liquor, which retains some sodium sulphate as well as the associated salts, is either diverted back to the original brine lake or to a subsurface disposal well. During the winter the salt that cakes the reservoir bottom is bulldozed into furrows to allow for drainage; it is subsequently loaded onto trucks by a backhoe, shovel, dragline,

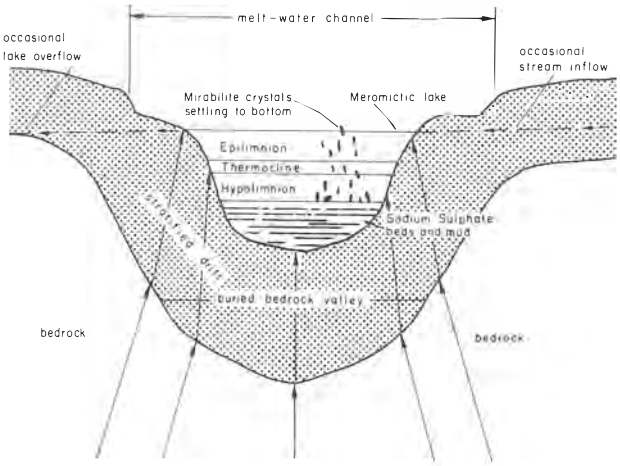

Figure 2-2.—Genesis of the sodium sulphate crystalline beds in a buried bedrock valley. Ascending ground water containing salts dissolved from the Prairie Evaporite (Devonian) at depth promotes chemically stratified brine and crystalline precipitation.

Figure 2-3.—Crystalline sodium sulphate (mirabilite).

or similar equipment and transported to storage piles adjacent to the processing plant. This procedure, as used at Chaplin Lake, is representative and is utilized in most of the Saskatchewan production. Another recovery method, used at Ingebright Lake, is the direct mining of the permanent salt bed. Subsurface solutional mining of thick salt beds is also being used at Ingebright Lake, Saskatchewan, and at Metiskow Lake, Alberta. These three recovery approaches are examined at each of the appropriate alkaline lakes.

CHAPLIN LAKE (SASKATCHEWAN)

Chaplin Lake is south of the village of Chaplin, adjacent to the Trans-Canada Highway, one hundred miles west of Regina. Commercial production at Chaplin Lake started in 1947 after a 1944 geological survey by a government of Saskatchewan crown corporation indicated that the lake would support commercial production. The lake area is roughly 18 square miles and the brine depth is 2 to 5 feet, so the lake contains approximately 3 million tons of recoverable sodium sulphate salt.

Chaplin Lake has only a thin bed of permanent crystalline precipitate, normally less than one foot thick. The brine is the commercial source. The gradual return to greater annual rainfall, after the arid 1930's, produced as much as 5 feet of brine on the west side of Chaplin Lake, but not of sufficient concentration for effective harvesting. The lake has been sectioned by a dam, and most of the brine in the east portion (5 square miles) is being pumped into the west portion (12 square miles) to allow the remaining shallow brine to increase in concentration. A constant and ample supply of water is necessary to regulate the process, and this has been assured by the creation of an artificial lake supplied by a 10-mile canal with a series of locks from Old Wives Lake and the Wood River. In the autumn months the brine is pumped into three 1,000-foot-square reservoirs, each approximately 10 feet deep (Fig. 2-5). The ensuing freezing conditions promote the deposition of approximately 5 feet of crystallized Glauber's salt. This hydrated sodium sulphate is windrowed to facilitate drainage and later to allow frost to penetrate the underlying bed. It is subsequently removed to a central stockpile area by conventional earthmoving equipment (Fig. 2-6).

All sodium sulphate deposits in Saskatchewan occur in semiarid regions almost completely free of natural windbreaks. Hence, windborne topsoil contamination is serious. The brine pumping method permits the drawing off of dense brine relatively free from settled dirt and also reduces chemical impurities to a minimum. When draining is begun in the autumn, the sodium sulphate is the first of the major salts to precipitate, and others, particularly magnesium sulphates and carbonates, are retained in the brine and recycled back to Chaplin Lake.

INGEBRIGHT LAKE (SASKATCHEWAN)

Ingebright Lake (South) is twelve miles from the village of Fox Valley. The lake covers approximately 700 acres in the center of a small drainage basin. Springs near the lake carry small amounts of dissolved salts, and brine seeps are found in the crystalline beds at the south end of the lake. In early summer there is usually 3 feet more brine at the north end than at the south. By the time the brine reaches its maximum concentration in late summer, there is but 1 foot remaining at the north end, and a dry alkaline flat covers most of the southern part.

Figure 2-4.—Pumping brine from Chaplin Lake into reservoir ponds.

Figure 2-5.—The three Chaplin Lake reservoirs, which have a 300-million-gallon brine storage capacity.

Figure 2-6.—At Chaplin Lake a dragline is utilized to harvest the salt bed that has precipitated in each of the 1,000-foot square reservoirs.

The area of the salt bed is approximately 680 acres; the average thickness is 22 feet, but locally the thickness is as much as 100 feet. It is the thickest permanent salt bed in the province, and calculated reserves exceed 9 million tons of sodium sulphate. At the northern end of the lake, the upper 25-foot section of the salt bed contains innumerable mud laminae, but the southern part is relatively free from such contamination. According to Tomkins (1954), analyses (dry)of the upper 25 feet show the following average compositions: insoluble, 12.5 percent; sodium sulphate, 72 percent; calcium sulphate, 6.5 percent; magnesium sulphate, 3 percent; sodium chloride, 2 percent; and minor sodium bicarbonate and sodium carbonate. This average quality persists generally to a depth of about 40 feet, but the quality improves to about 80 percent sodium sulphate down to the depths of 100 feet or more in the restricted areas towards the southern end of the lake.

Commercial developments at the lake did not begin until recently, although mineral leases have been valid since 1920. In 1967 the Saskatchewan Minerals Corporation started production by a newly designed method of *in situ* solution mining and by direct mining of the permanent salt beds. During the dry summer months, the southern end of the "lake", which is a shallow salt-encrusted basin about ½ mile in diameter, is directly mined by earth-moving equipment (Fig. 2-7), and the salt

Figure 2-7.—Direct mining of the permanent crystalline bed in the shallow basin at the south end of Ingebright Lake.

cake is trucked to the processing plant for separation of the various salts in crystallizers, melters, centrifuges, etc. At an adjacent area of the salt flat, a shallow subsurface *in situ* mining method is operational. Thirty holes, spaced 20 feet apart in a grid pattern, are drilled into the salt bed, and a 1.5-inch pipe is emplaced in each hole to introduce water at 120°F. The generated brine is then pumped through a pipeline from the surface of the brine pool to the plant, where cooling towers separate out the sodium sulphate.

METISKOW LAKE (ALBERTA)

The Metiskow Lake deposit is approximately 2 miles long, and the commercial area covers 408 acres. The thickness of the salt bed at the north end is only 30 feet, but the bed thickens southward to a maximum of 57 feet at the southern margin. The surface brine is only 2 to 3 feet deep, and in most years it is completely evaporated during the arid summer season. Mud stratified in the deposit ranges from 15 to 50 percent, but the deposit contains 3.5 million tons of sodium sulphate (dry), more than 200,000 tons of sodium carbonate, and only trace amounts of magnesium salts.

The Alberta Sulphate Company's approach to extracting the salts from this deposit has been shallow subsurface solution mining (Fig. 2-8), which was developed in an effort to overcome the two major defects of this deposit: lack of surface brine and the ubiquitous mud contamination. Normal subsurface solution mining tends to follow the horizontal bedding planes. The company has developed a method of forced vertical solution to separate the mud and allow it to settle to the bottom of the solution cavity. This action permits a relatively clear and concentrated brine to be decanted and pumped from the upper layers (MacWilliams and Reynolds, 1974).

At temperatures above 91°F, hydrated sodium sulphate will melt and dissolve in its own water of crystallization (55.9 percent water). Given a small amount of additional hot water, a brine solution of 20 to 30 percent sodium sulphate is formed. The process is commercially efficient: the silt contamination is eliminated, the need for voluminous quantities of fresh water is significantly reduced, and a uniform product quality is achieved.

The high quality standards for this plant's market requires that any accompanying salts and fine silt must

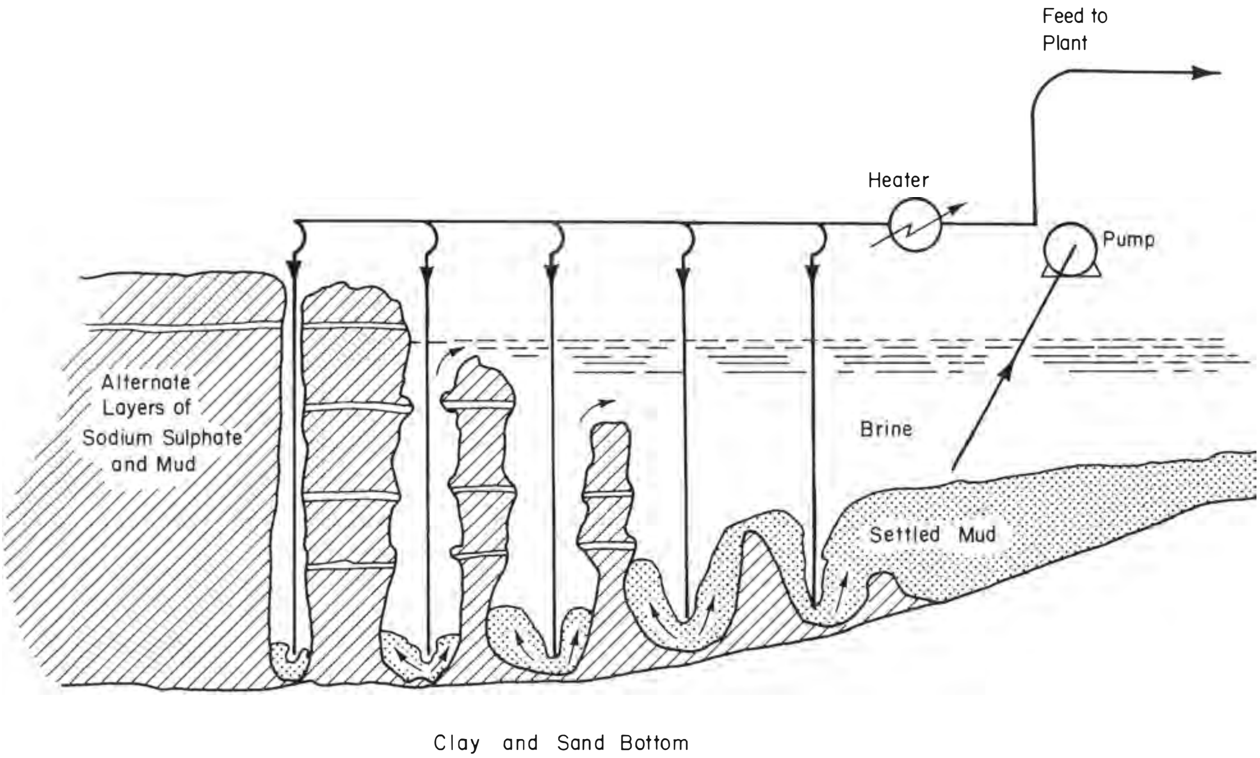

Figure 2-8.–Schematic diagram of subsurface solution mining at Metiskow Lake. Heated water is pumped into the salt beds to ensure vertical doming during solution. The mud settles, and the relatively clear brine is decanted.

be virtually eliminated. To achieve this purity, the Metiskow Lake plant incorporates a process whereby the brine is pumped from the subsurface and then cooled until the sodium sulphate recrystallizes separately from the mother brine, which retains the unwanted salts and silt impurities. This control is achieved in a modified cooling tower instead of winter precipitation reservoirs as at Chaplin Lake. The crystallizer is similar to an open-ended wind tunnel in which the brine is circulated from a bottom tank onto spray plates overhead. Cold air is circulated across the cascading brine, and the cooling permitted is only sufficient to precipitate the required amount of salt for the plant intake. Most of the sodium carbonate and other impurities remain with the solution to be wasted. The minor amount of clay contamination is separated by centrifuging.

THE MANUFACTURING PROCESS: ANHYDROUS SODIUM SULPHATE

A crucial step in the recovery of industrial sodium sulphate is a manufacturing process, which is essentially dehydration rather than refining. All the water of crystallization, which is almost 60 percent of the compound, is removed to reduce the $Na_2SO_4 \cdot 10\,H_2O$ to Na_2SO_4.

There are several methods of removing the water from hydrous sodium sulphate, but the most popular method being used in Saskatchewan is the Holland evaporator. From the stockpiles, the raw bulk salt is transported by conveyor belt (Fig. 2-9) to the processing plant's evaporators. At Chaplin there are five Holland evaporators with gas burners; at the Ingebright plant, there are six (Fig. 2-10).

The evaporator (Fig. 2-11) is essentially a rectangular chamber. On one side large ducts provide the entry of hot gases, and on the top are vents for the exhaust. The salt is fed directly into the evaporator, in which it melts in its own water of crystallization. The slurry is spewed into a hot gas stream by rotating paddles. Evaporation ensues, and the partly dehydrated salt collects on a conveyor belt. These evaporators utilize the heated exhaust gases from the final drying kilns. The slurry has been reduced to about 30 percent H_2O before it enters the rotary kilns 60 to 80 feet long (Fig. 2-12), which remove the remaining moisture at 2,000° F. Several of the smaller sodium sulphate plants in Saskatchewan by-pass the Holland evaporator circuit and feed directly into rotary kilns (Fig. 2-13).

The submerged combustion process (Fig. 2-14) is used for the dehydration at the Metiskow Lake, Alberta, plant. This process involves the maintenance of a natural-gas flame below the brine surface, and the resultant water vapor and combustion gases are evacuated. This provides very effective heat transfer and is undoubtedly the most efficient process where a relatively inexpensive natural-gas supply is available. By recycling and recrystallizing this slurry, the remaining minor impurities can be quickly eliminated, if desired.

The dry salt cake produced contains 97.5 to 99.0 percent sodium sulphate, Na_2SO_4.

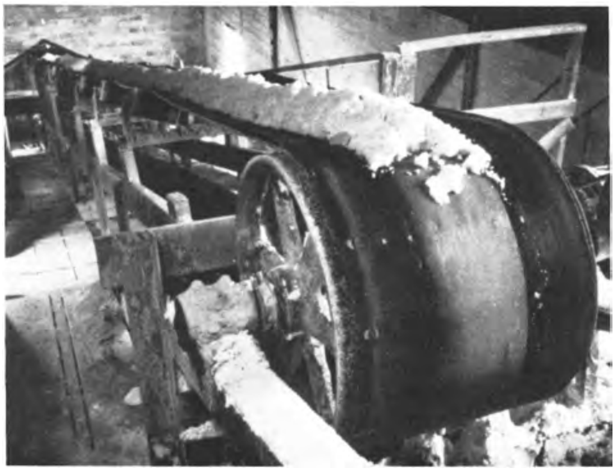

Figure 2-9.—From the stockpiles adjacent to the plant, the crushed raw salt is transported by conveyor belt to the evaporators.

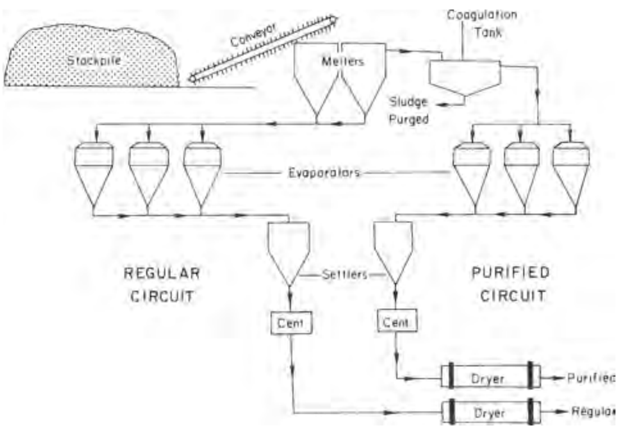

Figure 2-10.—Flow diagram of the Ingebright Lake plant, from stockpile, through melters and evaporators, centrifuges, and final drying kilns.

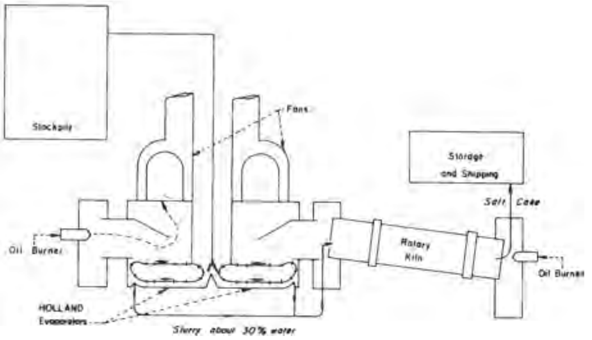

Figure 2-11.–Schematic diagram of the Holland evaporator system at Chaplin Lake, which produces a slurry feed into rotary kilns.

Figure 2-12.–The interior of one of Chaplin Lake's 60-foot rotary kilns.

PRODUCTION AND CONSUMPTION OF WESTERN CANADIAN SODIUM SULPHATE

Annual Canadian production is about 500,000 tons; domestic markets use about 400,000 tons and the rest is exported to the United States. For comparison, the United States produces about 1,400,000 tons by several means: byproducts of rayon manufacture, hydrochloric acid manufacture from sodium chloride, and from the manufacture of chromium salts from sodium dichromate, as well as from natural crystalline beds or brines in California, Texas, and Utah.

More than 90 percent of the sodium sulphate production of Saskatchewan for the domestic market is consumed in the paper industry for the manufacture of coarser brown "kraft" papers that are used in paper bags and cardboard. Sold under the name "Saltcake", it is an ingredient in the digestion of pulp to cellulose fiber, contributing a means of extending the fiber length and thereby increasing the strength of the finished paper product. The "kraft" brown paper process requires sodium sulphate that is between 97 and 98 percent pure, and this is satisfied by most of the Saskatchewan production. Nevertheless, a greater purity, 99+ percent, is required by a relatively small portion of the market for use in the manufacture of detergents, and production from the Metiskow Lake, Alberta, plant is designed specifically for this specialized market. Minor uses for Canadian sodium sulphate include glass manufacture (where it is added to the melt to prevent scumming), leather tanning, manufacture of blue pigments, fertilizers, textile dyes, and pharmaceuticals, smelting of nonferrous metals, and fillers in animal feed.

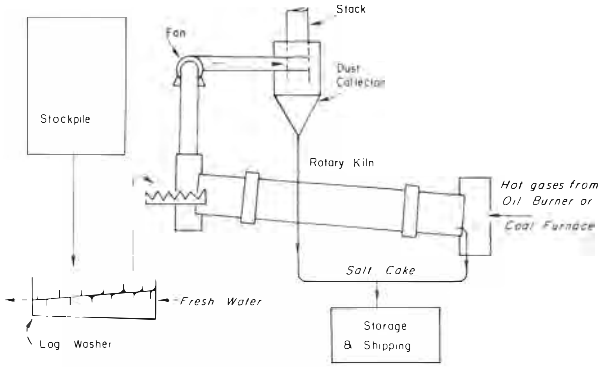

Figure 2-13.–Smaller sodium sulphate plants in southern Saskatchewan feed the bulk salt directly into the rotary kiln systems.

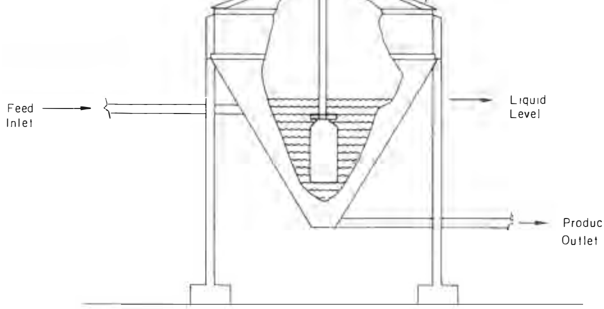

Figure 2-14.–Schematic diagram of the Metiskow Lake submerged combustion process, where a natural-gas flame below the brine surface evaporates the water.

CONCLUSIONS

It is probable that all of the alkaline lakes that would be commercial sources under present market conditions are being exploited. Considering this, initial reserves of these nine Saskatchewan and Alberta deposits are between 30 and 40 million tons, of which approximately a fifth has been extracted to date. Value of sodium sulphate production in Saskatchewan has fluctuated widely over the last several decades, despite the fact that there has been a steady year by year increase in production tonnage. It may be concluded that the known reserves may be near exhaustion in a few decades, and certainly by the early years of the next century. The new Rapson process, now slowly being introduced into the kraft paper industry, effectively eliminates the need for sodium sulphate. If its adoption becomes widespread, it could seriously affect the market. New uses for sodium sulphate, such as the manufacture of potassium sulphate fertilizer, may counterbalance its influence to some degree.

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INDUSTRIAL MINERALS: ALBERTA'S UNCELEBRATED ENDOWMENT

Wylie N. Hamilton*

ABSTRACT

Alberta's identity as a mineral-rich province is based essentially on the oil and gas resources, latterly also on the much-publicized Athabasca Oil Sands, and on the vast coal reserves of the province. In addition, Alberta possesses a rich variety of industrial minerals, but comparatively little recognition attains to these resources. The more important industrial minerals–those being exploited at present or having potential for near-future development–include deposits of bentonite, clay and shale, dimension stone, dolomite, formation brines, gypsum, limestone and marl, peat moss, salt, sand and gravel, silica (industrial) sand, and sodium sulfate; and in addition, industrial byproducts of oil sands processing (accessory "heavy" minerals, silica sand, clay), coal or coke combustion (fly ash), sour gas production (sulfur), and phosphate fertilizer manufacture (phospho-gypsum). Others of little known significance at present but which deserve brief mention for possible future importance include quartzite and phosphate rock.

INTRODUCTION

Alberta was abundantly endowed with mineral wealth and since 1971 has led all the provinces of Canada in value of mineral production. Most of this wealth is derived from oil and gas resources, and until recently Alberta sustained the identity as the oil province of Canada. With development of the much publicized Alberta Oil Sands deposits (now in its early stages) and with the upsurge in importance of the province's vast coal resources, this identity has broadened to embrace the energy resources sector in general, and Alberta now is known far and wide as the energy province.

Not so widely known is the fact that Alberta has plenty of other minerals, mainly industrial minerals. They exist in variety and quantity, but because Alberta is not a highly industrialized region the development of these resources has been, by comparison, slow and unheralded. Figure 3-1 shows the value of production of these industrial minerals in relation to the energy minerals, and explains, probably better than any other presentation, why this mineral endowment has gone uncelebrated.

In 1974, the value of production of industrial minerals (including sulfur[1]) was $125 million–only about 1 percent of the province's total mineral production. Readers will recognize, however, that this figure is not a true measure of value in the case of industrial minerals, for it does not reflect the value of the industries they support. Table 3-1 lists those industries in Alberta (i.e., those based essentially on industrial minerals) and their estimated values in gross production–clearly, a significant contribution to Alberta's economy. Yet some, perhaps most of these could not exist or would have difficulty existing without the local availability of the minerals.

Industrial minerals are especially important for the future of Alberta. Although energy resources will continue indefinitely as the principal source of mineral wealth, plans are now afoot to diversify the province's industrial base, and for example, to develop a world-scale petrochemicals industry. These and related developments will place a heavy demand on industrial mineral resources; indeed, such that they may finally achieve recognition as an important part of Alberta's mineral heritage.

GEOLOGICAL FRAMEWORK OF ALBERTA'S MINERALS

Except for its extreme northeast corner, the province of Alberta forms part of the vast Western Canada sedimentary basin, an area extending from the southern margin of the Prairie Provinces (the Canada-U.S.A. border) northward to the Mackenzie River delta bordering the Arctic Ocean. The region is underlain by assorted sedimentary rock types largely of Paleozoic and Mesozoic ages, essentially flatlying and uncomplicated in structure except along the western margin of the basin where, in Tertiary time, the basin sediments underwent a major orogenic disturbance that formed the Rocky Mountains and Foothills (Green, 1972). Subsequently, from early Tertiary time to the present, the geologic history of the basin has involved erosion rather than deposition, except for the brief period of glaciation during the Pleistocene epoch when unconsolidated glacial sediments of various types were deposited on the bedrock surface.

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[1] Sulfur production is shown separately in Figure 3-1 because of its singular importance and its occurrence as a byproduct mainly of natural gas production.

Table 3-1.–Values of Alberta industries[1] based on industrial minerals.

CONSTRUCTION MATERIALS INDUSTRIES	CHEMICAL & METALLURGICAL INDUSTRIES	OTHERS
CEMENT ($26 million) *Limestone and marl* *Shale* *Gypsum** *Fly ash (pozzolan)*	PULP PROCESSING ($150 million) *Salt (caustic soda, chlorine)* *Saltcake* *Sulfur* *Limestone*	AGRICULTURE-RELATED ($1 million) *Marl and coquina* *Peat moss*
CERAMICS ($5 million) *Clay* *Silica sand** *Fly ash*	FERTILIZERS ($80 million) *Sulfur* *Phosphate rock** *Potash**	SULFUR EXPORTS ($53 million)
GLASS ($16 million) *Silica sand**	LIME, LIMESTONE & DOLOMITE ($4 million) *Limestone* *Dolomite*	SALT ($4 million)
BUILDING PRODUCTS ($11 million) *Gypsum* (wallboard)* *Dimension stone* *Industrial (silica) sand*	MISCELLANEOUS ($1 million) *Bentonite* *Formation brines* ($CaCl_2$)	
AGGREGATES ($20 million) *Sand and gravel* *Expandable clay*		
**No Alberta production.*		

[1] Several industries utilizing industrial minerals, but not based essentially on these resources, are not included.

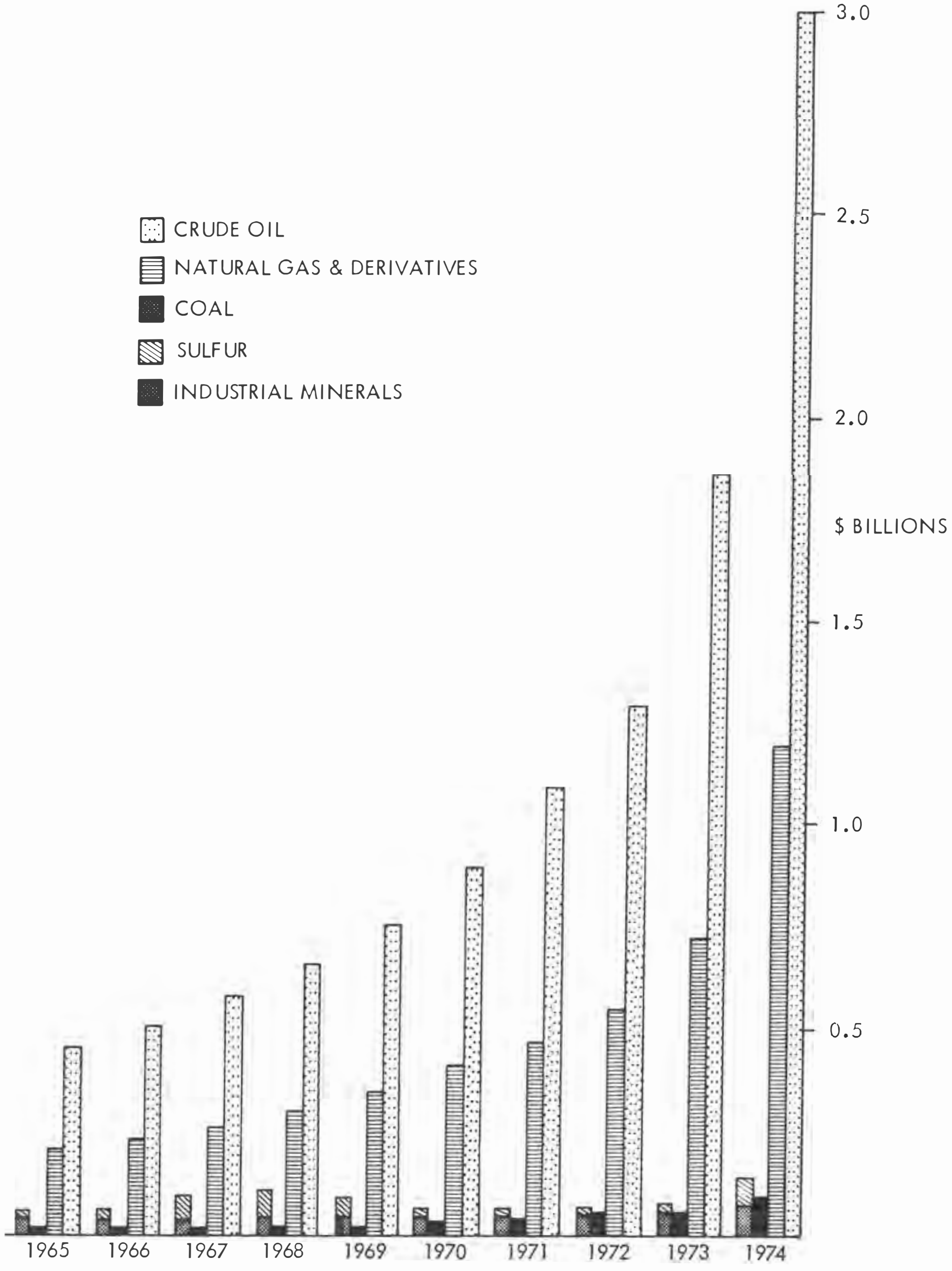

Figure 3-1.–Alberta mineral production 1965–1974.

PHYSIOGRAPHY AND BEDROCK GEOLOGY

Alberta is divisible into three broad physiographic regions, each distinctive in bedrock geology and topographic features (Fig. 3-2). These are:

(1) the Canadian Shield
(2) the Interior Plains
(3) the Cordillera, comprising the Rocky Mountains and Foothills.

The Canadian Shield occupies 6,000 square miles of the northeast corner, where it consists of Precambrian granite, gneiss, and schist. In other regions of Canada these Shield rocks contain important metallic mineral deposits; but in Alberta no commercial deposits have yet been discovered, except, ironically, for a nonmetallic deposit of possible value—namely, a granite rock that has good dimension stone qualities.

Most of Alberta lies within the Interior Plains, a region underlain by undisturbed, nearly flatlying strata, which have a slight regional dip to the southwest, such that successively younger strata form the bedrock toward the Rocky Mountains (Fig. 3-3). In the northeast, Devonian carbonate and evaporite beds underlie the lowlands marginal to the Canadian Shield, and dip gently beneath the Cretaceous cover toward the southwest. The Devonian rocks of this region contain large deposits of limestone, gypsum, and salt, the salt deposits continuing downdip to underlie much of eastern and central Alberta at greater depths. Also downdip, the projected Devonian carbonate strata contain much of the province's oil and gas reserves, which in turn give rise to mineral byproducts such as sulfur.

Over most of the Plains, the bedrock is formed of Cretaceous and Tertiary strata, a succession of nonmarine sandstone and shale formations alternating with marine shale units. Much of Alberta's mineral wealth is contained in these strata: the Alberta Oil Sands deposits, the subbituminous coal deposits, and a goodly portion of the province's conventional oil and gas reserves. They also contain important deposits of bentonite, ceramic clay, and silica sand, and as well, a very large deposit of iron.

The Rocky Mountains and Foothills form a relatively narrow belt of highly deformed strata along the southwestern margin of the province. In general, the Foothills consist of sandstone and shale beds of Jurassic and Cretaceous ages, the Rocky Mountains of carbonate and quartzite beds ranging in age from Precambrian to Triassic. In the Foothills, sour gas and high-grade bituminous coal are the principal resources, along with some clay deposits. In the Rocky Mountains, limestone and dolomite are found in great abundance along with scattered deposits of gypsum, quartzite, and phosphate.

GLACIAL DEPOSITS

Except for some of the higher ridges in the Rocky Mountains and for the Cypress Hills in the southeast, the province was covered by thick ice sheets during the Pleistocene epoch. Consequently, much of the land surface is mantled by unconsolidated glacial sediments—generally only a few tens of feet thick but in places several hundred feet thick. The deposits vary widely in composition, from fine lake clay to coarse outwash gravel, and to unsorted mixtures of various materials (till). Although glacial deposits obscure or otherwise hinder development of underlying bedrock minerals they also provide an important source of sand and gravel, clay, and lower grades of silica sand.

THE INDUSTRIAL MINERALS

Known deposits of the more important industrial minerals in Alberta—those being exploited now or having potential for development in the near future—are described briefly below. For convenience and order in presentation, the minerals are grouped into categories based on geologic mode of origin.

CHEMICAL AND BIOGENIC DEPOSITS

LIMESTONE

Limestone exists in vast quantities in Alberta (Fig. 3-4), in formations of Cambrian, Devonian, and Mississippian ages exposed almost continuously along the Rocky Mountains in western Alberta and in Upper Devonian strata exposed on the margin of the Shield in northeastern Alberta (Holter, 1973; this volume). Limestone also exists in the subsurface throughout the province (Fig. 3-3), but its shallowest depth near any major industrial area is below 3,000 feet—too deep for consideration as a raw material source.

The industrial potential is greatest for the western deposits that lie adjacent to railway lines. Quarries are operated in several of these deposits, the two largest quarries producing limestone for cement making. At Cadomin, 180 miles west of Edmonton, the quarried limestone is hauled by unit train to a cement plant in

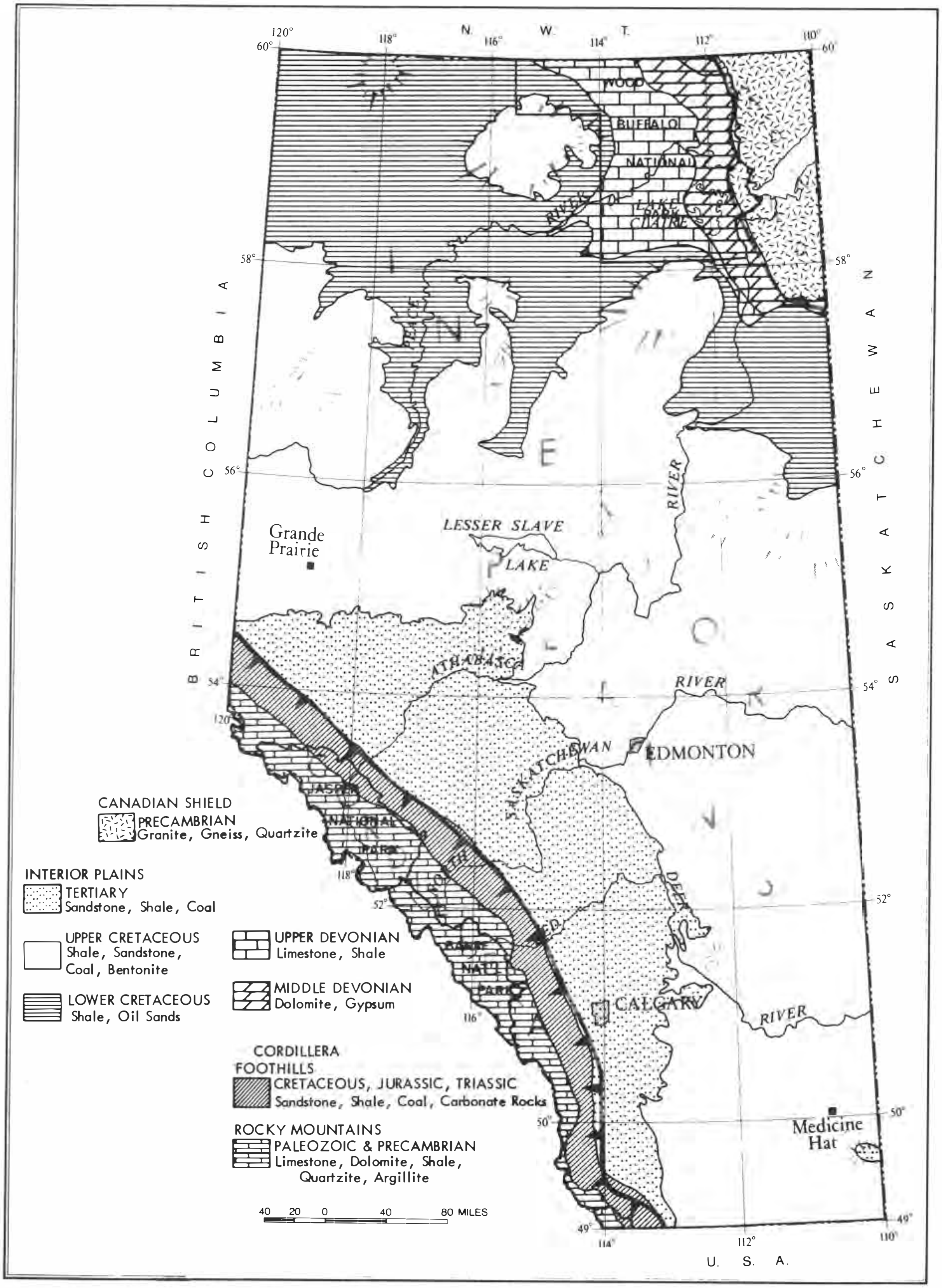

Figure 3-2.—Regional physiography and geology of Alberta.

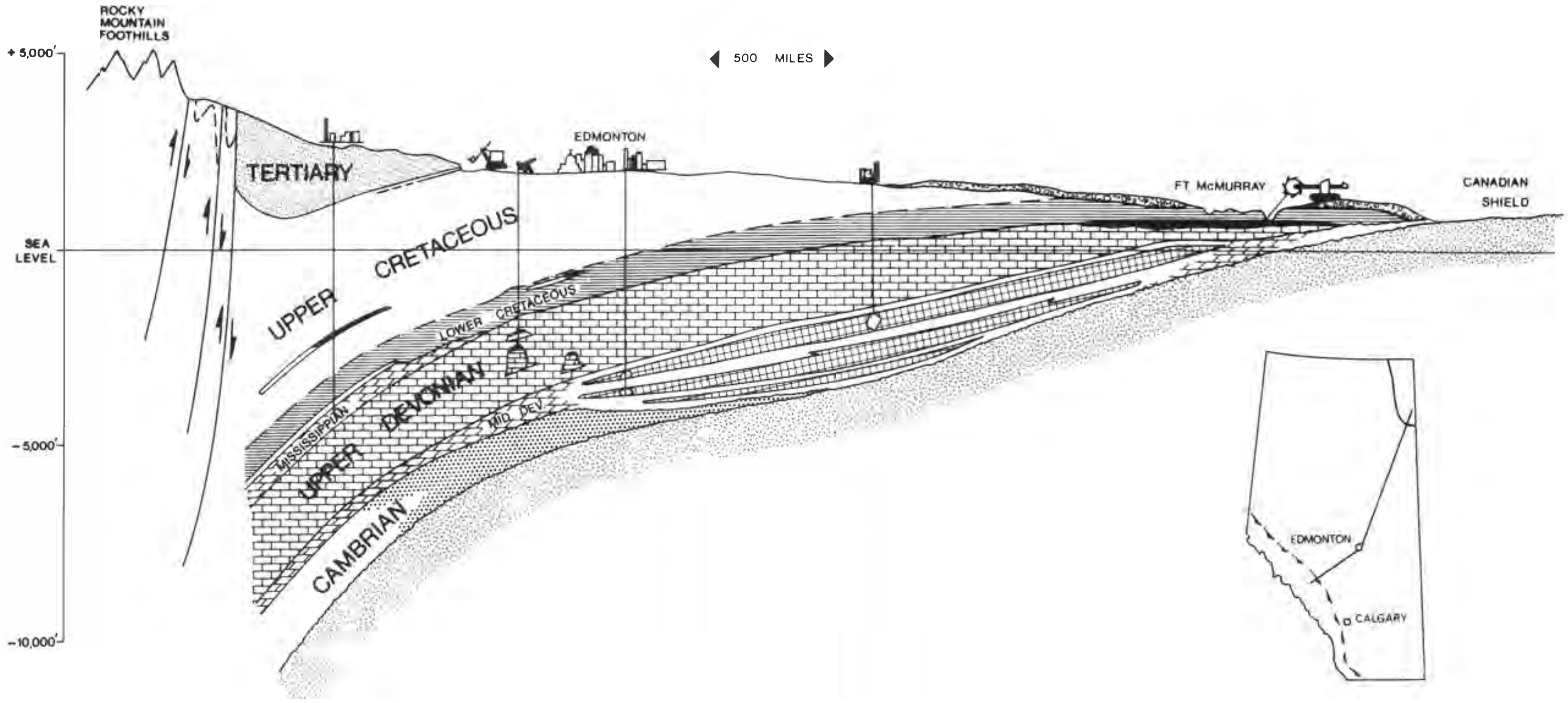

Figure 3-3.—Geological cross section of Alberta.

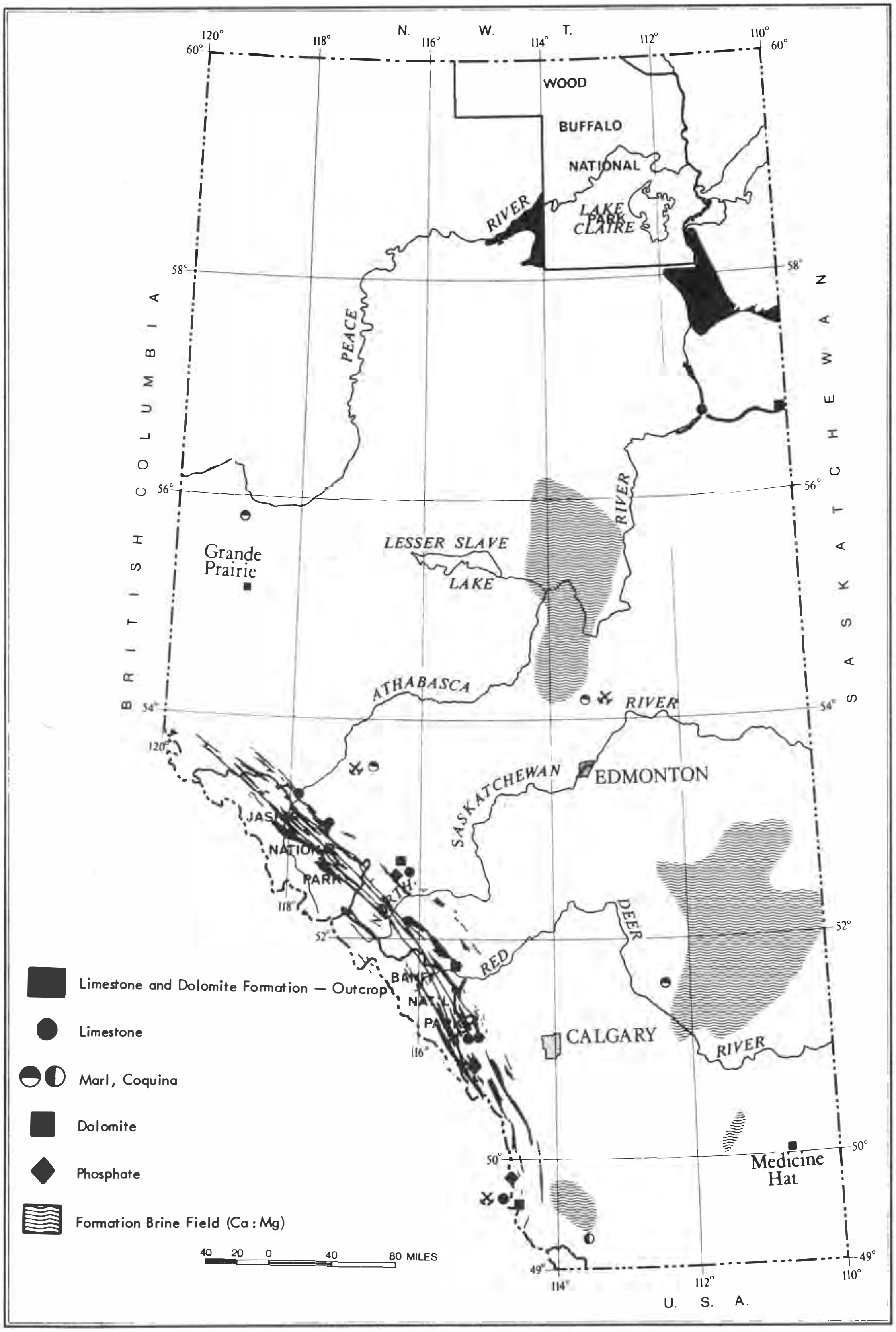

Figure 3-4.—Chemical and biogenic mineral deposits.

Edmonton. The limestone deposit is in the Palliser Formation, of Late Devonian age, and has a stratal thickness of 500 feet and proved reserves in excess of 20 million tons. Production is about 600,000 tons annually. At Exshaw in the Bow Valley, 160 miles southeast of Cadomin, a cement plant uses limestone of the same formation, quarried on the plant site, in roughly the same quantities as at Cadomin.

Other quarries in the mountains produce limestone mainly for lime manufacture. In the Crowsnest Pass, limestone from the Rundle Group (Mississippian) is produced near the site of a lime plant west of Crowsnest Lake. In the Bow Valley, limestone also from the Rundle Group is produced for use in a lime plant near Kananaskis, from quarries 9 miles west of the plant site. Production from these two quarrying areas is about 250,000 to 300,000 tons annually.

MARL AND COQUINA

Marl and coquina, potential substitutes for limestone in certain applications, form few deposits of significant size in Alberta (Fig. 3-4). Marl deposits—of Recent lacustrine origin—have indications of being widespread (Govett and Byrne, 1958), but many are thin, lensy, and of inappreciable extent. One deposit near Clyde, 40 miles north of Edmonton, is worked for use in a local cement plant. Others in the Peace River and Hand Hills areas have sizable indicated reserves (Holter, 1974a, 1974b).

The best known coquina deposit is found in southwestern Alberta, near Hillspring, where an oyster shell bed as much as 15 feet thick is exposed along the Belly River (Crockford, 1947). This bed has been quarried from time to time for agricultural purposes, but this and other known coquina deposits are too small to warrant any major exploitation.

DOLOMITE

Dolomite is extensive in the mountains of Alberta, its distribution closely paralleling that of limestone (Fig. 3-4). A small amount of dolomite is quarried in the Crowsnest Pass area, from strata in the Fairholme Group (Upper Devonian) and also from strata in the Rundle Group (Mississippian) for use as flux stone in British Columbia smelters. Dolomite is found also in northeastern Alberta in the Methy Formation (Middle Devonian), a reef rock unit that crops out on the Clearwater River and lies near the surface along the lower stretch of the Athabasca River (Hamilton and Mellon, 1973).

PHOSPHATE

Phosphate showings are fairly widespread in the Rocky Mountains (Fig. 3-4). The phosphate zones are found at four distinct stratigraphic horizons (Telfer, 1934):

(1) at the base of the Mississippian strata (Exshaw Formation).

(2) near the top of the Permian-Pennsylvanian succession (Rocky Mountain Group), in strata that correlate with the Phosphoria Formation of Montana and Idaho, where phosphate rock deposits are commercially exploited.

(3) at the base of the Jurassic strata (Fernie Formation).

(4) in a belemnite zone near the middle of the Fernie Formation.

None of the showings has indicated significant economic potential. The phosphate-bearing zones found thus far have all tended to be thin, discontinuous, and of low grade (when considered over a minimal thickness for mining). Moreover, the showings are all found in rugged terrain and most are in steeply dipping beds, making mining conditions less than favorable.

Despite all these negative aspects, it would be perhaps unwise to write off the economic possibilities of Alberta phosphate. In the present light of changing economics and predicted shortages for phosphate, it is conceivable that deposits subsequently found in Alberta could have potential. Phosphate rock was in fact mined in the Crowsnest Pass area prior to 1930, at a site just across the British Columbia border.

FORMATION BRINES

The formation brine fields indicated in Figure 3-4 outline areas under which formation waters of subsurface Devonian reservoirs contain high concentrations of calcium and magnesium; specifically, more than 60,000 mg/l for Ca and more than 9,000 mg/l for Mg (Hitchon and Holter, 1971). These brines are similar in composition to brines being commercially exploited in Michigan for calcium chloride. They could also be a potential source of magnesium metal, inasmuch as the Mg concentrations are several times that of sea water—the main commercial source of the metal.

EVAPORITES

Salt (halite) deposits underlie almost half of the province as shown in Figure 3-5. The salt beds, belonging to a group of strata of Middle Devonian age called the Elk

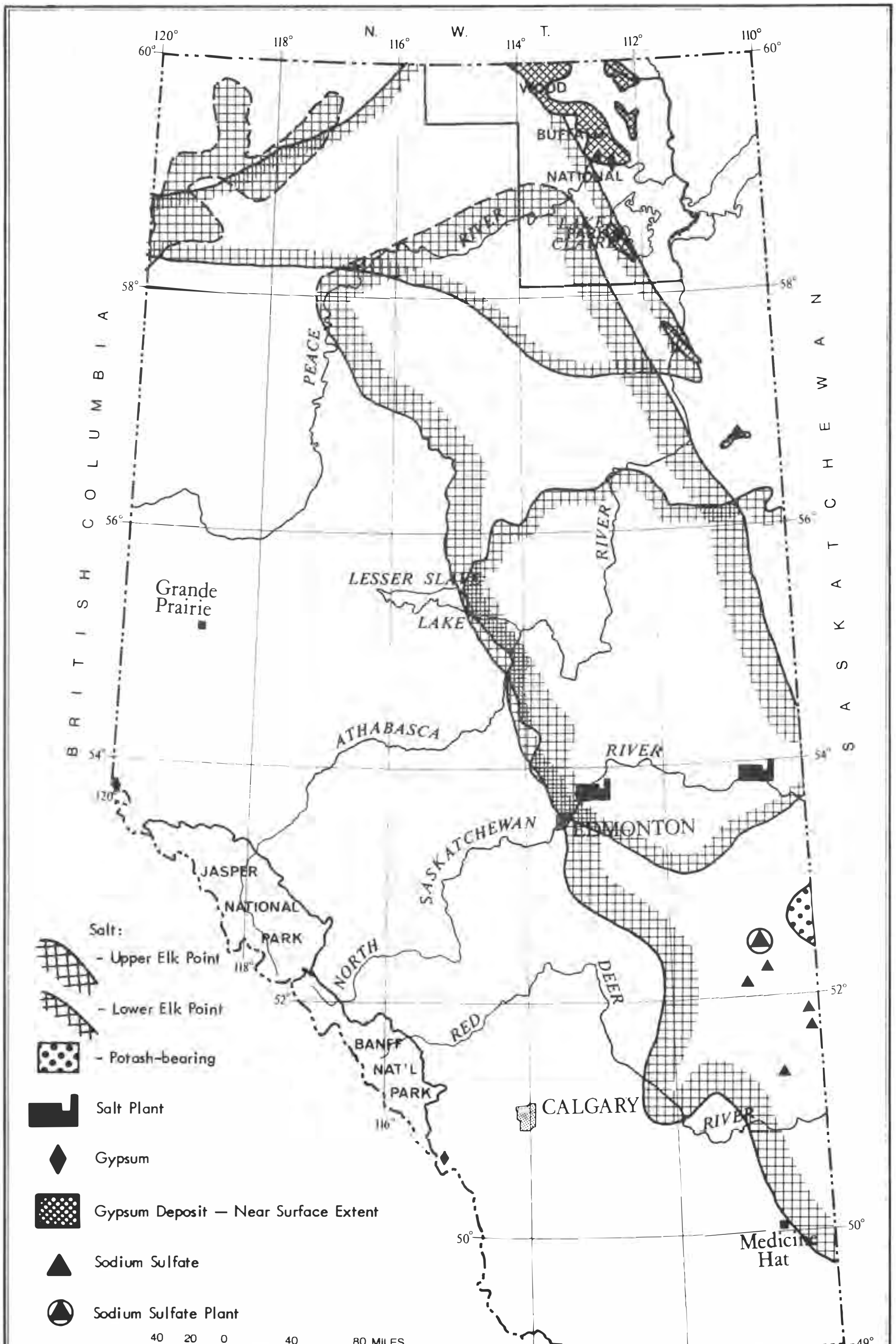

Figure 3-5.—Evaporite mineral deposits.

Point Group, dip southwesterly from a depth of 700 feet at Fort McMurray to about 6,000 feet at Edmonton and reach an aggregate thickness of nearly 1,400 feet at some point about 100 miles east-northeast of Edmonton (Hamilton, 1971). From here, the beds become thinner in all directions, but the salt (which is generally of excellent quality) retains brinable thicknesses sufficient to support a major brining operation almost anywhere within the salt-bearing area.

Two distinct types of salt deposits are represented in the Elk Point Group, as distinguished in Figure 3-5. The younger, shallower Upper Elk Point salt is a more or less "normal", first-cycle marine evaporite deposit, known as the Prairie Evaporite Salt, and it is of very great extent, continuing in a broad belt southeastward right across southern Saskatchewan where it contains extensive deposits of potash. Only in one small area of eastern Alberta, however, is the potash inferred to extend across the border, and here the potash deposit is subeconomic in terms of grade, thickness, and depth.

The older, deeper Lower Elk Point salt is more restricted in distribution, although it too is very thick and extensive. This salt is unusual in that it does not seem to be a normal marine evaporite. Instead, it has a complex history of solution and redeposition that resulted in extraordinarily pure deposits of sodium chloride in these beds.

Salt is produced at two localities in Alberta. At Fort Saskatchewan, a few miles northeast of Edmonton, salt is brined from beds as deep as 6,100 feet for the manufacture of chloralkali chemicals. At Lindbergh, about 120 miles east of Edmonton, salt for domestic and industrial use is brined from beds 3,600 feet below the surface. Total production is about 360,000 tons annually, of which 250,000 tons is for chemical use.

Salt beds are used also in an indirect way at three localities in the province for underground storage of petroleum products (in artificially created caverns).

GYPSUM

Several deposits of gypsum are known in Alberta. None is developed at the present time, owing to their remote locations and difficult accessibility. Deposits judged to have potential for future development are indicated in Figure 3-5.

The southernmost (and least remote) deposit lies in the vicinity of Kananaskis Lakes, in the Rocky Mountain front ranges, 80 miles southwest of Calgary. The deposit crops out high up a mountainside, where an 80-foot thickness of good grade gypsum is exposed in Middle Devonian strata (Halferdahl, 1969a). Grab samples assayed 90 to 92 percent purity, but the average grade and extent of the deposit are undetermined. The gypsum beds dip steeply into the mountain and would require underground mining methods for recovery. The Kananaskis Lakes region is one of great scenic attraction and high recreational and wildlife values, so any mineral development has been virtually ruled out for this sensitive area.

Another deposit straddles the Continental Divide on the Alberta-British Columbia border, about 270 miles due west of Edmonton (Govett, 1961). Its remote location is offset somewhat by proximity to the Alberta Resources Railway, passing 40 miles to the east. The deposit, in Triassic strata, seems to contain several million tons of ore, but estimation of reserves is hampered by structural complexities. The grade also is uncertain, owing to a discrepancy in assays reported for outcrop (95 percent) and test hole samples (75 to 80 percent); thus, development of this deposit is unlikely in the near future.

Large deposits of gypsum are present also in northeastern Alberta (Hamilton and Mellon, 1973). These are the updip, near-surface projections of anhydrite beds in the Prairie Evaporite Salt: along the evaporite subcrop the salt has been leached back, leaving the anhydrite beds, which were subsequently transformed to gypsum where the thick Cretaceous overburden is eroded, as along major river valleys. One such deposit 30 to 50 feet thick underlies the Clearwater River valley at depths ranging from near-surface to 300 feet over a distance of 18 miles; the average grade of the gypsum measured 84 percent (Hamilton, 1969). A similar deposit but of higher grade is postulated to lie beneath the Athabasca River valley 60 miles north of Fort McMurray.

Farther north, stratigraphically similar deposits of gypsum crop out over very extensive areas of Wood Buffalo National Park, where the Cretaceous cover also is absent. Best known are the deposits at Gypsum Cliffs on the Peace River, where cliffs about 80 feet high of almost solid gypsum are exposed along a 14-mile stretch of the river (Govett, 1961). Being in a National Park, these deposits are interdicted from exploitation, and in any case, are situated in an extremely remote part of the province. Nevertheless, they are professed to rank among the largest and highest grade of any in the world.

SODIUM SULFATE

Sodium sulfate deposits are found at many localities in eastern Alberta and Saskatchewan and are the source

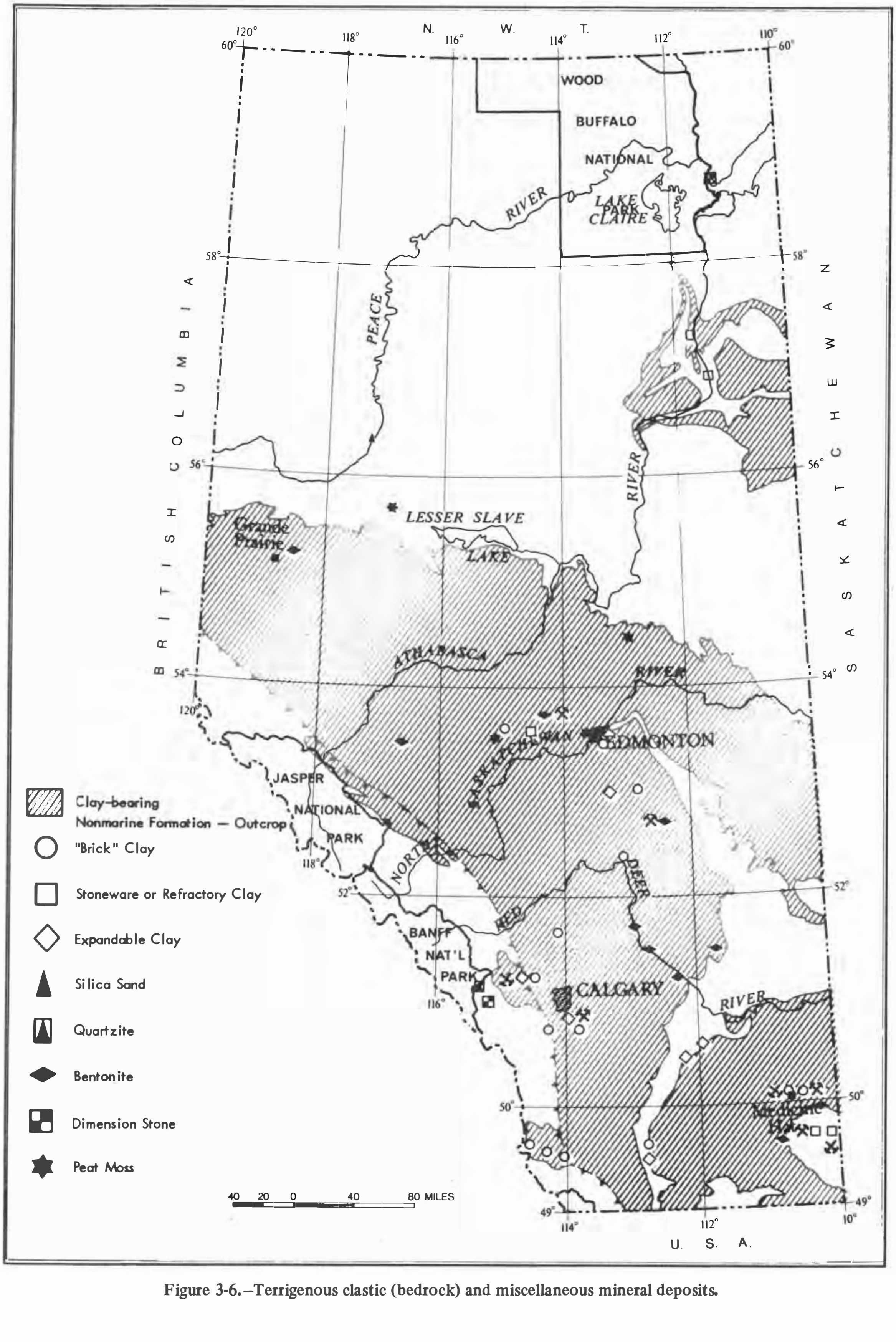

Figure 3-6.—Terrigenous clastic (bedrock) and miscellaneous mineral deposits.

of most Canadian salt cake production (Broughton, this volume). Only one deposit is worked in Alberta, at Metisko Lake 140 miles southeast of Edmonton (Fig. 3-5). This deposit contains reserves of 1.5 million tons, and annual production is about 75,000 tons. Several other known deposits in Alberta seem too small for economic development (Govett, 1958).

TERRIGENOUS CLASTICS - BEDROCK

CLAY AND SHALE

Clay or shale is found in virtually all the bedrock formations of the Alberta Plains, and shale is the dominant rock type in Mesozoic strata of the mountains. As ceramic materials, most of the clay beds are the low-grade type, suitable at best for low-value ware such as brick; a few deposits of intermediate grade stoneware clay and fireclay are known, but high-grade clay is unknown (Hamilton and Babet, 1975).

In general, the better grades and the best quality of all grades of clay are found in the nonmarine bedrock formations, which crop out within an area indicated accordingly in Figure 3-6. Outside this area the bedrock is mainly marine shale, which has little potential ceramic use. The deposits located in Figure 3-6 are those that have tested favorably for use, either as low-grade "brick" clay or intermediate-grade (stoneware or refractory) clay.

The better grades of clay are found especially in the Cypress Hills region of southeastern Alberta, in a distinctive stratigraphic unit known as the Whitemud Formation, of Late Cretaceous age. The Whitemud, undoubtedly the most important source of clay in Western Canada, is a thin but widespread unit that extends well into Saskatchewan where it yields high-grade ball clay and fireclay, although in Alberta it provides only stoneware clay (Crockford, 1951; Lindoe, 1965).

Other deposits of the better grade clay are found at Wabamun, 40 miles west of Edmonton, and at Fort McMurray in northeastern Alberta.

At Wabamun, good quality fireclay is found in extensive partings as much as 2 feet thick within coal measures that are being strip mined for electric power generation. The clay is potentially recoverable as a byproduct of this stripping operation; it is basically kaolinite, white burning, and shows promise for ceramic use. At present, this clay is being wasted as backfill at a rate of 200,000 tons yearly.

At Fort McMurray, deposits of stoneware clay grading to fireclay are found in places underlying the Athabasca Oil Sands and resting on eroded Devonian limestone (Halferdahl, 1969b). This is the so-called "oil sands underclay", not everywhere present beneath the oil sands and not everywhere of the same quality, but in some places it has interesting possibilities.

Clay and shale that exhibit bloating properties suitable for lightweight (expanded clay) aggregate production are fairly widespread in the province (Matthews, 1952). Good bloating materials are found most consistently in the marine shale formations (notably, the Bearpaw Formation), but outcrops of these formations are far from present markets. Closer in, some nonmarine shale units have also proven favorable: a plant in Calgary uses shale from the uppermost Tertiary beds of the Paskapoo Formation, quarried a few miles south of the city; formerly, this plant used shale from the Belly River Formation (Cretaceous) in the Foothills.

SILICA SAND

A few sources of good quality silica sand are known in Alberta, but are poorly situated with respect to transportation and markets, and are undeveloped. The only bedrock deposit of proven significance is found in northwestern Alberta, in a Cretaceous marine sandstone unit exposed along the Peace River (Fig. 3-6). The deposit is a friable zone 40 to 60 feet thick at the top of the sandstone unit, consists of relatively pure quartz sand of variable texture, easily upgradable to glass sand quality (Crockford, 1949). The remote location of the deposit has prevented development to date.

QUARTZITE

Quartzite deposits in Alberta have not been thoroughly evaluated as a potential source of silica. From an accessibility standpoint the Permian quartzite beds of the Rocky Mountain Group offer the best prospects, specifically, the exposures opposite Canmore in the Bow Valley, 50 miles west of Calgary (Fig. 3-6). Other quartzite formations of Cambrian and Precambrian ages in the mountains and the Athabasca Formation (Precambrian) in northeastern Alberta are too remote or access is too difficult for these to merit consideration.

Some of Alberta's river gravel deposits contain large percentages of quartzite, present as pebbles and cobbles that have been derived from Lower Paleozoic quartzite formations in the Rocky Mountains. These alluvial quartzite deposits have been evaluated favorably as a potential source of industrial silica (Halferdahl, 1969c).

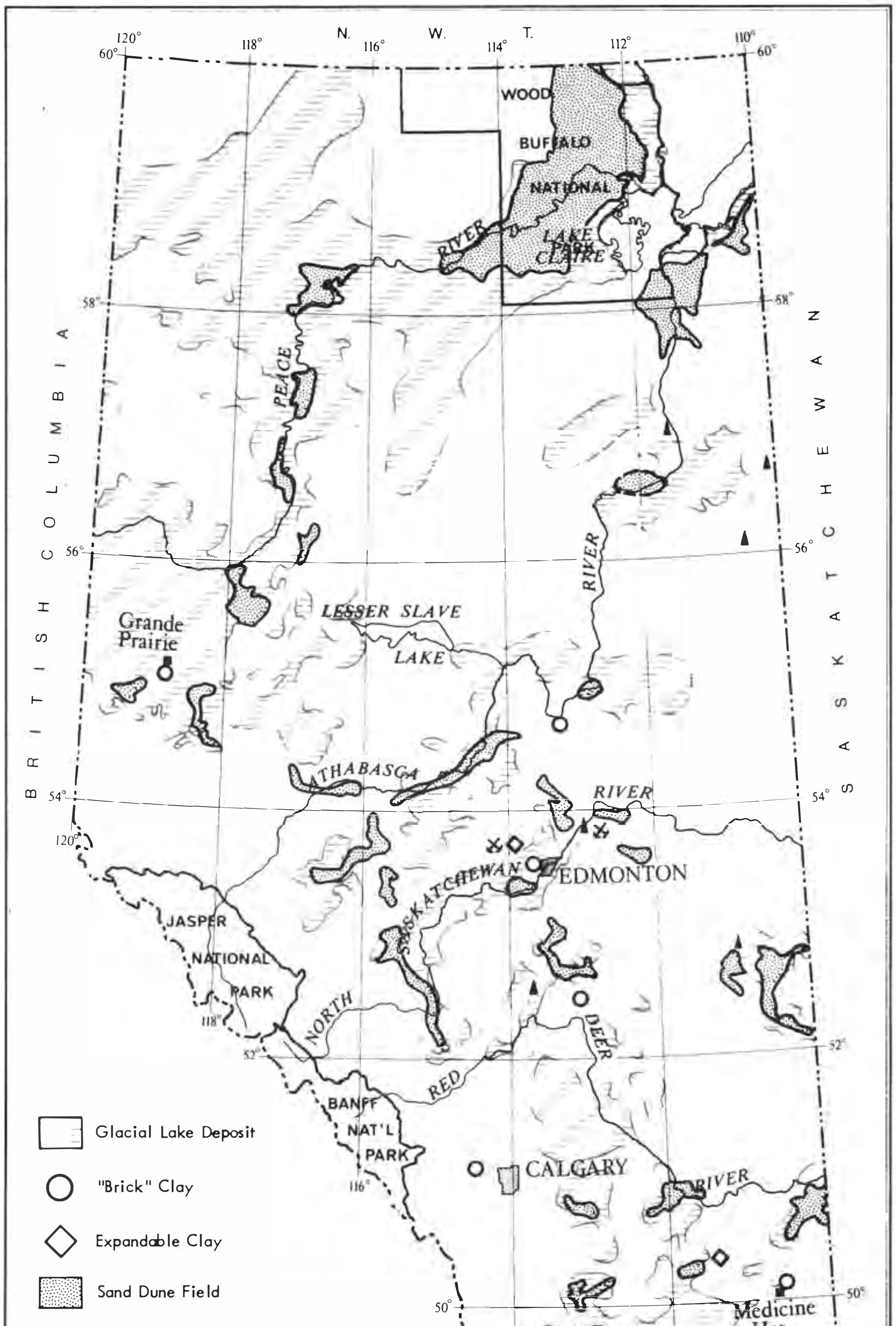

Figure 3-7.–Terrigenous clastic (surficial) mineral deposits.

TERRIGENOUS CLASTICS - SURFICIAL

CLAY

Surficial clay of potential ceramic use is found mainly in glacial lake sediments, which cover extensive areas of the province as shown in Figure 3-7 (Hamilton and Babet, 1975). These clay deposits are the low-grade type and not generally the best of quality, but being on the surface they are easily won; for this reason, surficial clay has been an important source of raw material in Alberta–mainly for brick making, latterly also for expanded clay aggregate and cement production.

INDUSTRIAL (SILICA) SAND

The best quality surficial sand deposits in Alberta are the dune sand deposits scattered over many parts of the province (Fig. 3-7). The sand of these deposits in general is too low grade to properly be called "silica sand"; the term "industrial sand" may be preferable, because the sand does have consistent, controllable properties that are sought for certain industrial applications (McLaws, 1971). The sand responds reasonably well to simple beneficiation treatment and can be upgraded for use in lower grades of glassware (Carrigy, 1970; Holter, 1971, 1972). Dune deposits near Edmonton are in fact now used for production of glass fiber products.

SAND AND GRAVEL

Plentiful supplies of sand and gravel in Alberta are found in three main geologic types of deposits: preglacial, glacial, and Recent, shown schematically in Figure 3-8.

Preglacial deposits include semiconsolidated gravel of late Tertiary age that caps several prominent bedrock highs (Cypress Hills, Hand Hills), and as well, the gravel that occupies preglacial bedrock channels. The latter type, although normally buried under glacial drift, is the more common commercial source. The quality of these gravel deposits is excellent, but economic deposits are few because of overburden. Edmonton is supplied principally from preglacial channel deposits (MacPherson and Kathol, 1973).

The most widespread are the glacial outwash gravel deposits, which supply most of the gravel needs of the province. Recent gravel generally is of poor quality and is used in areas deficient in the other types.

Annual production of sand and gravel in Alberta is about 20 million tons.

MISCELLANEOUS UNCLASSIFIED DEPOSITS

BENTONITE

Bentonite is very common in Alberta, distributed throughout the sedimentary rocks of Late Cretaceous age in the Plains region. Relatively pure seams are found at several localities (Fig. 3-6), but only two have the quality and extent sufficient to warrant exploitation (Scafe, 1975)–near Rosalind along the Battle River about 70 miles southeast of Edmonton, and at Onoway about 30 miles northwest of Edmonton.

The best bentonite comes from the deposit at Rosalind, some of it comparing in quality and yield values to the

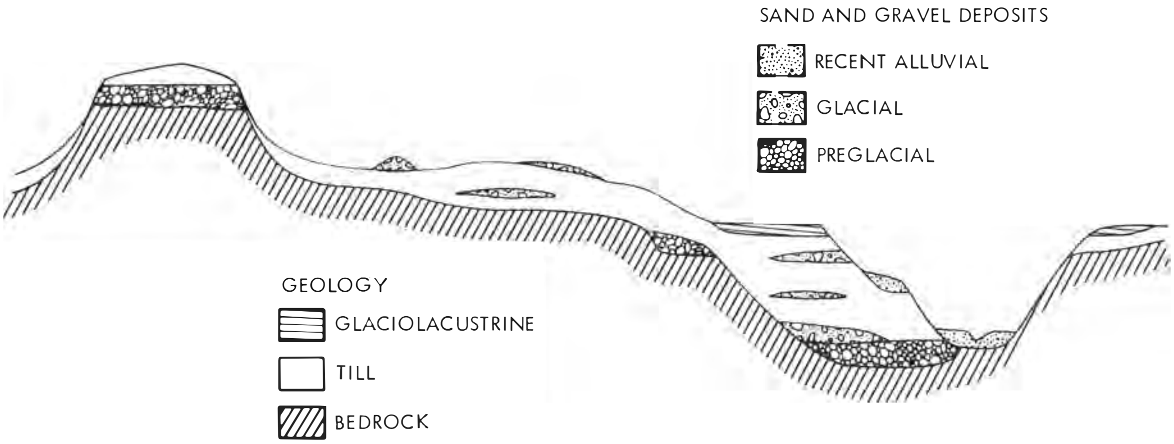

Figure 3-8.–Schematic cross section of Alberta sand and gravel deposits.

Wyoming bentonites (Babet, 1966; Scafe, 1975). Total production at Rosalind is approximately 12,000 tons a year and most is sold as foundry clay. The Onoway deposit has not been mined since 1968, but stockpiles are being processed at the rate of about 2,000 tons a year, mainly for use in drilling muds.

Another deposit which has excited investigators in the past is one at a place called Dorothy, 75 miles east of Calgary. The bentonite here is 33 feet thick, the thickest and most extensive seam found in Alberta, but the yield is low and the overburden prohibitive to development.

DIMENSION STONE

The only rock material currently produced as dimension stone in Alberta is a dolomitic siltstone from the Spray River Formation (Triassic), quarried in the Rocky Mountains near Canmore (Fig. 3-6). The rock is a hard, flaggy, medium-grey material known as "Rundle Stone"; it is used as rough building and decorative stone in houses, buildings, monuments, and so on. Annual production is only about 1,000 tons.

Potential may exist for granite found in northeastern Alberta in plutonic masses that crop out on the Precambrian Shield near Fort Chipewyan (Hamilton and Mellon, 1973). The red granite has all the properties of high-quality ornamental-building stone (Godfrey, 1971, 1972), its remote location being the main deterrent to development.

PEAT MOSS

Peat moss bogs are widespread throughout the northern two-thirds of Alberta, one-quarter to one-third of this region being bog covered to an extent greater than 60 percent. For most of the region, individual bogs are unclassified as to depth and plant colonies (only the sphagnum mosses are marketable), so that the commercial potential of the peat moss is undetermined. Undoubtedly, the potential is considerable.

Peat moss is commercially harvested at four localities (Fig. 3-6), the largest production coming from a plant near Evansburg, 50 miles west of Edmonton. Annual production for the province is about 9,000 tons.

INDUSTRIAL BYPRODUCT MINERALS

Most of the minerals included in this category (viz., accessory "heavy" minerals, silica sand, clay, sulfur, and fly ash) are byproducts of processing oil sands (Fig. 3-9); except for sulfur none is recovered commercially as yet, although all seem to have excellent potential. Additional byproducts are fly ash from coal combustion in power plants, sulfur from sour natural gas production (the principal source), and gypsum from phosphoric acid manufacture, all indicated by plant site locations in Figure 3-10.

ACCESSORY "HEAVY" MINERALS

The McMurray Formation sandstone, principal host rock of the Athabasca Oil Sands, contains about 0.3

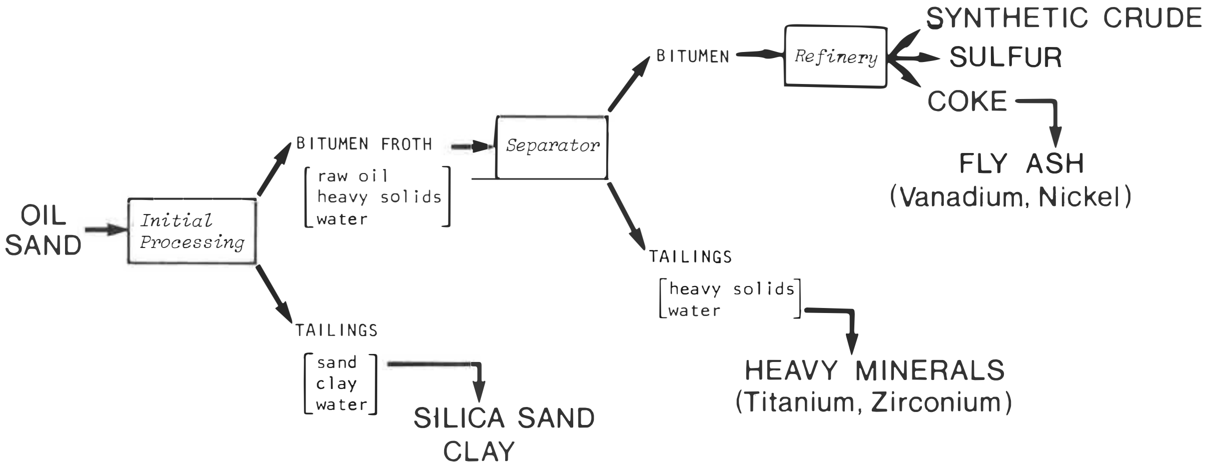

Figure 3-9. –Flow diagram of oil sands extraction process and byproduct minerals evolved.

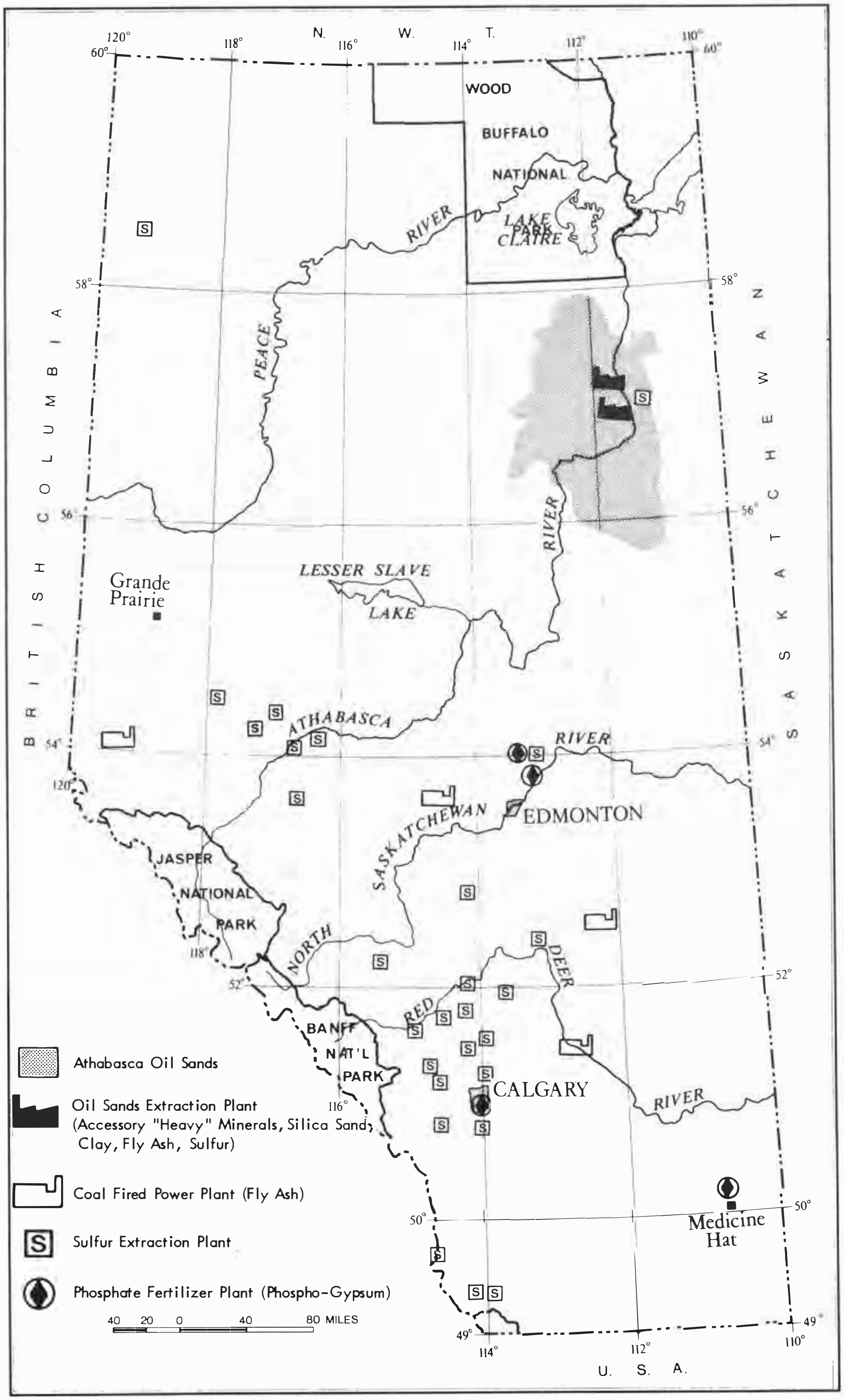

Figure 3-10. –Industrial byproduct minerals

weight percent of accessory, or "heavy" minerals in its petrologic make-up (Carrigy, 1962). These "heavies" (S.G. greater than 2.95) are rich in titaniferous minerals and zircon, and they show a tendency to become concentrated in the bitumen froth during the flotation process for bitumen extraction (Hamilton and Mellon, 1973). Results of studies to date have indicated that the heavies form 30 percent or more of the mineral solids in the froth, an increase of 100-fold from their concentration in the original sand. The heavies fraction in turn assays as much as 25 percent titanium and 10 to 20 percent zirconium, thus constituting a potential source for these metals and their oxides.

Although the percentage of heavies in the raw sand seems practically negligible, the net amount becomes significant because of the enormous tonnages of sand handled in the extraction process. For example, a 100,000-barrels-per-day plant[2] would process 200,000 to 250,000 tons of raw oil sand, which would include about 600 tons of heavies also put through the process each day. How much of this amount of heavies would collect in the bitumen froth (and hence, be recoverable for beneficiation and treatment) remains to be determined; present operating experience suggests that most of it would.

SILICA SAND

The tailings sand from the oil extraction process grades 98 percent silica without any treatment (Hamilton and Mellon, 1973), and is probably the best potential source of high-grade silica sand in Alberta. Despite its high silica and very low iron content, the tailings sand would require beneficiation for use as glass sand, to eliminate "fines", mica flakes, and residual oil film, but this seems feasible on the basis of studies currently in progress.

It is useful to bear in mind the enormous tonnage of silica sand potentially available from this source. By way of illustration, a single day's production of tailings from the existing oil sands plant, approximately 100,000 tons, could supply Alberta's current silica requirements for one entire year.

CLAY

The clay fraction of the oil sands tailings may have some ceramic potential if ceramic tests currently underway show the clay to be worth recovering. No conclusive test results are available, but the mineralogy of the clay fraction of McMurray Formation sand suggests possibilities for a good grade of ceramic clay (Hamilton and Mellon, 1973).

FLY ASH

Fly ash is also an oil sands byproduct, although the main accumulations of fly ash in the province are from coal-fired power plants (Fig. 3-10). The fly ash from oil sands processing results from combustion of residual bitumen coke, which is burned for boiler fuel at the oil sands plant; this ash is particularly important for its high vanadium and nickel concentrations (Hamilton and Mellon, 1973).

In the oil extraction process, one of the basic steps involves thermal coking of the separated bitumen to produce an upgraded distillate crude, leaving a residual product of bitumen coke. Virtually all of the mineral solids and most of the trace metals present in the bitumen accumulate in the residual coke and constitute 3 percent of the coke by weight. These solids accumulate as fly ash and bottom ash containing vanadium and nickel concentrations of 3.5 and 1.2 percent, making the ash a potential source for these metals in the future—when oil sands development reaches a more mature stage. At present, with just one plant operating, the amount of ash produced is small—less than 100 tons daily.

Other fly ash in the province has found limited use as pozzolans and as an additive in ceramic clay bodies.

SULFUR

Alberta has the world's largest production of sulfur from hydrocarbon sources, and accordingly has become a major world producer and exporter of this commodity. Sulfur happens to be another byproduct of oil sands processing (Fig. 3-9), a smaller percentage being recoverable from the synthetic crude oil, but most of the sulfur is a byproduct or coproduct of sour natural gas production. Sulfur-recovery plants are scattered throughout the province as indicated in Figure 3-10. In some of these sour gas fields the hydrogen sulfide concentration exceeds 50 percent, although in most it is between 3 and 20 percent. As a rule, the H_2S percentage increases to the southwest, with the increasing depth and formation temperature.

Annual sulfur production in Alberta is about 7 million tons, of which about two-thirds currently finds markets. Unsold production is stockpiled. Proved recoverable reserves of sulfur from Alberta's sour gas fields total 170 million long tons.

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[2] Thought to be the average economic plant size for future plants.

PHOSPHO-GYPSUM

Gypsum originates as a byproduct of phosphoric acid manufacture in four fertilizer plants in Alberta (Fig. 3-10), located at Redwater and at Fort Saskatchewan, both a few miles northeast of Edmonton, at Calgary, and at Medicine Hat, 160 miles southeast of Calgary. The amount produced is not reported but can be estimated to be on the order of 1.5 million tons annually. No commercial use is made of the phospho-gypsum at present, the material being wasted in disposal ponds at the plant sites. Investigations of two of the sources, however, indicate that the material has potential as a substitute for natural gypsum in the manufacture of gypsum products (Collings, 1972).

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LIMESTONE RESOURCES OF ALBERTA

M. E. Holter*

ABSTRACT

Limestone-bearing strata are exposed in seven areas of Alberta, each situated adjacent to rail and road facilities. Six of these centers are along the eastern edge of the Foothills and Front Ranges of the Rocky Mountains in western Alberta. The other is in northeastern Alberta, along the eastern margin of the Alberta Basin.

High-grade limestone is present in Middle Cambrian, Upper Devonian, and Mississippian strata. Eldon Formation limestone has been exploited only in the Exshaw area west of Calgary, where it formerly was used for lime production. Limestone beds of the Palliser Formation are exploited at Exshaw and at Cadomin in west-central Alberta for the manufacture of cement. Reserves of high-grade limestone also are available in the Palliser Formation near Crowsnest Lake in southwestern Alberta and near Brûlé, west of Edmonton. Upper Devonian limestone of the Waterways Formation is widespread in the Fort McMurray area of northeastern Alberta, but available data indicate that its quality is inferior to that of the limestone deposits of the Rocky Mountains regions. The Livingstone Formation contains large reserves of high-grade limestone at several localities in the Rocky Mountains and Foothills. Commercial development of the unit is now under way at Crowsnest Lake and at Exshaw for lime production, and future exploitation of the beds is feasible at Blairmore and Nordegg.

INTRODUCTION

In 1974, more than 1.5 million tons of limestone was quarried in Alberta. During the same year approximately 1 million tons of cement and 150,000 tons of lime were manufactured, representing a total production value of more than $27 million. The bulk of these commodities is consigned to local markets in Alberta, and the projected economic growth of the province indicates that the limestone and dependent industries will continue to expand to meet the requirements of Alberta's construction and manufacturing industries. For this reason, it is timely to review the existing sources of limestone in Alberta and also limestone resources that are available for future development.

SOURCE OF DATA

The data upon which this review is based were obtained from detailed field investigations carried out for the Research Council of Alberta in 1971 (Holter, 1976). Limestone-bearing formations were measured and sampled in seven areas of the province located near centers serviced by rail and road facilities. Six of these areas are along the Foothills and Front Ranges of the Rocky Mountains in southern and central Alberta, and the other is near Fort McMurray in northeastern Alberta (Fig. 4-1).

Standard field procedures were used to measure, describe, and sample selected limestone-bearing strata in each of the seven areas shown in Figure 4-1. More than 700 spot samples were obtained in the field, from which 115 composite samples were analyzed by standard wet-chemical methods. Also, each of the spot samples was subjected to x-ray fluorescence analysis. The thickness of sampled section ranges from 5 to 100 feet, depending on rock quality, bedding consistency, and availability of outcrop. About 6,000 feet of stratigraphic section is available for study in the Rocky Mountains and Foothills, and this thickness of section is repeated locally by thrust faulting as many as four times. Such stratigraphic and structural complexities, together with incompleteness of outcrop and difficult access in some areas, present problems in evaluating limestone resources.

Several sources of published and open-file material have been utilized to supplement recent investigations. Especially worthy of note is the work of Goudge (1945), Matthews (1960, 1961), and Halferdahl (1967).

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GEOLOGIC SETTING

Limestone-bearing formations crop out extensively within the Rocky Mountains and Foothills of western Alberta and around the margin of the Canadian Shield in the northeast part of the province. In the Rocky Mountains, dominantly carbonate strata range in age from Precambrian to Triassic, but rock units containing potentially commercial limestone resources are restricted to Cambrian, Devonian, and Mississippian strata (Fig. 4-2). The rocks are folded and faulted to varying degrees, forming a series of northwest-trending "en echelon" outcrop belts in which repetition of rock-units by low-angle west-dipping thrust faults is common.

East of the Foothills, Paleozoic strata extend beneath the cover of younger Mesozoic formations, intersecting the surface in northeastern Alberta in the lowlands adjacent to the lower Peace and Athabasca Rivers. In this region only Devonian strata are exposed (Fig. 4-2), generally along the valleys of the larger rivers and streams. The beds are nearly flat lying, the regional dip being only a few feet per mile to the southwest, but solution of underlying salt deposits has induced local structures in some of the limestone exposed along the Athabasca River.

DESCRIPTION OF DEPOSITS

CROWSNEST LAKE AREA

The Crowsnest Lake area, situated in the Crowsnest Pass region of southwestern Alberta, is traversed by the main line of the Canadian Pacific Railway and Alberta Highway No. 3 (Fig. 4-1). The bedrock geology has been mapped by several investigators, the most recent of whom was Price (1961).

Quarrying operations have been maintained for more than 30 years by Summit Lime Works Limited near Crowsnest Lake just east of the Alberta-British Columbia border. The present production rate is approximately 50 tons of limestone per day. At this locality Paleozoic strata are thrust over Upper Cretaceous beds along the trace of the west-dipping Lewis fault. Paleozoic strata, which include a thick succession of Devonian and Mississippian

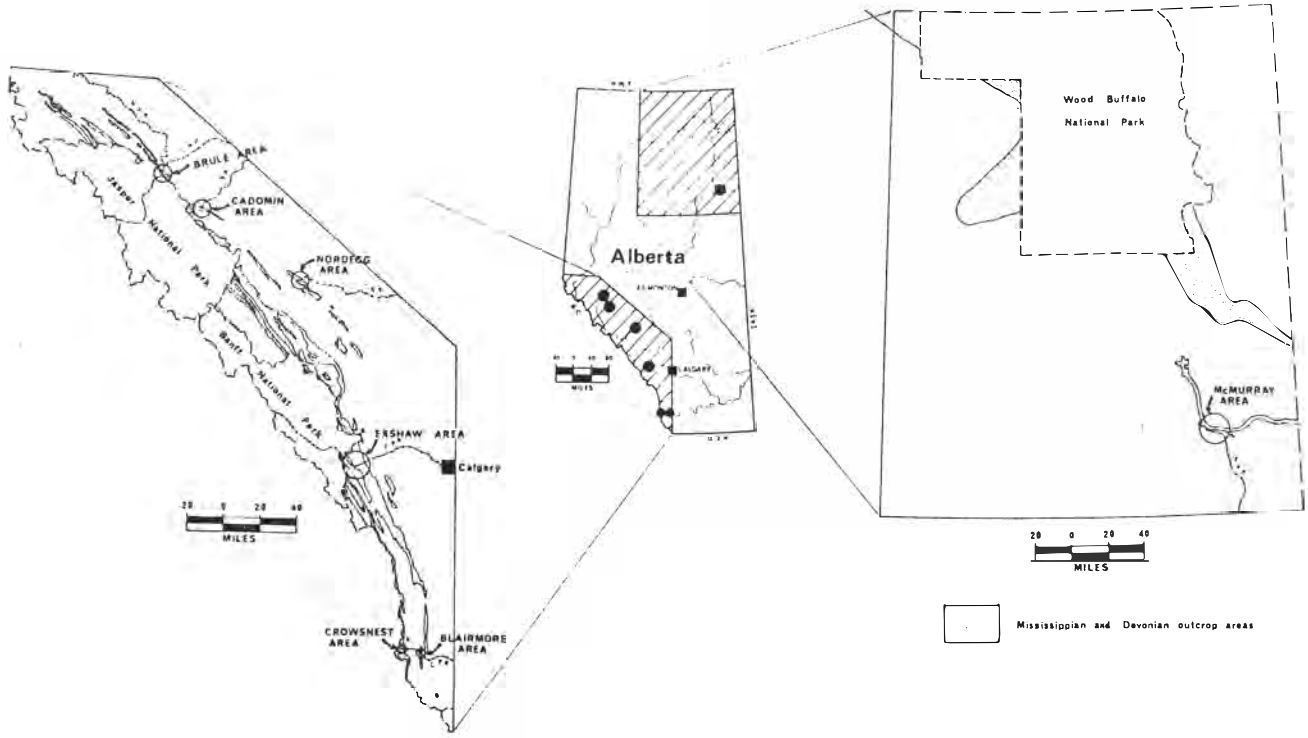

Figure 4-1.–Location map.

carbonate formations, strike north and dip west 30 to 70 degrees (Fig. 4-3).

Quarrying of limestone is under way in beds of the Livingstone Formation and the basal part of the Mount Head Formation. In addition, a small amount of dolomite is quarried from the Fairholme Group south of Crowsnest Lake. Sections were sampled along the north side of Crowsnest Lake adjacent to the railway, west to Island Lake (including the quarries of Summit Lime Works Limited). Exposures along Highway No. 3 to the south also were tested. The sampling complements the earlier work of Goudge (1945).

The Palliser Formation is approximately 1,000 feet thick and contains high-calcium limestone grading as much as 96 percent $CaCO_3$, which warrants further investigation. Potential reserves are very large, although quarrying may be difficult because of rugged topography. Samples from the Alexo Formation and Fairholme Group proved to be very dolomitic and not suitable for industrial use.

BLAIRMORE AREA

The Blairmore area is located in the Crowsnest Pass region 10 miles east of Crowsnest Lake, on the main Canadian Pacific Railway line and Highway No. 3 (Fig. 4-1). Mississippian strata are exposed within a doubly plunging anticline, which forms an outlier of the main ranges of the Rocky Mountains to the west (Norris, 1963). Beds exposed along the railway on the west flank of the anticline strike north and dip west as much as 60 degrees (Fig. 4-4).

Two quarries have operated within beds of the Livingstone Formation—one south of the railway to supply a cement plant, and another north of the railway for producing lime. The former was described in some detail by Goudge (1945).

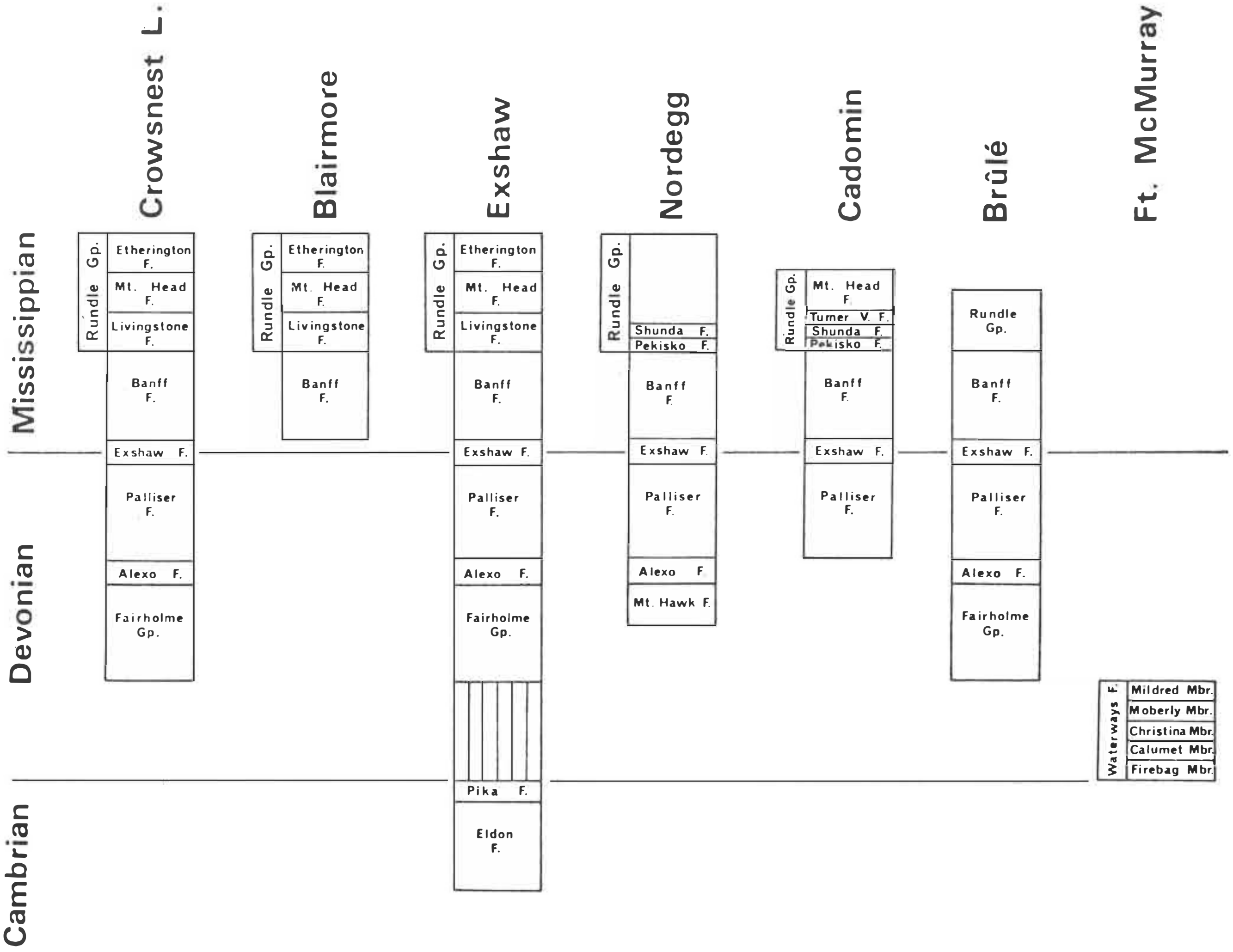

Figure 4-2.—Table of formations.

Sections of the Banff and Livingstone Formations were sampled along the railway. The Banff Formation contains numerous argillaceous, cherty and dolomitic beds and is therefore of no interest for exploitation. Approximately 400 feet of the Livingstone Formation is exposed, and the limestone is generally of high grade, but interbeds of siliceous and dolomitic strata tend to make definition of high-calcium limestone deposits difficult. Medium-sized reserves of limestone are available in positions that are relatively easy to quarry.

EXSHAW AREA

The Bow River valley between the eastern margin of the Rocky Mountains Front Ranges and Banff National Park is the major limestone-producing area of Alberta, and undeveloped deposits extend across the strike of the Front Ranges for a distance of 15 miles (Fig. 4-5). Exshaw is situated near the eastern margin of the Front Ranges, adjacent to the main transcontinental line of the Canadian Pacific Railway and to Highways 1 and 1A (Fig. 4-1).

Near Exshaw, the Front Range of the Rocky Mountains exposes a thick succession of Paleozoic carbonate strata ranging in age from Cambrian to Mississippian (Fig. 4-5). The strata lie above the McConnell Fault, strike northwest, and dip 30° to 60° southwest. To the west the succession is repeated by three major thrust faults. The most recent bedrock geology compilation was by Price (1970).

Quarries now are operating at Exshaw (Canada Cement Lafarge Limited) in Palliser beds and on Grotto Mountain 4 miles east of Canmore (Steel Brothers Limited, Lime Division) in Livingstone strata. Quarries for supplying lime plants formerly were located in beds of the Eldon Formation east of Exshaw and within the Livingstone Formation on Grotto Mountain. Canada Cement Lafarge Limited quarries approximately 2,400 tons

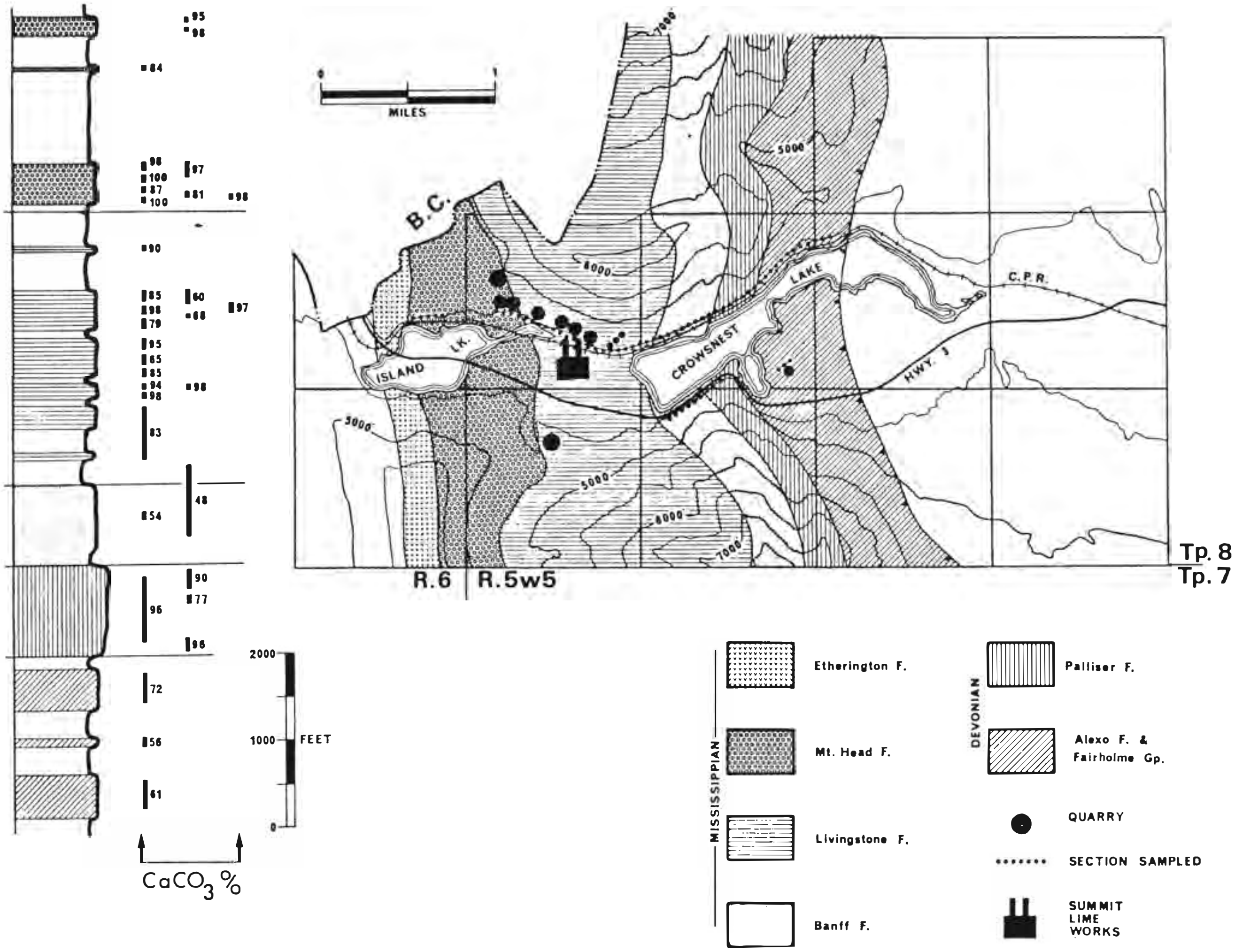

Figure 4-3.—Crowsnest Lake area.

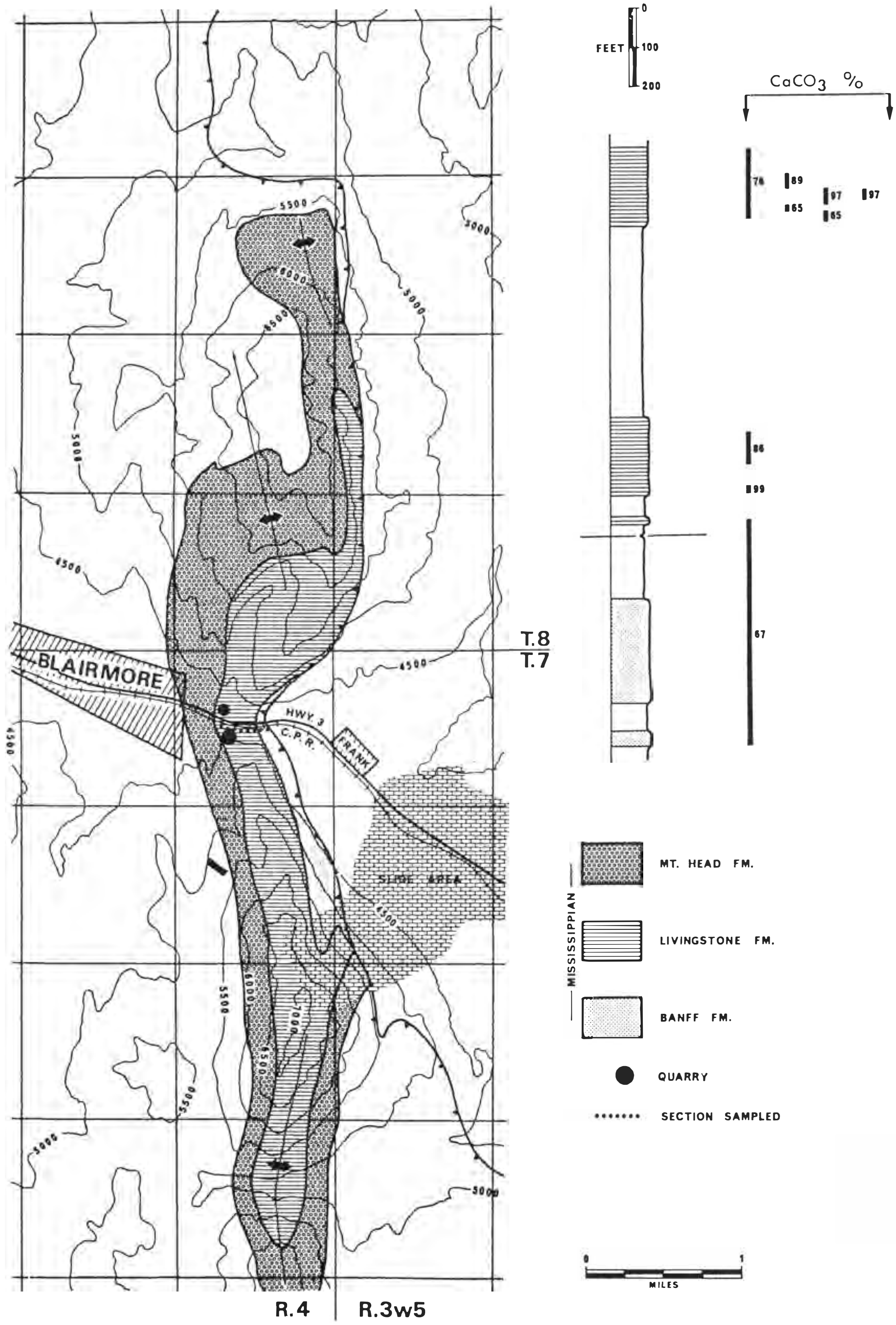

Figure 4-4.—Blairmore area.

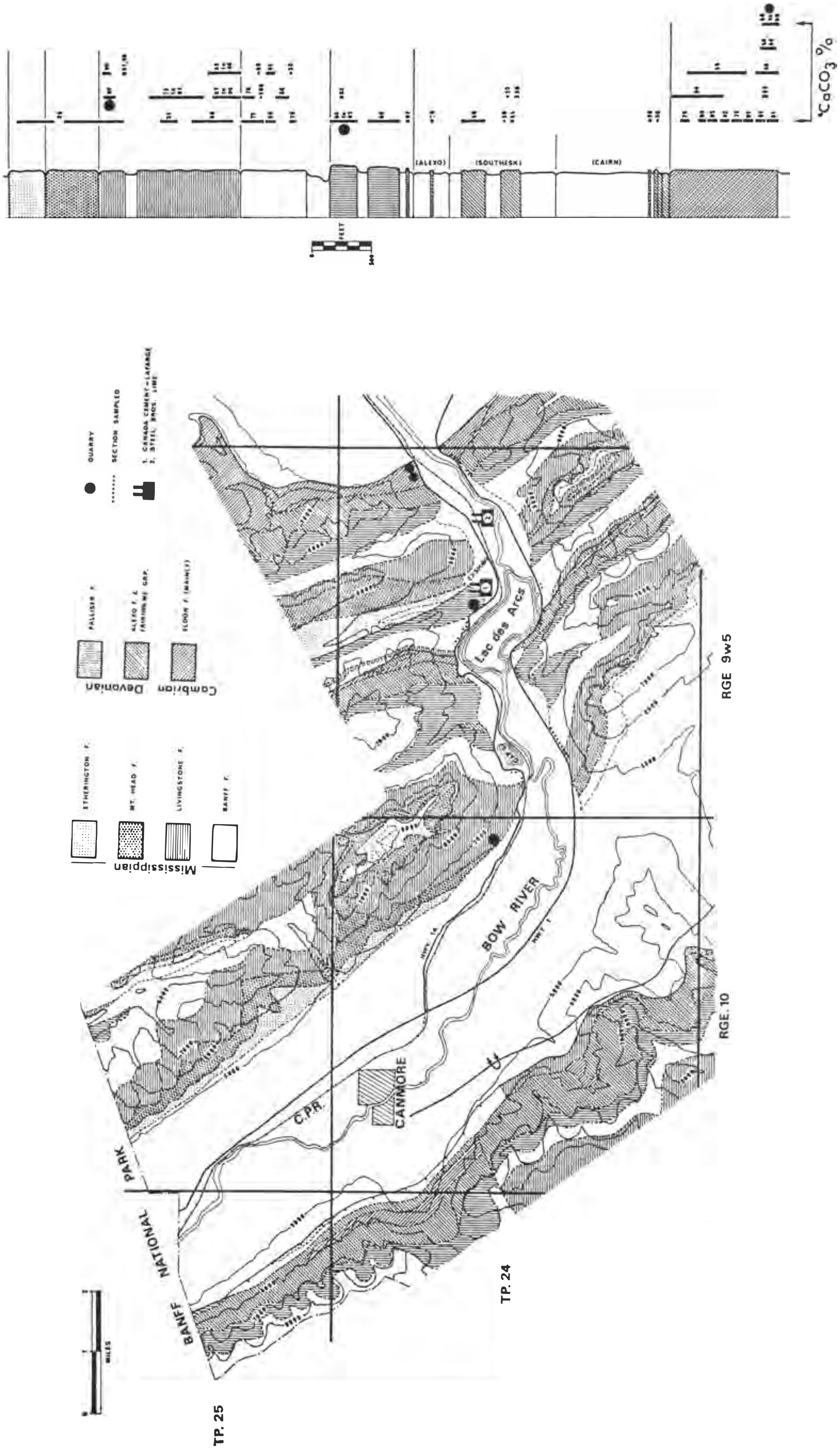

Figure 4-5.—Exshaw area.

of limestone per day for cement manufacturing, and Steel Brothers Limited produces about 1,000 tons per day for lime-making and aggregate.

Sections through the major limestone-bearing formations exposed along Highways 1 and 1A were measured and sampled (Fig. 4-5). The total stratigraphic thickness of section involved is approximately 6,500 feet, of which approximately 2,000 feet contains potential commercial limestone beds. In addition, samples were obtained from the quarries listed above and from the Eldon Formation north of Kananaskis (Sec. 12, T. 25, R. 9) and Mississippian strata exposed in Cougar Canyon east of Canmore (Sec. 34, T. 24, R. 10). These data supplement previous work by Goudge (1945) and by Matthews (1960), who sampled the Livingstone Formation on Heart Mountain (Sec. 13 and 24, T. 24, R. 9).

The Eldon Formation is nearly 1,000 feet thick in the Exshaw area. Considerable amounts of dolomitic mottling are found throughout the section, thus resulting in reduced grades in many places. Reserves of good quality rock, free of dolomitization effects, are large, but easily quarriable localities are not common.

The entire succession of the Alexo Formation and Fairholme Group exceeds 2,000 feet. Less than 25 percent of the section was studied, and no limestone beds were delineated.

The Palliser Formation is about 700 feet thick and ranges in grade from 68 to 97 percent $CaCO_3$. Both dolomitic and calcareous sections tend to be thick and consistent in chemical composition. Therefore, where high-calcium limestone successions can be verified, little contamination by dolomitic strata is likely. There is scope for much further study of the Palliser Formation to define reserves more fully.

The Banff Formation, approximately 700 feet thick, is generally thin bedded. Content of $CaCO_3$ is variable, and although selected beds of limestone are of very high grade, they do not constitute meaningful reserves.

The Livingstone Formation is approximately 1,200 feet thick, and sections as much as 100 feet thick contain high-calcium limestone, particularly near the top of the formation. The limestone strata are medium to thin bedded and contain siliceous and magnesian interbeds. Large reserves of readily quarriable limestone have been outlined west of Gap Lake, east of Exshaw, and on Heart Mountain.

The Mount Head and Etherington Formations (500 feet and 300 feet thick, respectively) were sampled at Cougar Canyon, west of Canmore. X-ray fluorescence analyses of individual samples verify $CaCO_3$ contents of as much as 98 percent in the Mount Head Formation, but no prospective quarry sites were noted. The Etherington Formation contains large amounts of chert, which greatly diminishes the grades.

NORDEGG AREA

The Nordegg area is situated in the central Alberta Foothills about 100 miles east of the city of Red Deer. The area is crossed by Highway 11 (David Thompson Highway) and also can be reached by a local Canadian National Railway line, which extends west from Rocky Mountain House (Fig. 4-1). Since closure of the Brazeau Collieries at Nordegg in the 1950's there has been no regular rail service.

Devonian and Mississippian carbonate strata are exposed in the core of the northwest-trending Brazeau Anticline, a Paleozoic outlier, which marks the inner Foothills boundary (Fig. 4-6). Beds on the northeast flank of the structure are faulted out along the Coliseum Fault and overturned at steep angles. The southwest limb generally dips at angles less than 20 degrees (Douglas, 1956, 1958; Erdman, 1950).

Two quarries are located within the area, and both have served as sources of railway ballast. The smaller of the two is in the Palliser Formation at Mile 147 on the railway (Fig. 4-7), and the larger, which is close to Nordegg, is located in strata of the Pekisko Formation.

Good exposures are found adjacent to the railway, and a few small outcrops are present along Highway 11 (Fig. 4-7). Goudge (1945) obtained samples for analysis along the railway and within the quarry near Nordegg. Matthews (1960) also carried out detailed studies on the quarry. Samples were obtained for the present study to complement existing data.

Devonian rock units have little potential for economic development. Uppermost strata of the Mount Hawk Formation were sampled along Highway 11, but the rocks are extremely dolomitic. The Alexo Formation, overlying the Mount Hawk Formation and sampled at the same location, is also of very low grade. The Palliser Formation exceeds 800 feet in thickness and is well exposed along the railway on both flanks of the Brazeau Anticline. No beds of high-calcium limestone were delineated within the formation.

More than 700 feet of Banff Formation carbonate and shale is present in the area. Representative beds were

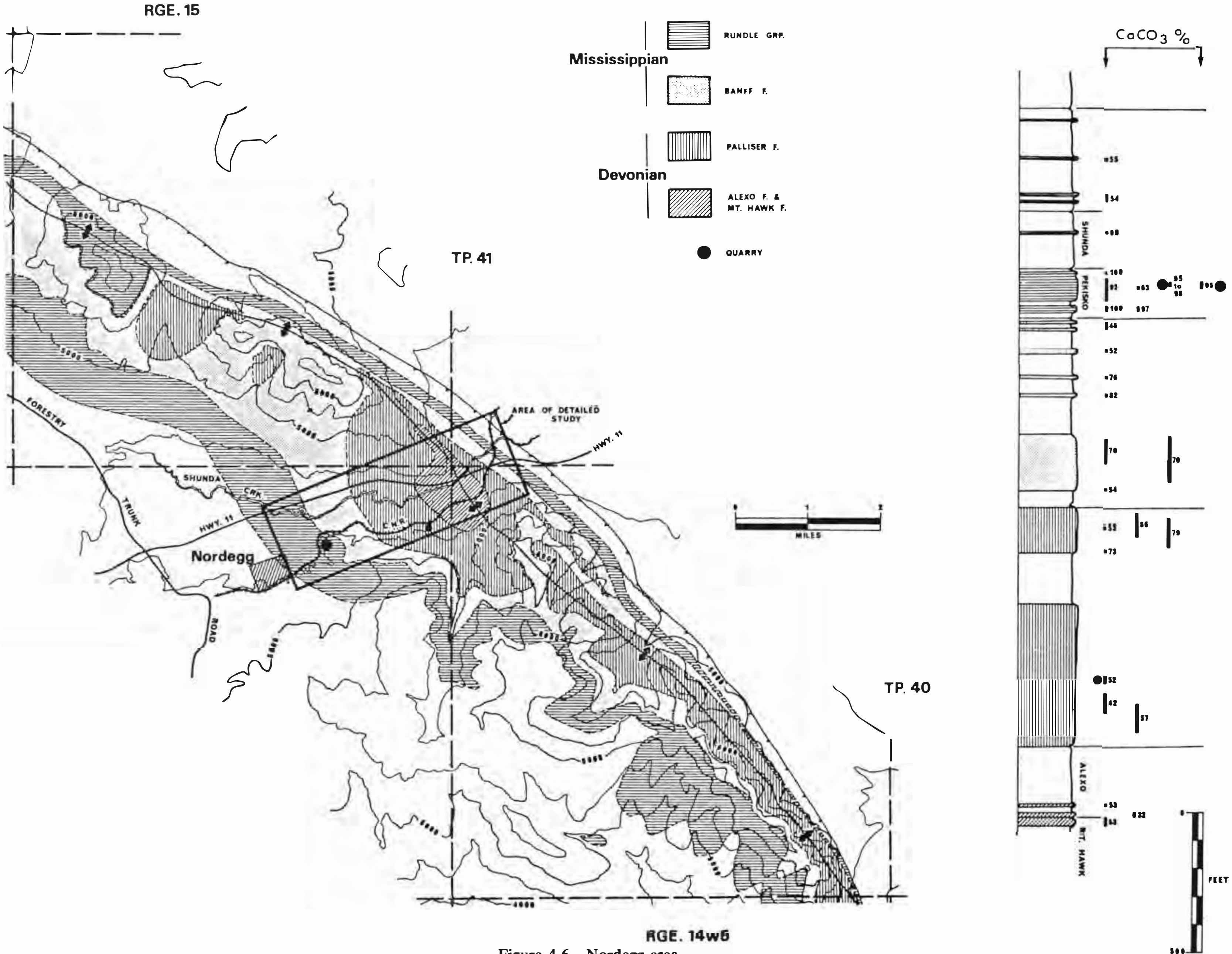

Figure 4-6.—Nordegg area.

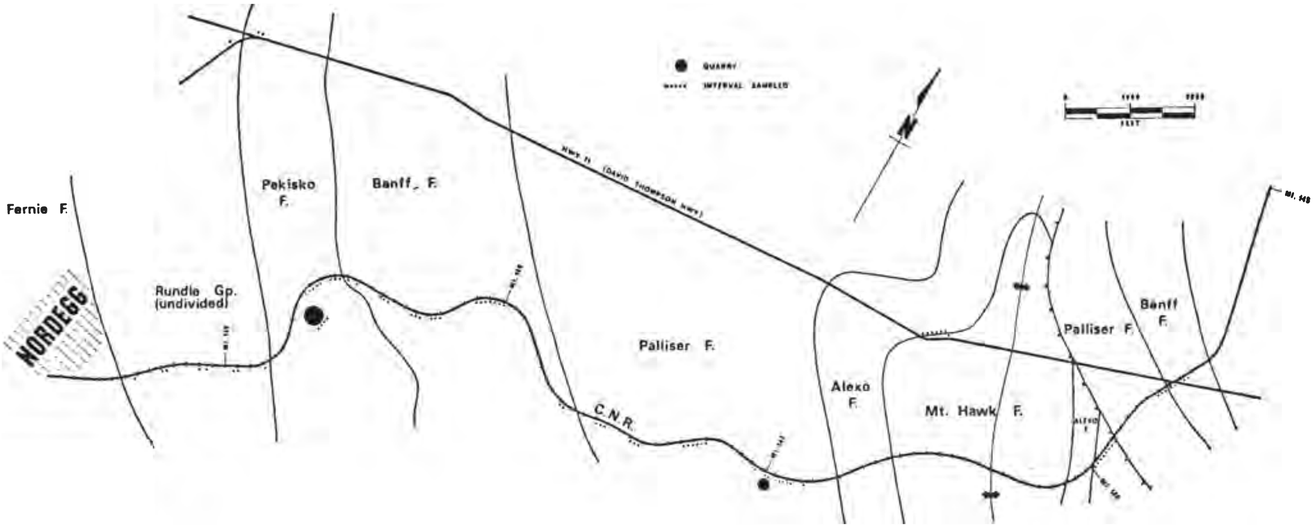

Figure 4-7.—Quarries and intervals sampled in the Nordegg area.

sampled along the railway, but the analyses indicate consistently low calcite contents.

The Pekisko Formation, which is less than 200 feet thick in the Nordegg area, is of good to excellent grade (normally greater than 95 percent $CaCO_3$). Good exposures are present in readily quarriable positions. Approximately 200 feet of the Shunda Formation is present in the area, but only one exposure was observed along the railway. The samples graded 98 percent $CaCO_3$, indicating that the formation deserves further investigation.

Upper strata of the Rundle Group crop out along the railway east of Nordegg, but because of high magnesia content, none of the beds tested are of economic importance.

CADOMIN AREA

The Cadomin area lies within the inner Foothills of west-central Alberta about 190 miles southwest of Edmonton (Fig. 4-1). Part of the so-called "Coal Branch", the area is served by a local line of the Canadian National Railways and by Highway 47, which extends southwest from the town of Edson on the main transcontinental line of the CNR.

At Cadomin, Paleozoic carbonate-bearing strata are exposed along the crest of the Nikanassin Range, a southeast-plunging anticlinal structure thrust northeastward over complexly folded and faulted Cretaceous strata. The Paleozoic strata dip southwesterly at attitudes averaging about 40 degrees, and the section is repeated in part by a secondary thrust fault lying to the south of the trace of the main Nikanassin fault (MacKay, 1929b).

In the past a small quarry operated in the Palliser Formation, adjacent to the railway about 1 mile south of Cadomin, to supply a local lime plant. Currently, the Inland Cement Company operates a much expanded quarry on the same site. Formerly, the company opened a smaller quarry in Palliser beds south of the existing quarry in the "southern" thrust block, but this no longer is utilized. Inland Cement now mines approximately 2,000 tons of highgrade limestone per day at its Cadomin operation, transporting it to Edmonton for processing in the company's cement plant.

The two Inland Cement Company quarries described above present an almost complete succession of the Palliser Formation and therefore were sampled in some detail (Fig. 4-8). Additional sections of this formation were sampled on the opposite side of the McLeod River valley. Halferdahl (1967) also sampled exposures of the Palliser Formation on Leyland Mountain 2 miles west of the Inland Cement quarry. Mississippian carbonate strata are accessible south of the existing quarries along the railway and also on the opposite side of the valley.

The Palliser Formation is about 600 feet thick in the Cadomin area. Beds in the quarries contain as much as 96 percent $CaCO_3$ within 50- to 100-foot sections of composite sampling. Some problems are encountered with dolomite in the form of scattered mottling in limestone successions ranging from 20 to 100 feet thick. Sections sampled across the valley show lower $CaCO_3$ content (less than 92 percent). The Palliser beds studied by Halferdahl are of good to excellent grade (mainly 95 percent or greater $CaCO_3$). Reserves of limestone in the Palliser

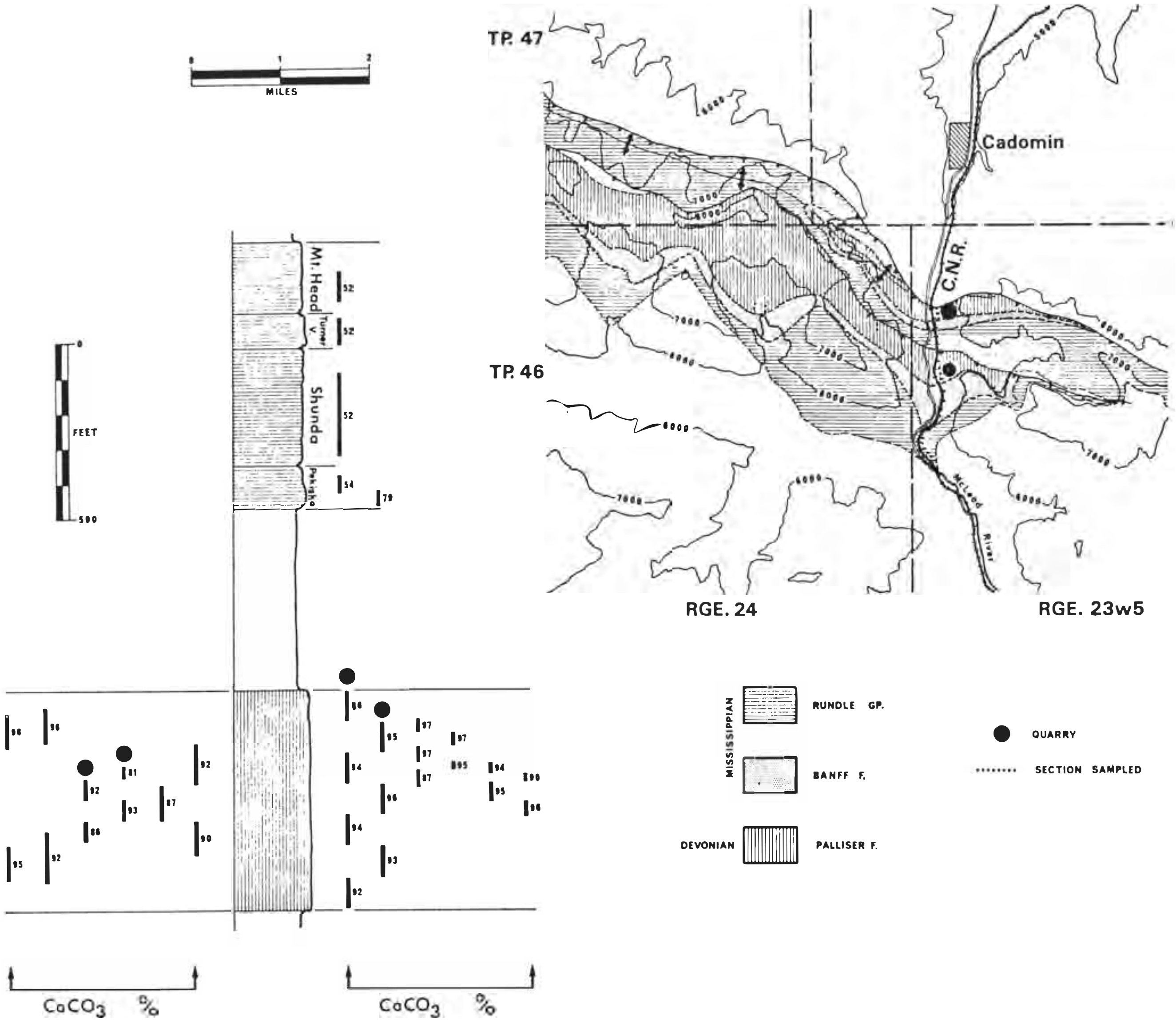

Figure 4-8.—Cadomin area.

Formation are large, but future quarry sites are scarce owing to rugged topography.

The Banff Formation is very argillaceous and thin bedded and is not recommended for evaluation. Rundle Group strata proved to be consistently low in $CaCO_3$ in sections sampled on both sides of the McLeod River.

BRÛLE AREA

Brûlé, a former coal-mining area, is on the main transcontinental line of the Canadian National Railway, about 190 miles west of Edmonton near the eastern boundary of Jasper National Park (Fig. 4-1). The region is also adjacent to Highway 16 (Yellowhead Highway), which extends along the south side of the Athabasca River valley.

Devonian and Mississippian limestone and dolomite beds are exposed along the Front Ranges of the Rocky Mountains and in the core of the Folding Mountain Anticline, a Paleozoic outlier 2 miles east of the Jasper Park boundary on Highway 16 (Fig. 4-9). The regional strike of the beds is northwest, and dips range between 30 and 60 degrees southwest. There is much structural complexity in the form of small-scale folding and thrusting. Carbonate strata along the mountain front are bounded to the east by the Brûlé Thrust Fault, and the adjacent Perdrix Fault has resulted in repetition of some of the section (Lang, 1947; Mountjoy, 1959).

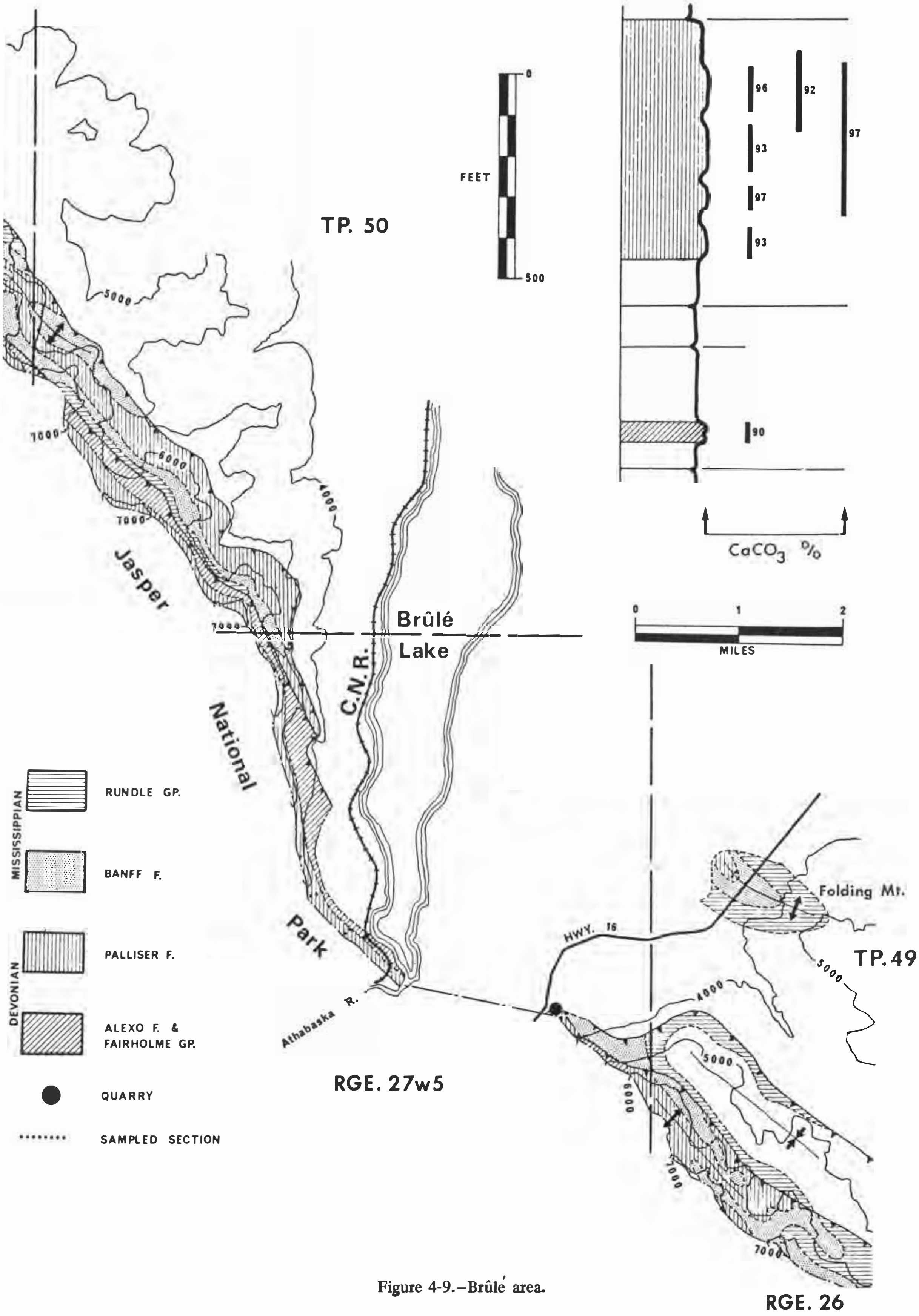

Figure 4-9.—Brûlé area.

A small quarry, just east of the Jasper Park boundary on Highway 16, has been developed in the Palliser Formation as a source of riprap for local construction. There has been no large-scale quarrying of limestone for industrial uses, although the carbonate strata of the area have been investigated for this purpose (Goudge, 1945).

Rugged topography and heavy vegetation cover limit the access to sections in the area. Among the formations successfully sampled are beds of the Mount Hawk Formation adjacent to the railway and the Palliser Formation limestone west of the railway, at Folding Mountain, and within the quarry near Highway 16.

The Mount Hawk Formation, 300 feet thick, contains limestone that analyzes 90 percent $CaCO_3$ over a 50-foot section. Although grades are low, there is some merit in further evaluation of the formation. The Brûlé area seems to be the only area in western Alberta in which Devonian beds stratigraphically lower than the Palliser Formation have economic potential.

The Palliser Formation, approximately 700 feet thick, contains medium- to high-calcium limestone in sections sampled at the southwest end of Brûlé Lake (92 to 96 percent $CaCO_3$) and the quarry near Highway 16 (97 percent $CaCO_3$). Although reserves are large, some difficulty may be posed in establishing quarry sites west of Brûlé Lake. Samples from Folding Mountain indicate low-calcium rock, and beds containing chert nodules are common.

FORT McMURRAY AREA

The Fort McMurray area is situated in northeastern Alberta at the junction of the Athabasca and Clearwater Rivers, about 300 miles northeast of Edmonton (Fig. 4-1). The area is renowned for its large reserves of oil sands found in the McMurray Formation of Early Cretaceous age. The area can be reached by the Northern Alberta Railway, which extends from Edmonton to Fort McMurray, and by Highway 63 (Fig. 4-10).

The limestone resources of northeastern Alberta are found in Devonian carbonate strata, which underlie the Cretaceous oil sands throughout the Fort McMurray region. These strata (Waterways Formation) are exposed in the major river and stream valleys wherever erosion has cut through the mantle of Pleistocene drift and Cretaceous bedrock, for example, along the Athabasca and Clearwater Rivers. Outcrops of the Waterways Formation (Calumet, Christina, and Moberly Members) are within

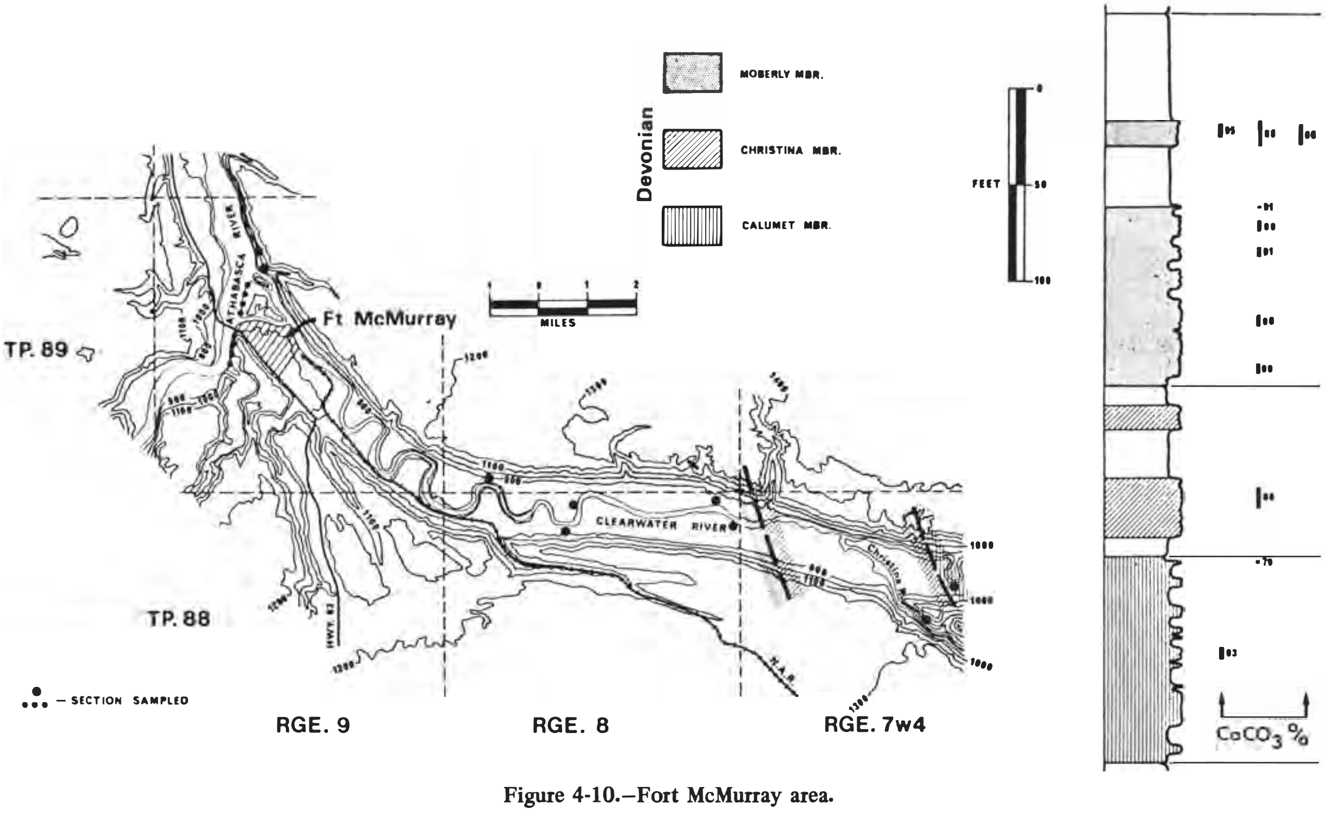

Figure 4-10.–Fort McMurray area.

easy reach of Fort McMurray. The beds are nearly flat lying except for minor local flexures induced by solution of underlying salt deposits, and they dip southwest beneath the cover of Cretaceous strata. Downstream from Fort McMurray on the Athabasca River and about 40 miles upstream on the Clearwater River, the Waterways Formation is succeeded at the surface by older Middle Devonian strata–mainly dolomite, gypsum, and some calcareous beds. Norris (1963) presented the most recent and detailed study of the Devonian geology of the area.

The limestone deposits of the Fort McMurray area remain undeveloped, and only a few analytical data concerning their composition and properties have been published (Carrigy, 1959). Samples for the present study were collected from Devonian strata exposed along the Athabasca River near Fort McMurray and along the Clearwater River upstream from Fort McMurray to a point just beyond the mouth of Christina River (Fig. 4-10). Outcrops in this area are generally low (less than 20 feet), discontinuous shelves or benches of hard calcareous beds, which provide only partial successions of strata for measurement. Limestone of the Waterways Formation exposed along the Athabasca River downstream from Fort McMurray has not been sampled or analyzed.

The Calumet Member of the Waterways Formation is about 100 feet thick. One sample obtained from strata near the middle of the formation, 10 miles east of the mouth of the Christina River, contains 93 percent $CaCO_3$ (Carrigy, 1959). A sample obtained by the writer near the top of the formation 2 miles east of the mouth of the Christina River is of very low grade (79 percent $CaCO_3$).

The Christina Member, 100 feet in thickness, was sampled on the Christina River, but analyses indicate low-quality rock (66 percent $CaCO_3$). Although analyses of spot samples grade as high as 91 percent $CaCO_3$, thin beds containing excessive iron and silica reduce the overall grade.

The Moberly Member is nearly 200 feet thick in the Fort McMurray area. The lower part of the formation was sampled at outcrops along the Clearwater River. Stratigraphically higher beds were sampled at good exposures along the Athabasca River near the mouth of the Clearwater. The analyses show 86 to 95 percent $CaCO_3$. Magnesia content is moderate (less than 5 percent $MgCO_3$), and the relatively low amounts of $CaCO_3$ are due in part to high silica contents (2 to 5 percent). Large reserves of limestone are available, and quarrying conditions are favorable.

CONCLUSION

Alberta has abundant reserves of high-calcium limestone, and future development is feasible in seven areas of the province. In the Crowsnest and Exshaw areas, large reserves are exploitable in the Livingstone and Mount Head Formations, and in the Palliser Formation. At Blairmore and Nordegg, high-grade beds are confined to strata equivalent to the Livingstone Formation. The Cadomin and Brûlé areas have large reserves of good-quality limestone in the Palliser Formation. In the Fort McMurray area, within the Moberly Member of the Waterways Formation, limestone of good to moderate quality can be developed. The variability of the rock in each area, however, necessitates detailed evaluation to define the quality and extent of actual reserves.

The writer acknowledges personnel of Summit Lime Works Limited, Crowsnest Pass; Steel Brothers Canada Limited, Lime Division, Exshaw; the Canada Cement Lafarge Company, Exshaw; and the Inland Cement Company, Cadomin, for their cooperation during investigations of quarries.

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SASKATCHEWAN POTASH IN 1975–AN UPDATE ON OUR KNOWLEDGE

Colin E. Dunn*

ABSTRACT

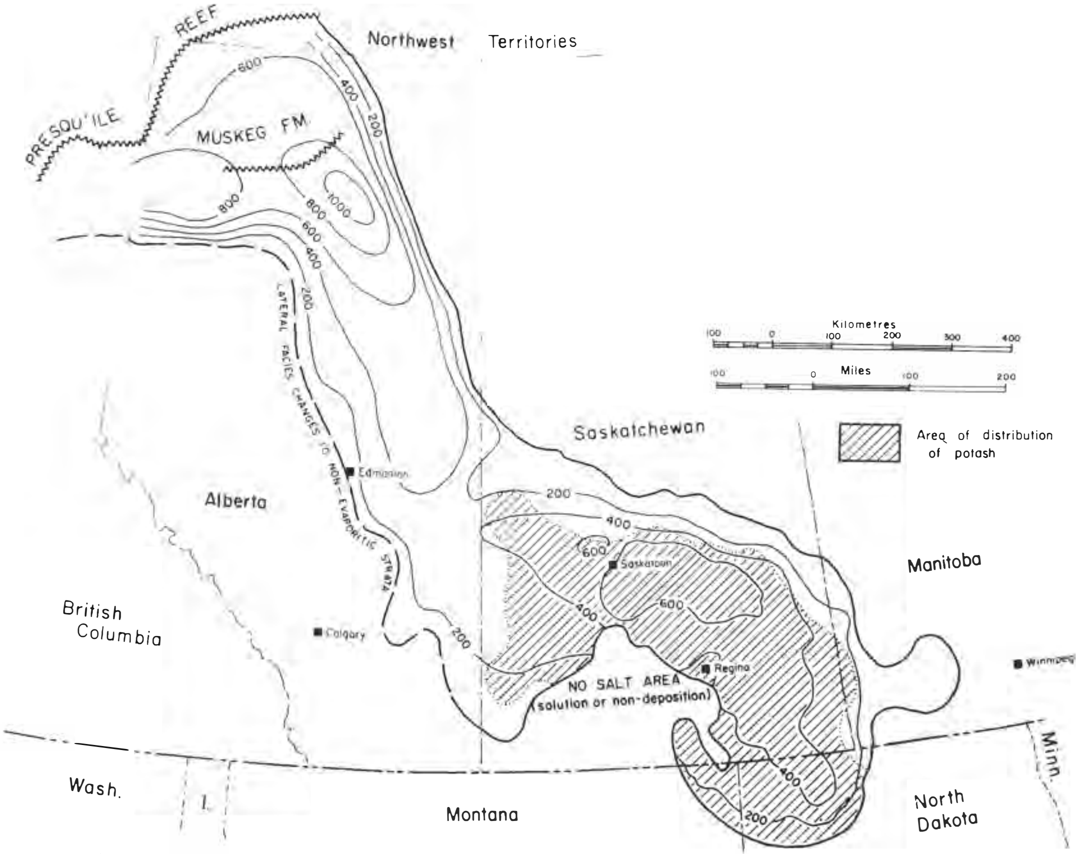
Since the discovery in 1943 that Saskatchewan has potash deposits within the Prairie Evaporite (Middle Devonian), three potash-rich seams have been exploited. Sylvite is the desired mineral, but a small quantity of carnallite can be tolerated. Other potassium and magnesium evaporites are absent. Although the basic geology is understood, details are still being unraveled as more holes are drilled, more seismic work is carried out, and the nine conventional mines and one solution mine continue to expand.

Geological problems include (1) the significance of the underlying carbonate banks–are they potential hazards if acting as hydrocarbon reservoirs? (2) the proximity of overlying clay seams and water-bearing strata; (3) the distribution of solution 'sinks' and 'salt-horses'; (4) the significance of Rb and Br distributions through the evaporites; (5) rates of subsidence over the mines.

The estimated recoverable 74 billion short tons K_2O represents, at the current rate of extraction, guaranteed income for the Province for thousands of years. A Crown Corporation, the Potash Corporation of Saskatchewan, has recently been established, and the government is giving consideration to participating in the potash industry.

INTRODUCTION

It was an oil exploration drill hole in 1943 that first chanced upon potash ore in Saskatchewan. This was near Parry, about 50 miles south of Regina (Fig. 5-1), at a depth of 7,500 feet. Although too deep for commercial exploitation, it did spark interest farther to the north



After M.E.Holter (1969)

Figure 5-1.–Isopach map of the Prairie Evaporite in the Elk Point Basin.

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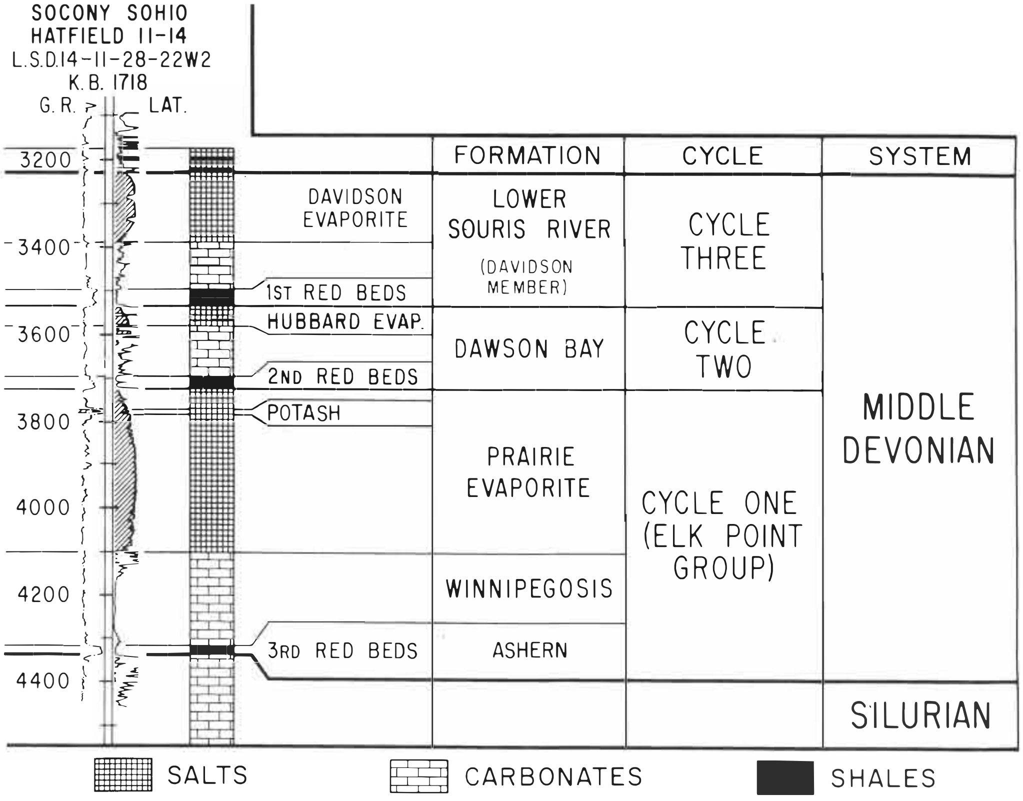
*Saskatchewan Geological Survey, Regina, Saskatchewan.

where the same stratigraphic unit occurs at shallower depths. Three years later, core grading 21.6 percent K_2O over an 11-foot section was encountered at about 3,500 feet near Unity, 100 miles west of Saskatoon. At this depth commercial development became a distinct possibility, and in 1951 the Western Potash Corporation attempted to set up a solution mine in the Unity district. The technique employed proved unsuccessful, so the next year a shaft was begun. The operation was beset with problems and was finally abandoned eight years later when the shaft was inundated by water from the overlying Blairmore sands of the Cretaceous. Meanwhile extensive exploration was taking place in the Saskatoon area, and the Potash Company of America succeeded in sinking a shaft from which the first commercial potash was brought to the surface at the end of 1958.

Canadian, American, and European companies have commenced more conventional mining operations in the Saskatoon District, and close to the Manitoba border (near Esterhazy) where the International Minerals and Chemical Corporation (Canada) Limited operates the world's largest potash mine. Solution mining is being successfully carried out just to the west of Regina at Belle Plaine.

STRATIGRAPHY AND SEDIMENTOLOGY

Potash salts occur within the Prairie Evaporite (Middle Devonian) (Fig. 5-2). This formation is a major part of the Elk Point Group of sediments, which were deposited in a basin that extended over a thousand miles [from northernmost Alberta southeastwards into North Dakota (Fig. 5-1)]. Locally, the Prairie Evaporite exceeds 700 feet in thickness, and in Saskatchewan it lies at a depth of 1,300 feet at its northernmost subcrop and about 9,000 feet in the southeast (Fig. 5-3). These evaporite beds rest conformably upon carbonate rocks of the Winnipegosis Formation (Fig. 5-4) and locally they are draped over banks, which may extend several hundred feet above



After D.M. Lane (1959)

Figure 5-2.–Columnar section showing Middle Devonian evaporite cycles.

the laminated carbonate beds that characterize the Winnipegosis. Resting upon these laminated carbonate beds are laminated anhydrite beds, which contain abundant disseminated bituminous or argillaceous material.

The sediments of the Prairie Evaporite are dominated by halite, with which minor amounts of anhydrite and carbonate are associated. The potash salts occur in the upper part at three levels (Fig. 5-4) (in ascending order: the Esterhazy Member, as much as 103 feet thick; the Belle Plaine Member, as much as 151 feet thick; and the Patience Lake Member, as much as 88 feet thick). Figure 5-4 shows that these beds are eroded in the east and taper out to the west.

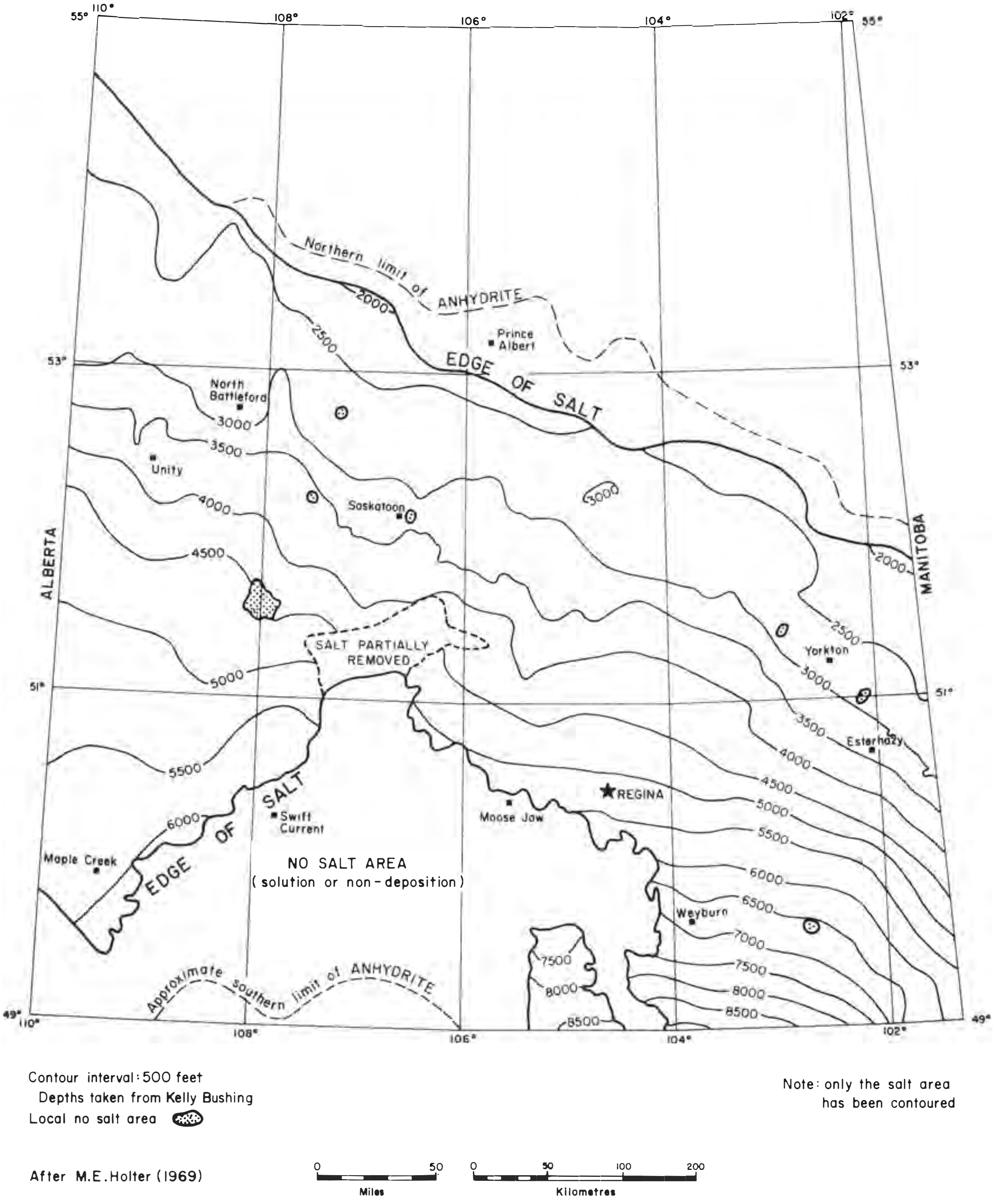


Figure 5-3.—Depth of burial of the Prairie Evaporite in Saskatchewan.

The salts of the Prairie Evaporite generally have an irregular but sharp contact with the overlying red beds, which constitute the basal 20 to 30 feet of the Dawson Bay Formation (Fig. 5-5a). Locally the contact is diffuse (Fig. 5-5b), suggesting mixing of the uppermost salts during deposition of the superposed terrigenous material.

The nature of the beds that overlie and underlie the Prairie Evaporite is of prime concern in a discussion of Saskatchewan's potash, because the economics and safety of a potash mine are considerably dependent upon the fluid content of these confining strata. These problems will be discussed later.

DEPOSITIONAL HISTORY

The Prairie Evaporite is thought by many to represent the closing stage of a major cycle of deposition. Most interpretations suggest that the cycle commenced with red-bed deposition (the Ashern Formation) followed by a marine incursion and the deposition of Winnipegosis Formation carbonate. Toward the end of "Winnipegosis" times the Presqu'ile barrier reef developed across the northern entrance to the Elk Point Basin (Fig. 5-1), greatly restricting access of marine water to the basin. Large carbonate banks within the basin further restricted water circulation. Figure 5-6 is a hand-smoothed computer-plotted version of an isopach map of the Winnipegosis Formation, which serves to emphasize the positive features (i.e., banks), and thus gives some impression of the topography at the end of "Winnipegosis" times, hence the sort of local features that inhibited water circulation during "Prairie Evaporite" time. Sulphate precipitation took place followed by the deposition of a considerable thickness of halite that probably rapidly infilled the relief, accumulating in what was by then a huge hypersaline inland sea. The last stages of evaporation are represented by the highly soluble salts of potassium and magnesium, which precipitated at the southeastern end of the basin. Alternation of evaporite strata is an indication that brine was periodically freshened by incursions, or by circulation, of less salty water. Small-scale cycles are indicated by the periodic appearance of veneers of clay minerals and anhydrite in cored sections of halite (Fig. 5-5c).

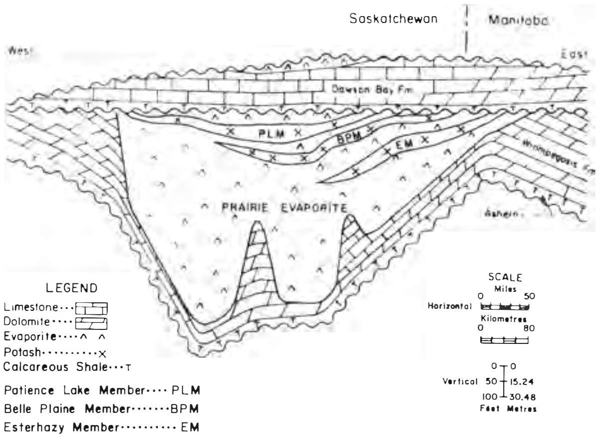


Figure 5-4.—Diagrammatic cross section of the Prairie Evaporite and adjacent formations in the commercial potash area of Saskatchewan (modified after Christopher and others, 1971).

After evaporite deposition there was probably emergence and some erosion before the evaporite beds were sealed by the argillaceous deposits of the basal part of the Dawson Bay Formation. These red beds are generally thought to represent the start of a new cycle of sedimentation, but a case can be made for treating them as the final stage of the sedimentary cycle, the new cycle commencing at the marine transgression over the red beds.

MINERALOGY AND GEOCHEMISTRY

The Prairie Evaporite comprises, in ascending order, anhydrite (much of it mixed with carbonate), halite, and sylvite. Mixtures of these minerals result in interbedded dolomite and anhydrite, lenses of anhydrite in halite, and 'sylvinite'—a mixture of sylvite and halite. Carnallite is locally present forming 'carnallitite' where mixed with halite. Clay minerals are disseminated throughout, but become increasingly common in the upper part of the formation, appearing as seams and beds and interstitially between salt crystals.

Unlike most other potash deposits of the world, the mineralogy of the Saskatchewan deposits is simple. Only halite, sylvite, and carnallite are present, and the potassium and magnesium sulphates typical of the classic German Stassfurt deposits are apparently absent.

The halite may be transparent, translucent, brownish, grayish, or reddish where associated with traces of iron oxides. Chevron crystals are present, and patches of blue or violet halite locally occur. The blue coloration is due, not to the incorporation of trace impurities, but to slight distortion of the crystal lattice (Przibram, 1954).

Sylvite is the desired mineral, as it is almost pure KCl. It occurs mainly as cloudy white or pinkish anhedral crystals as large as 1½ inches. Its lustre is vitreous, and many crystals have reddish rims owing to the incorporation of fine-grained iron oxides.

Carnallite ($KMgCl_3 \cdot 6H_2O$) in Saskatchewan ranges from white to yellow to red to translucent black. It is deliquescent and may leave traces of its former presence in the form of a pinkish somewhat metallic-looking insoluble residue. Mine operators try to avoid ore combining abundant carnallite and insoluble residues, because of their detrimental effects on mine stability, ore grades, and refining processes. Carnallite can contain 8.7 percent (by weight) magnesium, however, so it has economic potential in its own right.

Greatest developments of carnallite occur toward the northern limits of the potash subcrop, at depths of a little below 3,000 feet. The uppermost two potash members are the richest sources, which are well developed in a belt 15 to 30 miles wide by 150 miles long, extending southeast from the area around Saskatoon. Lateral and vertical changes from carnallitite to sylvinite are abrupt, and there are local pods of carnallite in the sylvite. Petrographic and geochemical studies (e.g., Schwerdtner, 1964; Streeton, 1967; MacIntosh, 1967; Wardlaw, 1968) suggest that the sylvite is secondary after carnallite, and locally there has been nucleation of sylvite into lenses or pods, owing to magnesium chloride dewatering of the carnallite. The net effect is considerable variation in the distribution of magnesium over short distances.

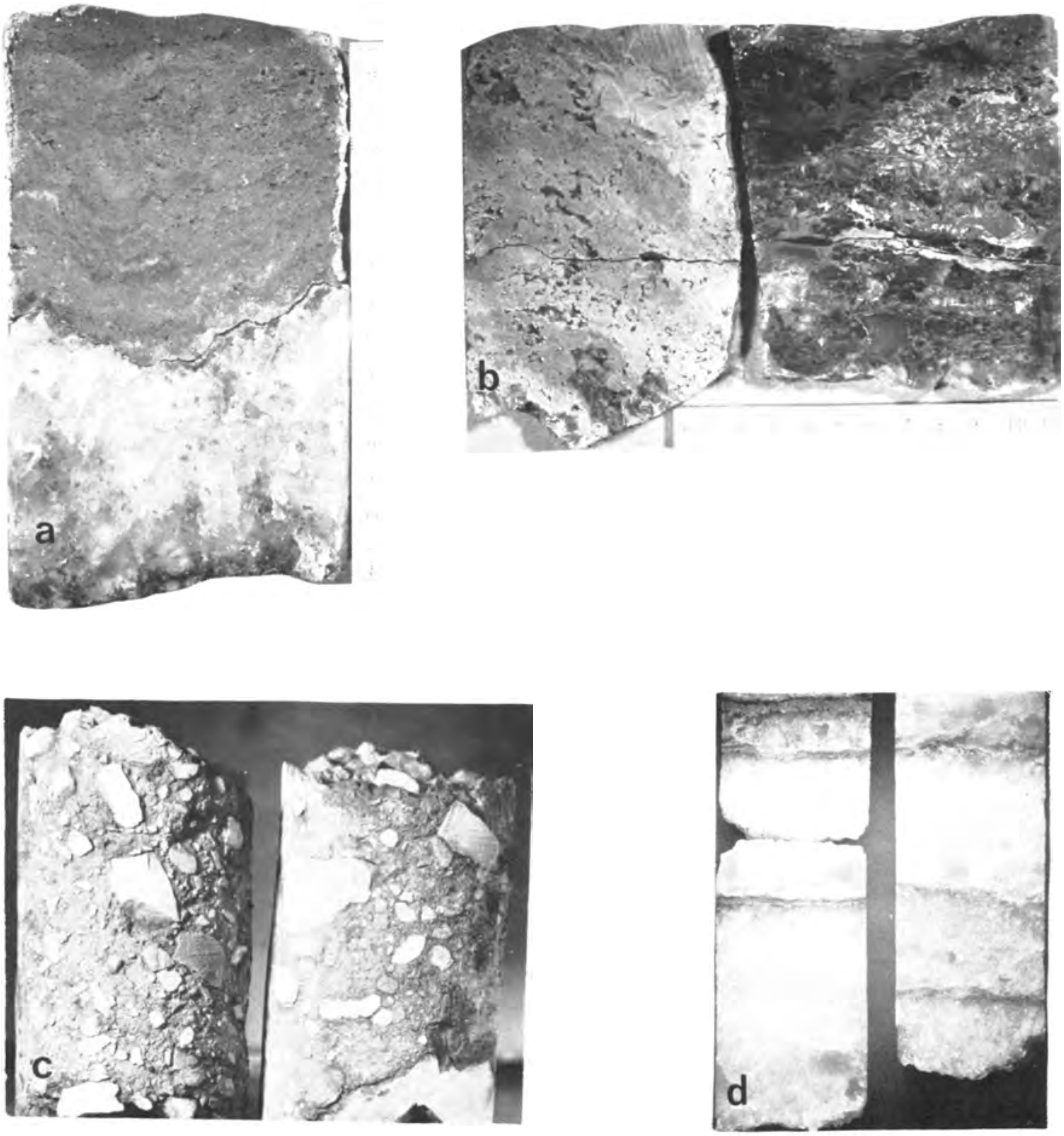


Figure 5-5.—Photographs of drill cores. (a) Sharp contact between the "Second Red Beds" of the Dawson Bay Formation and underlying halite of the Prairie Evaporite; (b) Transitional contact between the Dawson Bay Formation and the Prairie Evaporite; (c) Breccia of carbonate fragments set in a red mudstone matrix, basal part of Dawson Bay Formation (4-inch core); (d) Halite 'cycles' in the Prairie Evaporite (2-inch core).

Geochemical affinities permit the substitution of bromine for some chlorine, and rubidium for some potassium in the potash minerals. Studies of bromine and rubidium distributions in minerals have thrown useful light upon the origins of evaporite deposits, because the quantities of the two elements retained in the salts bear a definite relationship to the Br and Rb in the original brine (Braitsch, 1962). The bromine/chlorine ratio in crystals increases with increasing salinity, so in theory the acmes of salinity can be deduced by determining the points of maximum bromine/chlorine ratios. Whereas the relationship follows the theory in some natural deposits, such is not the case with the Prairie Evaporite (e.g., Van der Plank, 1962; Schwerdtner, 1964; Wardlaw, 1964, 1968; Streeton, 1967). In both sylvite and carnallite the bromine values are lower than they would be in primary precipitates; rubidium values are too high in sylvite and about right in carnallite. The conclusion reached has been that nearly all crystals must be secondary in order to account for the present trace-element distributions. Petrofabric studies support this interpretation (Clark, 1964).

WINNIPEGOSIS BANKS

In recent years attention has been drawn to the possible hazards connected with Winnipegosis carbonate banks (Baar, 1974), because they are porous and extend upwards into the Prairie Evaporite, attaining heights of 350 feet above the inter-bank evaporites. Winnipegosis interbank sedimentary rocks are organic rich and locally contain oil in small quantities, hence the banks would seem to be ideal hosts for oil and gas accumulation. In view of the fact that the banks locally lie only a short distance beneath the potash ore zones, it is fortunate for the potash operations that no significant hydrocarbon shows have been found in bank sections. The potential dangers of these banks are controversial—some believe that the risk of hydrocarbon and hydrogen sulphide bursts is great, whereas others take the opposite view. A study by Wardlaw and Reinson (1971) showed that the Winni-

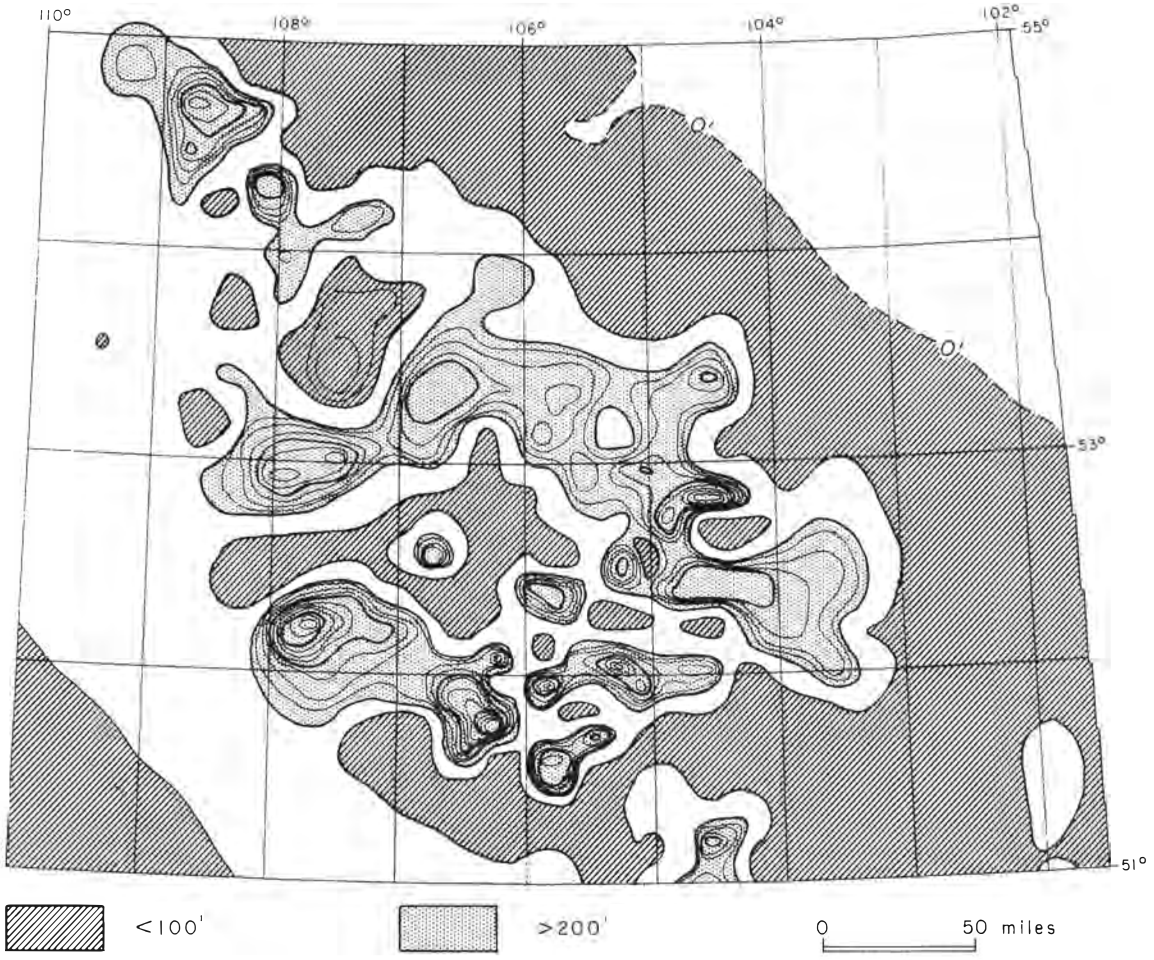


Figure 5-6. —Isopach map of Winnipegosis Formation, Saskatchewan.

pegosis hydrocarbons are immature, perhaps explaining the absence of producing reservoirs. Kendall (pers. comm.) is currently investigating the problem, and is of the opinion that hydrocarbons have not accumulated in the carbonate banks simply because of a lack of escape routes for the hydrocarbons from the laminated bituminous carbonate into the banks. Evidently, in any potash mine development, consideration should be given to the possibility that Winnipegosis banks *may* contain hydrocarbons, hence they are best avoided.

SALT SOLUTIONING

There are areas where it appears that salt was once present but has been dissolved, to the extent of locally removing several hundred feet of salt. Overlying strata have foundered to fill the cavity created, forming breccias (Fig. 5-5d) composed of fragments of the Dawson Bay and Souris River carbonate rocks. These are set within a reddish matrix derived from the insoluble residues of the Prairie Evaporite and from the overlying red beds. The geographic extent of these solution 'hollows' is gradually being delineated as more wells are being drilled. Taking, for example, the potash production area that is centered upon Saskatoon, the structure contour map of the Prairie Evaporite surface (Fig. 5-7) can be subjected to a trend surface analysis in order to clearly separate the 'highs' from the 'lows'. Figure 5-8 shows the third-degree trend-surface residuals and reveals several extensive topographic depressions, which are interpreted as salt solution 'sinks'. The map is a mathematical expression of the possible extent of the salt solutioning—more detailed seismic work and drilling are necessary in order to verify details and to delineate the depressions more precisely.

Major areas of salt solutioning can be avoided when selecting a mine site, but small-scale features are, as yet, unpredictable. These take the form of washouts or 'salt horses' (bodies of barren halite within the potash beds). They are an expensive nuisance to the mine operators, because there are only the choices of ploughing through in the hope that a halite body is only a few feet thick or moving off in another direction to circumvent it. In recent years underground seismic work has met with success in predicting the lateral extent of such barren bodies once encountered, thereby helping to relieve the mine operator of one of his worries.

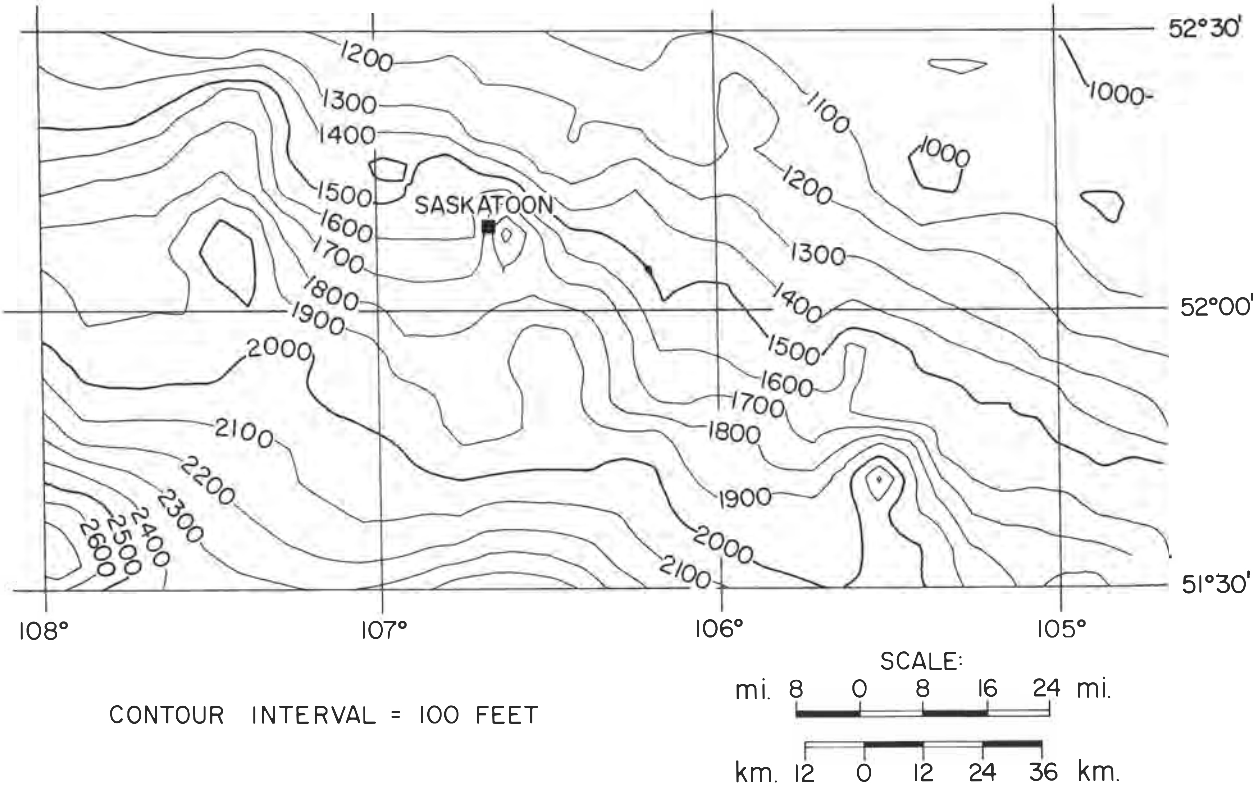


Figure 5-7.—Computer-plotted structure contours on top of the Prairie Evaporite.

MINING OPERATIONS

The vast underground workings are being extended by machines making cuts 7 to 11 feet high and 18 to 24 feet wide. About 65 percent of the ore is left in the ground to provide support, and room and pillar, modified room and pillar, or gallery methods of mining are employed.

One consideration when mining potash is the proximity of overlying clay seams, because they act as planes of weakness in the salt body, from which roof falls may occur. A thickness of 30 to 50 feet of 'salt-back' above the ore is desirable—particularly under the poorly consolidated mudstone of the Dawson Bay red beds.

Another concern is the proximity to water-bearing zones, because the mines must remain absolutely dry. The greatest potential water hazard is the Blairmore Formation (Cretaceous), which consists mainly of sand containing water at pressure as great as 800 psi. This problem has been overcome during shaft sinking by freezing or grouting, then installing watertight shaft linings. The Dawson Bay carbonate beds are locally fluid-free because pore spaces have been plugged with halite deposited by ground water. Figure 5-9 illustrates an interpretation, based upon available drill-stem-test data, of the areas around Saskatoon that do, or are thought likely to, contain water within the Dawson Bay Formation. All potash mines in the area are situated in areas of 'dry' Dawson Bay, but some are not far removed from water-bearing Dawson Bay beds. If water should get into a mine it presents a real problem; there is nowhere for it to drain because of the effective seal of the salt itself. If more than a trickle of water enters, it must either be pumped out or a permanent barrier must be constructed at considerable cost.

Subsidence over potash mines was originally thought unlikely to be transmitted as far as the ground surface (about 3,500 feet above). It was thought that if only 35 percent of the ore was removed, the gradual collapse of the mine galleries would be taken up by the salt and by unconsolidated sand in the Cretaceous strata. Recent measurements at the surface have shown this not to be the case. Over a period of five years, subsidence at the surface has amounted to only a few inches (Fig. 5-10), but the maximum possible subsidence could reach 4 feet (as there is usually 35 percent removal and 11-foot-high corridors). The question now arising is will all this subsidence be transmitted to the surface, or will part be absorbed by the poorly consolidated Cretaceous sand? The current consensus is that the maximum subsidence will be about 1 foot.

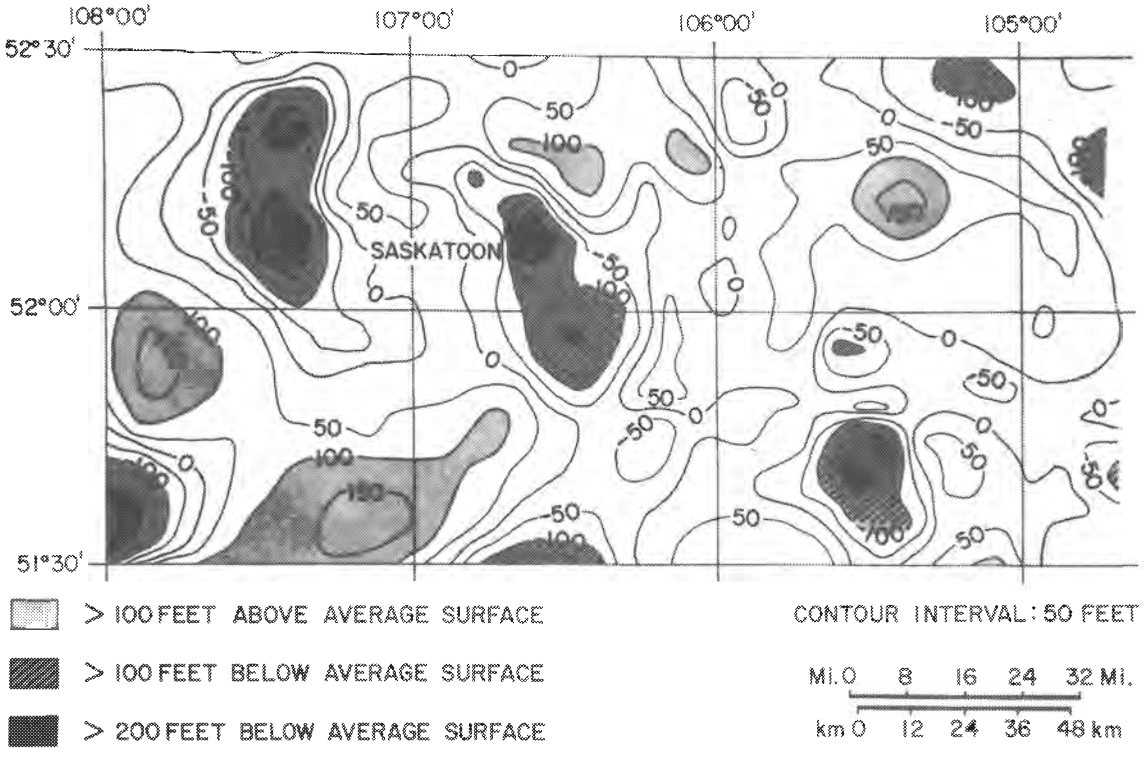


Figure 5-8.—Trend surface third degree residuals on top of the Prairie Evaporite.

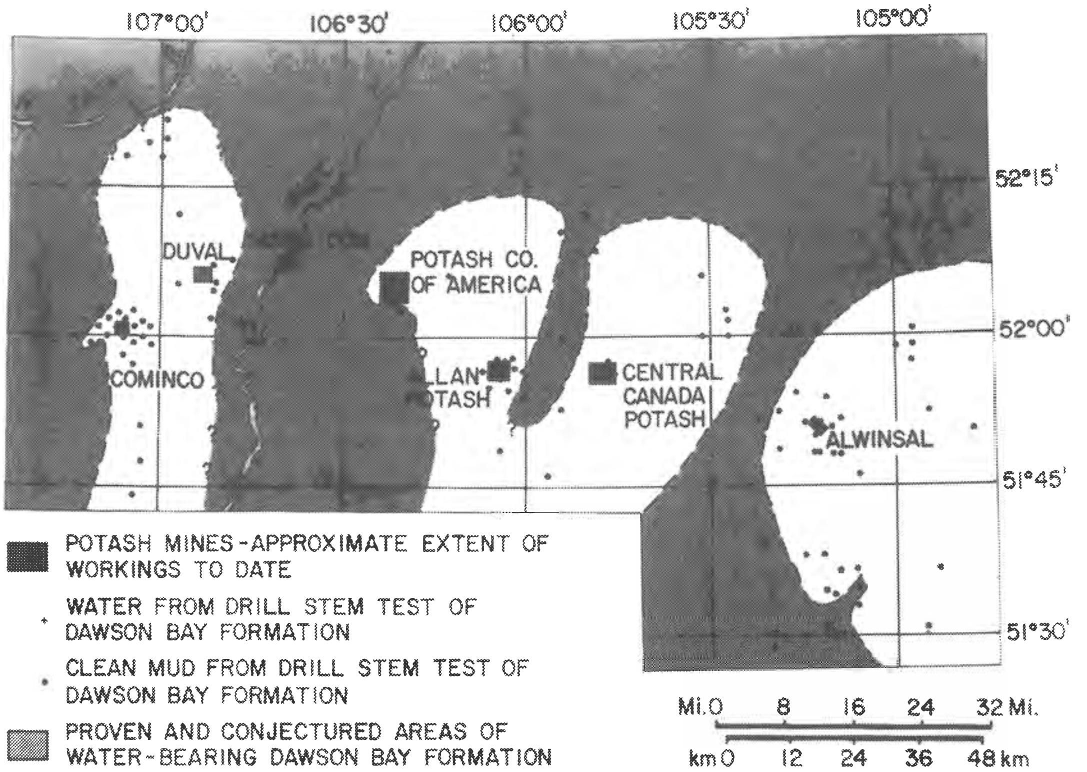


Figure 5-9.—Conjectured distribution of water-bearing Dawson Bay strata.

There is a slightly elevated rim to the depression (Fig. 5-10), giving it a crater-like morphology, for which no satisfactory explanation has yet been offered. Current investigations are trying to determine the angle between the rim at the surface and underground operations. Is it acute, as drawn, or obtuse? This is of importance for calculating the size of boundary pillars between mines. It is also of importance to know this angle for planning the location of shaft pillars. If the angle is acute, then a shaft sunk at the outer limit of workings will not be susceptible to the kinking resulting from differential transmission of subsidence through strata exhibiting diverse physical properties.

Additional features of interest that have been observed in the mines are minor puffs of gas and migrating 'weeps' of water, which periodically occur. The latter may be pockets of connate brine or seeps from overlying strata. Fortunately, they seem to exhaust themselves rapidly, either because of their small magnitude or because the fractures through which they pass heal rapidly.

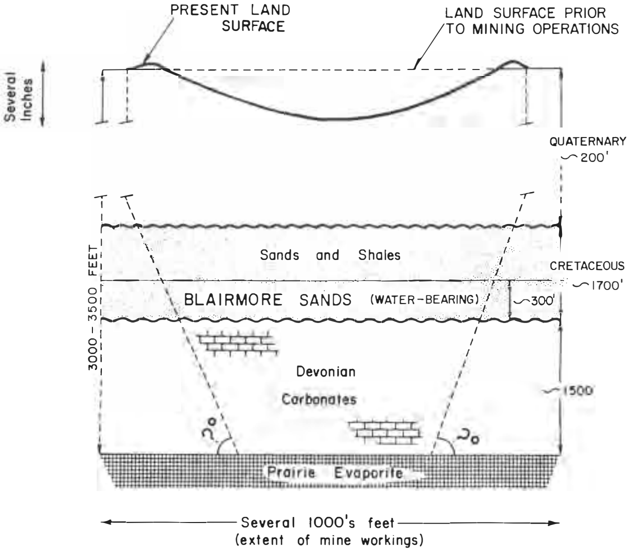


Figure 5-10.—Diagrammatic representation of surface subsidence over potash mines.

The author thanks the Saskatchewan Department of Mineral Resources for permission to publish this paper. Dr. D. F. Paterson, Dr. W. Potts, Dr. A. C. Kendall, and Mrs. A. Fuzesy of the Department supplied much useful advice and information, and Dr. Kendall kindly reviewed the manuscript. Thanks are also extended to the drafting division for preparation of the figures.

PRESENT AND FUTURE

Today nine conventional mines and one solution mine are in operation. In 1974 Saskatchewan's production of six million tons K_2O represented about 25 percent of the world's production. Total recoverable reserves in Saskatchewan have been estimated to be about 74 billion short tons K_2O (Holter, 1969), which gives a supply at the present rate of production that would last for 12,000 years. This vast reserve is being viewed by the Saskatchewan government with an eye to investing in any new mine development, either on a shared basis with a private company or starting its own mine. Late in 1974 a Crown Corporation was set up, and in February of 1975 the Minister of Mineral Resources stated that "...the people of the Province can anticipate significant developments in the near future". At the time of writing (August 1975) the Crown Corporation has recently submitted a feasibility report for a potash production unit, and it is now up to the government to decide on its future involvement in the potash industry.

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REVIEW OF THE WESTERN PHOSPHATE FIELD

James A. Rhodes*

ABSTRACT

The Western Phosphate Field constitutes one of the major phosphate deposits of the world. Mining and processing of phosphate rock from the western field are important factors in the mineral economy of the northwest.

High-grade phosphorite deposits, composed principally of fluorapatite, occur in the Phosphoria Formation (Permian) and its lateral equivalents, the Park City and Shedhorn Formations. These strata, of marine origin, underlie about 130,000 square miles in Montana, Idaho, Wyoming, and Utah, and contain vast phosphate reserves. Exposures of phosphorite occur principally in the folded and faulted ranges in the western part of the field. The lithologic character and thickness of the Phosphoria Formation vary significantly over the field. The thickest and highest-quality phosphorite is in the Meade Peak Member of the Phosphoria Formation in southeastern Idaho; and this area is the center of the western phosphate industry.

Most of the phosphate ore is recovered by surface mining methods. Mining and ore-handling techniques vary to meet local needs and conditions. Production from the western field in 1974 is estimated at 6,000,000 tons of phosphate rock (24% P_2O_5+). Most of this was converted into fertilizer and elemental phosphorus.

INTRODUCTION

The Phosphoria Formation of the Western Phosphate Field contains reserves of high-grade phosphate rock estimated in the billions of tons. These vast reserves are the largest in North America and rank with the major phosphate deposits of the world. In the last thirty years the mining and processing of the western phosphate rock have become important factors in the mineral economy of the Northwest.

The Western Field ranks behind Florida and North Carolina in domestic phosphate production, accounting for about 14 percent of the total national phosphate output. The 1974 U. S. Bureau of Mines statistics list the Western Field production at 6.3 million tons of high-grade phosphate rock having a market value of about 80 million dollars. The large part of the production was from southeast Idaho. About 50 percent of the western phosphate is utilized by the fertilizer industry and 50 percent is used in manufacturing elemental phosphorus.

GEOLOGIC SETTING

The phosphatic strata in the Phosphoria Formation underlie about 130,000 square miles in Montana, Idaho, Wyoming, and Utah (Fig. 6-1). They are marine in origin and were deposited over both the platform and miogeosynclinal portions of the Cordilleran structural belt. The region is geologically diverse; it includes parts of the Northern Rocky Mountains, the Basin-and-Range, and the Wyoming Basin Provinces.

The eastern part of the field conforms closely to the ancient platform area and is characterized by gentle dips around broad domes and basin structure. Faulting is far less common than in the western part of the field, and large unfaulted areas of nearly horizontal strata are present. By contrast the western part of the field is situated in the old geosynclinal belt and is structurally complex. The area is characterized by steep dips, sharp closely spaced folds, and abundant faults of diverse types and magnitudes. The western part of the field also contains the thicker phosphate section and is the locale of most of the phosphate mining.

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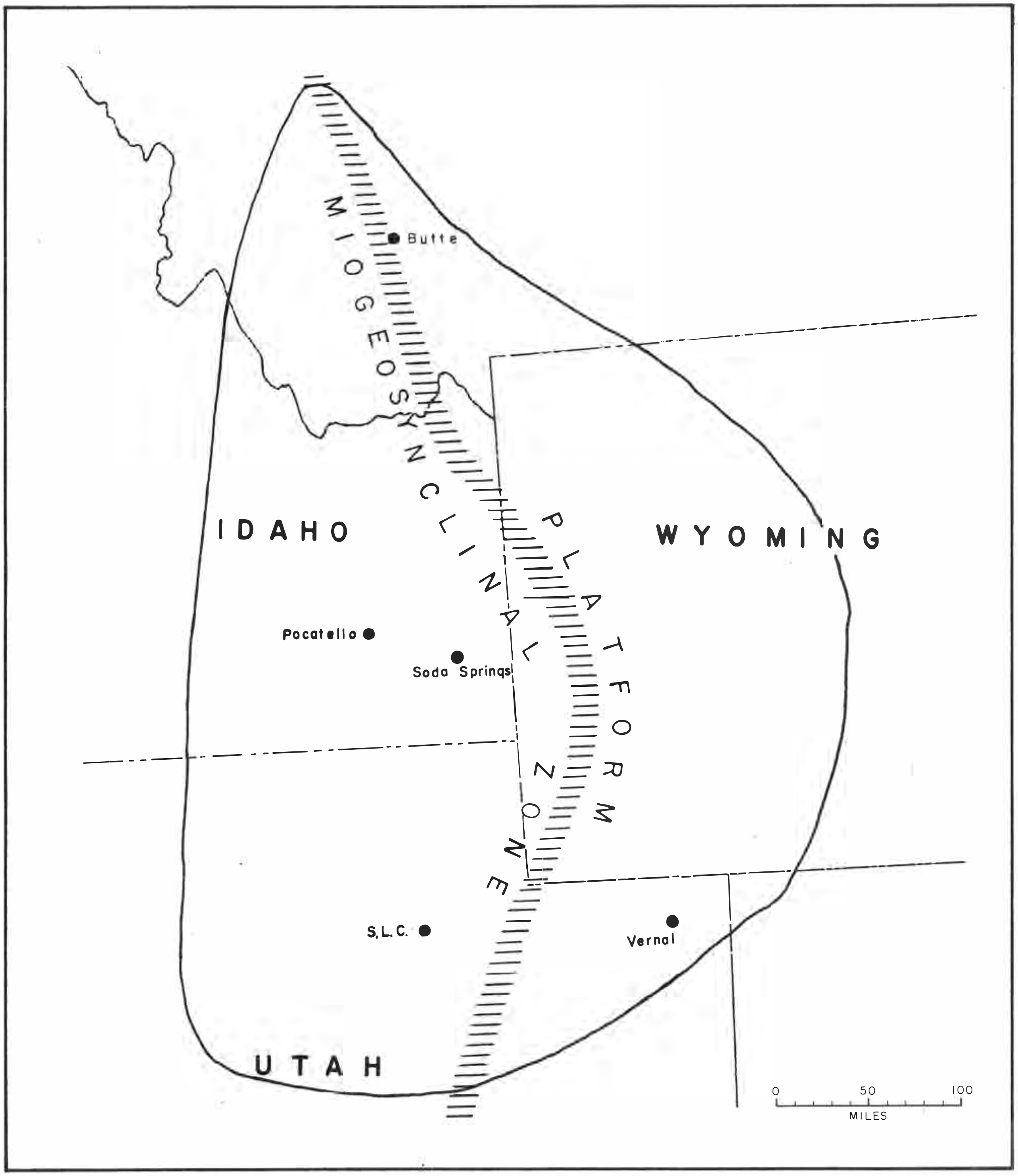

Figure 6-1.–Areal extent of Western Phosphate Field.

STRATIGRAPHY

The Middle and Upper Permian strata of the Western Phosphate Field are assigned to the Phosphoria, the Park City, and the Shedhorn Formations (McKelvey and others, 1959, p. 2-5). The three formations are regarded as end-member types, which interfinger and whose lithic character can be recognized over much of the Western Phosphate Field. The Phosphoria Formation, composed of phosphate rock, carbonaceous mudstone, and cherty rocks, is best developed in eastern Idaho and adjacent areas. The Park City Formation, consisting of carbonate rocks and subordinate sandstone, is best developed in northern Utah and western Wyoming. The Shedhorn Sandstone is best developed in southwestern Montana and northwestern Wyoming.

The Phosphoria Formation in the vicinity of its type locality in southeastern Idaho is between 250 and 450 feet thick (McKelvey and others, 1959, p. 20). It is subdivided into five members: (1) the Meade Peak Phosphatic Shale, (2) the Rex Chert, (3) the Cherty Shale, (4) the Retort, and (5) the Tosi. Phosphate rock is mined from the Meade Peak Member in Idaho, Wyoming, and Utah, and from the stratigraphically higher Retort Member in Montana. The thickness and quality of phosphate rock in these units vary considerably over the Western Field.

LITHOLOGY AND MINERALOGY

The most distinctive visual characteristic of the western phosphate rock is a fine- to medium-pelletal texture. The pellets are composed principally of apatite and are cemented with apatite. The pellets are typically rounded and slightly elongate, though some are nearly spherical. They commonly range between 0.1 and 1 mm and are typically internally structureless, but some are oolitic.

The composition of sixty phosphorite samples from the Phosphoria Formation is shown in Table 6-1. The samples used by Gulbrandsen (1966) in compiling this table constitute high-grade phosphate ore. All samples contain more than 60 percent apatite and average about 80 percent. In addition, quartz, muscovite-illite, feldspar, iron oxide, and organic matter are nearly ubiquitous components that compose the rest of the phosphate rock.

Table 6-1.—Chemical composition of 60 samples of phosphorites from the Phosphoria Formation, by weight percent (from Gulbrandsen, 1966).

SiO_2	11.9	K_2O	0.5
Al_2O_3	1.7	H_2O	2.2
Fe_2O_3	1.1	P_2O_5	30.5
MgO	0.3	CO_2	2.2
CaO_3	44.0	SO_3	1.8
Na_2O	0.6	F	3.1
Organic matter	2.1		
Oil	0.2		

ORE CLASSIFICATION

Industry has tended to classify phosphate rock into three general ore categories depending upon P_2O_5 content:

(1) Acid-grade rock, 30%± P_2O_5 content, to be used without beneficiation for the manufacture of phosphoric acid and superphosphate fertilizer.

(2) Furnace-grade rock, 24 to 30% P_2O_5, to be used directly in electric furnaces for the manufacture of elemental phosphorus.

(3) Beneficiable grade rock, 18 to 24% P_2O_5, commonly stockpiled or beneficiated and upgraded to furnace or acid grade.

The Idaho Meade Peak section is characterized by sharp vertical changes in the P_2O_5 content of the rock layers. This permits the mining of either acid- or furnace-grade rock without the mining of low-grade shale, and makes for efficient mining and optimum utilization of the ore body.

MINING AREAS

Mining is being carried out in three widely separated localities in the Western Field:

(1) Southeastern Idaho and the adjacent part of Wyoming and Utah,

(2) Garrison, Montana, area north of Butte,

(3) Northeastern Utah on the southeastern edge of the Uinta Mountains.

These localities, situated near the center, the north, and the southeast edges of the Western Field, are characterized by different ore sections and structural conditions and accordingly utilize different mining methods.

Southeastern Idaho, the location of thickest and richest phosphorite deposition, is the area of greatest activity. The area contains five large active surface mines having an estimated 1974 production of 5 million tons of combined furnace- and acid-grade phosphate rock.

The Gay Mine, on the Fort Hall Indian Reservation, 25 miles northeast of Pocatello, is the largest phosphate rock producer in the Western Field and had an estimated 1974 production of 2 million tons.

The acid-grade rock, about one-third of the production, is utilized by the Simplot Company for the manufacturing of fertilizer. The rest, consisting of furnace-grade rock, is utilized by FMC in their Pocatello furnace operation for manufacturing elemental phosphorus.

The other Idaho mines are 45 miles farther east near Soda Springs, in Caribou County. Of these, the Conda Mine, operated by Simplot, is on fee property; the other three mines, operated by Monsanto, Stauffer, and Agricultural Chemical Products Company, are on federal lease land. An estimated one million tons of ore mined from Monsanto's Henery Mine is used in their Soda Springs furnace operation and converted to elemental phosphorus. Most of the Stauffer Wooley Valley production is freighted to Silver Bow, Montana, for manufacturing elemental phosphorus. The production from the Simplot Conda Mine and Agricultural Chemical Products Mine is used for manufacturing phosphate fertilizers.

The Meade Peak Member of the Phosphoria Formation has fairly uniform stratigraphic character over the Soda Springs area. The section shown in Figure 6-2 is a composite from several surface sections and, accordingly, assays may reflect a 2 to 3 percent higher P_2O_5 content than commonly occurs in deeper unweathered phosphate rock. The upper ore zone contains 14 feet of 26% P_2O_5

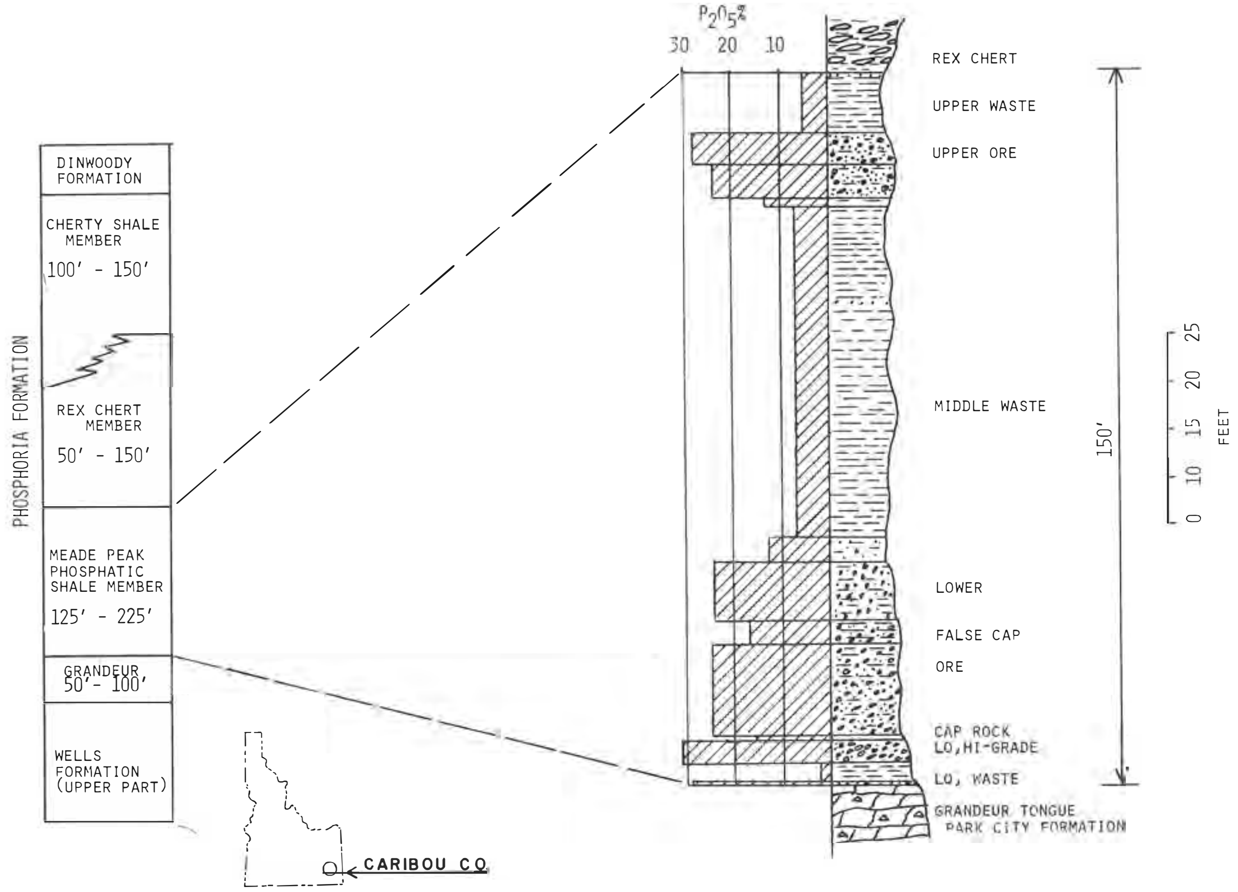

Figure 6-2.–Stratigraphic position and phosphate content of Meade Peak Phosphatic Shale Member of Phosphoria Formation in Caribou County, Idaho.

rock. The lower ore zone contains both acid- and furnace-grade rock, each of which could be recovered with selective mining, but if considered as a unit, it contains 41 feet of 24.3% P_2O_5 rock, which qualifies as furnace-grade ore. The combined ore sections considered as furnace-grade rock are 55 feet thick.

Surface mining practices are similar at all of the Soda Springs mines and in essence consist of systematic earth-moving accomplished with scrapers and dozer tractors. Phosphate ore is mined from the outcrop down dip to the economic limit of overburden removal.

Stauffer operates two small surface mines peripheral to southeastern Idaho, one at Leefe in westernmost Wyoming and one in the Crawford Mountains in northeastern Utah. The phosphate ore in these outlying areas is considerably thinned, probably averaging 10 feet or less in thickness. The total phosphate production from the Stauffer mines, estimated at 400,000 tons, is directed to the fertilizer industry.

MONTANA PHOSPHATE

In contrast to the Idaho phosphate industry, the southwestern Montana phosphate production has traditionally been associated with underground mining. Commercial production was begun in the Garrison District north of Butte in 1929, and the district has remained the prime Montana producer to date. The principal operator has been Montana Phosphate Products Company, a subsidiary of Cominco. High-grade phosphate ore from the district's two active mines, estimated at 200,000 tons a year, has been shipped by rail to Cominco's fertilizer plant in Trail, British Columbia. The Permian section of southwestern Montana is dominated by the Shedhorn Sandstone, but it contains well-developed tongues of the Park City and Phosphoria Formations (Fig. 6-3). Commercial phosphate rock occurs mainly in the Retort Member of the Phosphoria Formation. In the Garrison District, the Retort typically contains 2½ to 5 feet of hard phosphorite, which averages better than 30% P_2O_5. The phosphorite is overlain and underlain by dense sandstone or quartzite, which forms a hard footwall and hanging wall that greatly facilitate the underground mining.

Outcrops of the Retort Member are mainly in the limbs of tight steeply dipping faulted folds. Mining techniques employed are similar to underground hard-rock operations. Tunnels are driven from the valley floor into the hillside through the hanging-wall formations and into the Retort phosphorite. From the tunnel, drifts are cut along the footwall below the phosphorite; and raises are

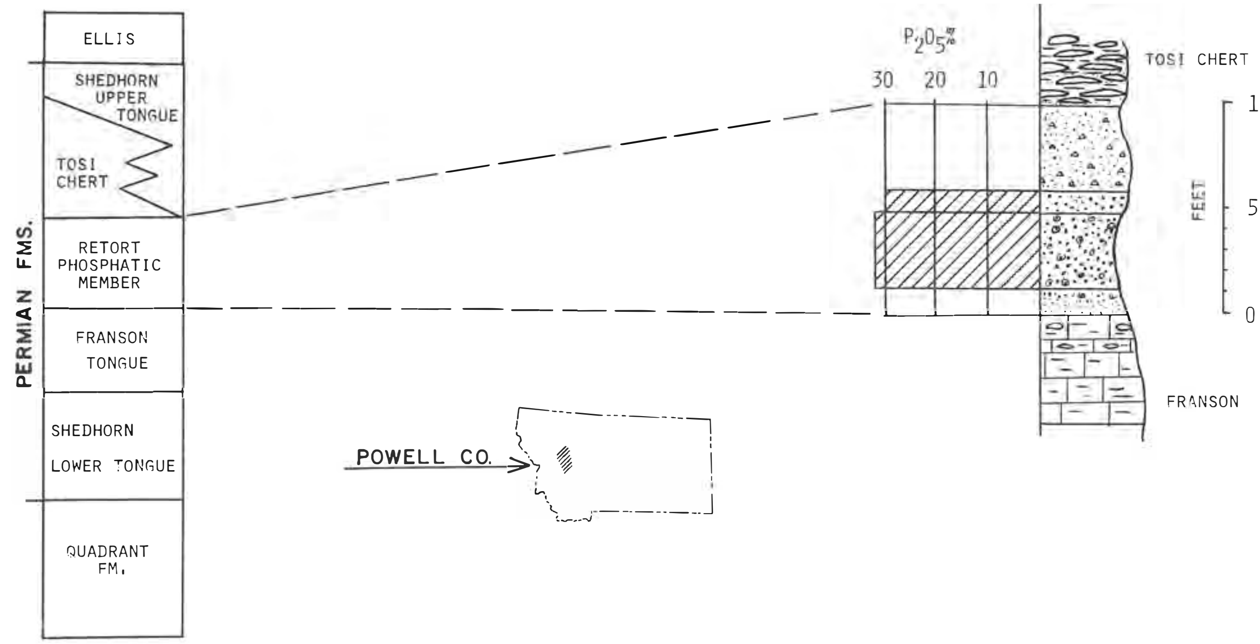

Figure 6-3.—Stratigraphic position and phosphate content of Retort Phosphatic Member, Powell County, Montana.

driven updip and open-stope mining methods are used, pillars being left between adjoining stopes. It is estimated that about 70 percent of the in-place ore is recovered by this method. Grade changes in the ore, variations in dip and strike, and the type and frequency of faulting have a great influence on mining methods and costs.

The Montana phosphate ore reserves above adit level are estimated at more than one billion tons. Because of the thin phosphate ore zone and the high unit cost of underground operations, Montana phosphate mining has difficulty competing with the surface phosphate mines of southeastern Idaho.

UTAH PHOSPHATE

Both of Utah's active phosphate mines are operated by Stauffer Chemical Company. These include the Crawford Mountain mine, previously mentioned, and the Vernal mine on the southeast edge of the Uinta Mountains near the Colorado state line. In geologic respects the Vernal area differs markedly from the phosphate-producing areas of Idaho and Montana. It is characterized by plateau structure, which is free of faulting, and the Park City Formation carbonate-shelf facies.

The structure is homoclinal, with uniform southward dips between 5 and 15 degrees. The Park City Formation forms a dip slope over more than 25 square miles of mining property. The formation contains a basal Meade Peak Phosphate Member, which overlies the hard Weber Sandstone (Fig. 6-4). The Meade Peak Member crops out as a narrow band in numerous small canyons, but it is principally covered by the resistant Franson Limestone of the Park City Formation. For the most part, it is necessary to drill, shoot, and remove the resistant capping limestone beds in order to mine the phosphatic shale. Typically, only the lower Franson Limestone, which covers several square miles and constitutes 25 feet of overburden, is removed with the present mining. Accordingly, this property has the potential of becoming the largest surface mine in the Western Field.

The phosphate ore section is 18 feet thick and averages 19.5% P_2O_5. It consists of an alternating sequence of medium-grade phosphorite beds ranging between 20 and 28% P_2O_5 and argillaceous beds containing 10% or less P_2O_5.

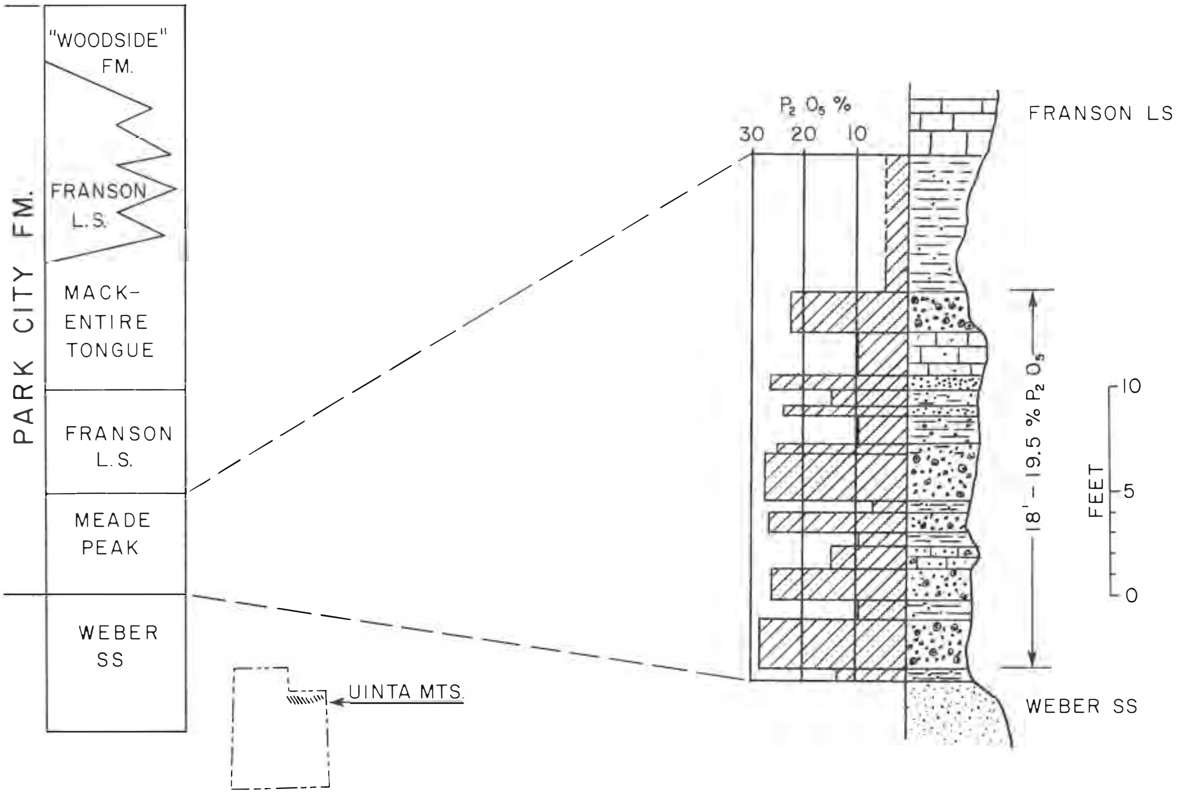

Figure 6-4.–Stratigraphic position and phosphate content of Meade Peak Member of Park City Formation in eastern Uinta Mountains, Utah.

After the overburden has been removed, the phosphate ore is drilled and shot and loaded into open-end dump trucks with a shovel and hauled as far as two miles to a concentrating plant. The ore is crushed, deslimed, and floated, and a 32%+ P_2O_5 concentrate is recovered. The concentrate is trucked 140 miles to a railhead east of Salt Lake City. The operation currently produces about 400 thousand tons of concentrate a year, most of which is exported to Cominco's fertilizer plants in British Columbia.

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ZEOLITES IN SEDIMENTARY DEPOSITS OF THE NORTHWESTERN UNITED STATES–POTENTIAL INDUSTRIAL MINERALS

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ABSTRACT

Zeolites have been reported from sedimentary deposits since 1891, but their utilization as industrial minerals is in its infancy. Zeolites occur in rocks that are diverse in age, lithology, and depositional environment, but they are most common in sedimentary rocks that originally contained abundant vitric material. Most zeolites in sedimentary deposits formed during diagenesis mainly by the reaction of vitric material with interstitial water. Of the more than thirty naturally occurring zeolites, only eight commonly occur in bedded deposits of the Northwest. These are analcime, chabazite, clinoptilolite, erionite, heulandite, laumontite, mordenite, and phillipsite. Most zeolitic sedimentary rocks consist of two or more zeolites as well as authigenic clay minerals, silica minerals, or feldspar, and relict glass and crystal and rock fragments. Extensive and relatively pure beds of zeolite, however, occur in Cenozoic deposits of the Northwest.

The ion exchange, adsorption, molecular sieve, and reversible dehydration properties of zeolites, coupled with their seemingly low cost of mining, suggest a variety of industrial applications. Uses or potential uses include hydrocarbon separations, purification and drying of gases, removal of cesium and strontium from radioactive wastes, removal of ammonia from sewage and agricultural effluents, and production of high-purity oxygen from air. Zeolites are also used as soil amendments, carriers of pesticides and herbicides, and dietary supplements for pigs and chickens. Certain properties of zeolitic tuffs, such as their light color, light weight, and low abrasiveness, permit uses as building stone, lightweight aggregate, and pozzolan in cement, and as filler in paper.

INTRODUCTION

Zeolites belong to a group of naturally occurring minerals known as framework silicates, which also include feldspars and feldspathoids. The name to this remarkable group of minerals was given in 1756 by Baron Cronstedt, a Swedish mineralogist. The name is derived from the Greek *zein*, to boil, and *lithos*, stone, in allusion to the intumescence of most zeolites with a borax bead. Specifically, zeolites are crystalline hydrated aluminosilicates of the alkali and alkaline-earth elements. They have an infinitely extended framework structure that encloses interconnected cavities occupied by the relatively large cations and water molecules. The fundamental building block of the zeolites is a tetrahedron of four oxygen atoms surrounding a relatively small silicon or aluminum atom. The framework structure of zeolites consists of SiO_4 and AlO_4 tetrahedra such that each oxygen is shared between two tetrahedra. Thus, the atomic ratio, O:(Al+Si), is equal to 2. Because aluminum has one less positive charge than silicon, the framework has a net negative charge and is balanced by the exchangeable cations. These cations are chiefly monovalent sodium and potassium and divalent calcium and magnesium, but divalent barium and strontium are essential constituents of some natural zeolites.

Since zeolites were discovered more than two centuries ago, more than thirty distinct species have been recognized. Numerous zeolites have also been synthesized, but most of these have no natural counterparts. Zeolites occur in rocks that are diverse in lithology and age, and they have formed in many different geological environments. The common and perhaps best known occurrences are in the cavities and fractures of igneous rocks, particularly basaltic rocks. Most of the large, attractive zeolite specimens in museum collections have been obtained from igneous rocks. In recent years zeolites have been recognized as important rock-forming constituents in low-grade metamorphic rocks and in various sedimentary rocks (Hay, 1966). The zeolites in sedimentary rocks are very finely crystalline and do not appeal to mineral collectors, but deposits of this type are voluminous and have economic potential for many industrial and agricultural processes.

Zeolites are among the common authigenic silicate minerals that occur in sedimentary rocks. Since the discovery by Murray and Renard (1891) of phillipsite in deep-sea deposits, zeolites have been recognized from many different sedimentary rocks and depositional environments. Although about twenty different zeolites have been reported from sedimentary rocks throughout the world, only analcime, chabazite, clinoptilolite, erionite, heulandite, laumontite, mordenite, and phillipsite commonly make up the major part of zeolitic rocks of the Northwest. Analcime and clinoptilolite are by far the most commonly reported.

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DESCRIPTION AND PROPERTIES OF ZEOLITES

Most natural zeolites show considerable ranges in chemical composition, including ranges in the water content, the cation content, and the Si:Al ratio. Summaries of their composition are given by Deer, Howie, and Zussman (1963), Hay (1966), Sheppard (1971), and Utada (1970). The formulas and ranges in simplified form are given in Table 7-1. Except for heulandite and laumontite, the zeolites in sedimentary rocks are generally alkalic and are more siliceous than their counterparts that occur in mafic igneous rocks. The indices of refraction of zeolites are low for silicate minerals and are generally in the range of 1.46 to 1.52. The specific gravity is notably low as a consequence of the porous structure of the zeolites and is generally 2.0 to 2.3. Hardness is about 3.5 to 5.5.

The wide diversity of applications and potential applications of natural zeolites is due to a unique set of properties, some of which were recognized more than a century ago. These properties include reversible dehydration, cation exchange, adsorption, and thermal and acid stability. These properties for both natural and synthetic zeolites were recently discussed in detail by Breck (1974) and will not be further reviewed here. When zeolites are dehydrated, the remaining crystalline solid is characterized by molecular-size voids that have a large internal surface area. Once so cleared of water, the cavities are capable of adsorbing other molecules that are small enough to pass through the apertures that connect the voids. This ability to select one or more components from a gas or liquid mixture to the exclusion of the others is known as molecular sieving. Thus, natural zeolites and their synthetic counterparts are commonly termed molecular sieves.

Zeolites in sedimentary deposits are finely crystalline, commonly in the range of 1 to 60 μm. Because of their fine crystallinity and similar optical properties, these zeolites were generally overlooked until the widespread use of x-ray powder diffraction techniques in the late 1950's. X-ray powder diffraction analysis of bulk samples is now the technique generally used for identification of the zeolites. This method also permits a semiquantitative estimate of the abundance of zeolites and associated minerals in the sample.

Scanning electron microscopy has recently been applied with success to the study of finely crystalline zeolites. This method is especially useful for the determination of the size and shape of the crystals in the bulk rock and for the study of the paragenesis of the diagenetic minerals. Figures 7-1 through 7-6 show scanning electron micrographs of analcime, chabazite, clinoptilolite, erionite, mordenite, and phillipsite in zeolitic tuffs. Because of the characteristic morphology of many zeolites in sedimentary deposits, the electron microscope also supplements the use of the x-ray diffractometer for identification.

OCCURRENCES IN THE NORTHWEST

Zeolites in sedimentary deposits of the northwestern United States occur in many rock types from lacustrine, fluviatile, and marine environments. The occurrences are briefly described in Table 7-2 and are shown in Figure 7-7. Although the zeolites are most abundant in rocks of Cenozoic age, they have been reported from rocks as old as Triassic. Bradley (1928) was the first investigator to identify zeolites in sedimentary rocks of the Northwest. He identified analcime in the Green River Formation of Wyoming and adjacent parts of Colorado

Table 7-1.–Formulas of zeolites that commonly occur in sedimentary rocks.

[Formulas are standardized in terms of a sodium end member that has one aluminum atom, except for the formulas of heulandite and laumontite, which are standardized in terms of a calcium end member.]

Name	Dominant cations	Formula
Analcime	Na	$NaAlSi_{1.5-2.9}O_{5.0-7.8}\cdot 0.8\text{-}1.3H_2O$
Chabazite	Na, Ca, K	$NaAlSi_{1.5-4.1}O_{5.0-10.2}\cdot 2.7\text{-}4.7H_2O$
Clinoptilolite	Na, K, Ca	$NaAlSi_{3.4-5.5}O_{8.8-13.0}\cdot 2.5\text{-}4.0H_2O$
Erionite	Na, K, Ca	$NaAlSi_{2.9-3.8}O_{7.8-9.6}\cdot 2.4\text{-}3.4H_2O$
Heulandite	Ca, Na, K	$Ca_{0.5}AlSi_{2.7-3.8}O_{7.4-9.6}\cdot 2.5\text{-}3.1H_2O$
Laumontite	Ca, Na, K	$Ca_{0.5}AlSi_{1.9-2.2}O_{5.8-6.4}\cdot 1.6\text{-}1.8H_2O$
Mordenite	Na, Ca, K	$NaAlSi_{4.5-5.3}O_{11.0-12.6}\cdot 3.2\text{-}3.5H_2O$
Phillipsite	Na, K, Ca	$NaAlSi_{1.3-3.4}O_{4.6-8.8}\cdot 1.7\text{-}3.3H_2O$

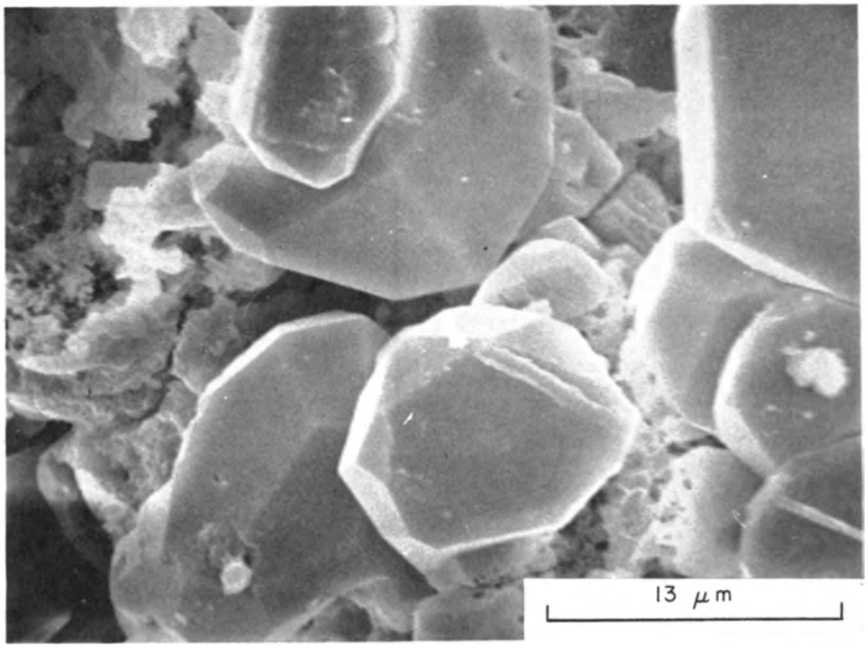

Figure 7-1.—Scanning electron micrograph of an analcime-rich tuff from the Barstow Formation (Miocene) near Barstow, California, showing trapezohedrons of analcime. Electron micrograph by J. D. Tucker, U. S. Geological Survey.

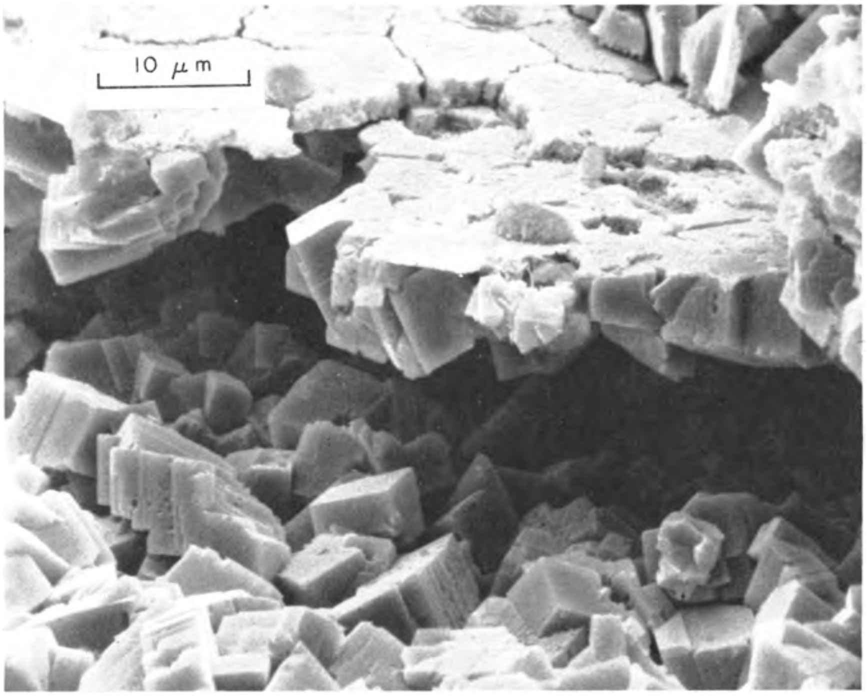

Figure 7-2.—Scanning electron micrograph of a chabazite-rich tuff from a Pliocene lacustrine deposit near Durkee, Oregon, showing the rhombohedral morphology of the chabazite. Electron micrograph by R. A. McGrew, University of Colorado.

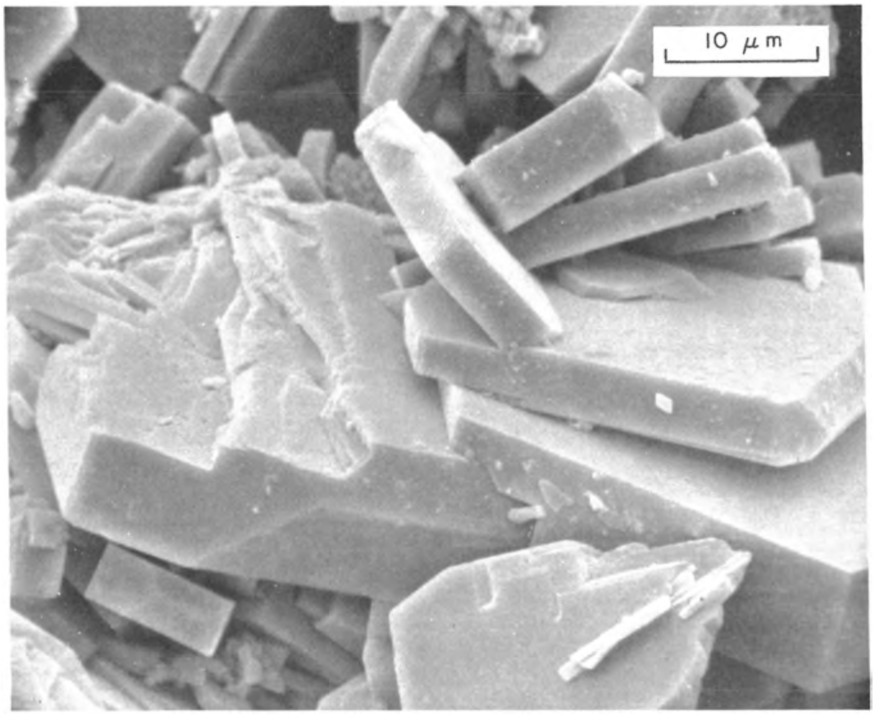

Figure 7-3.–Scanning electron micrograph of a clinoptilolite-rich tuff from a Pliocene lacustrine deposit near Durkee, Oregon, showing tabular clinoptilolite. Electron micrograph by R. A. McGrew, University of Colorado.

Figure 7-4.–Scanning electron micrograph of an erionite-rich tuff from a Pliocene lacustrine deposit near Durkee, Oregon, showing bundles of prismatic erionite. Electron micrograph by A. L. Tarshis, University of California at Santa Cruz.

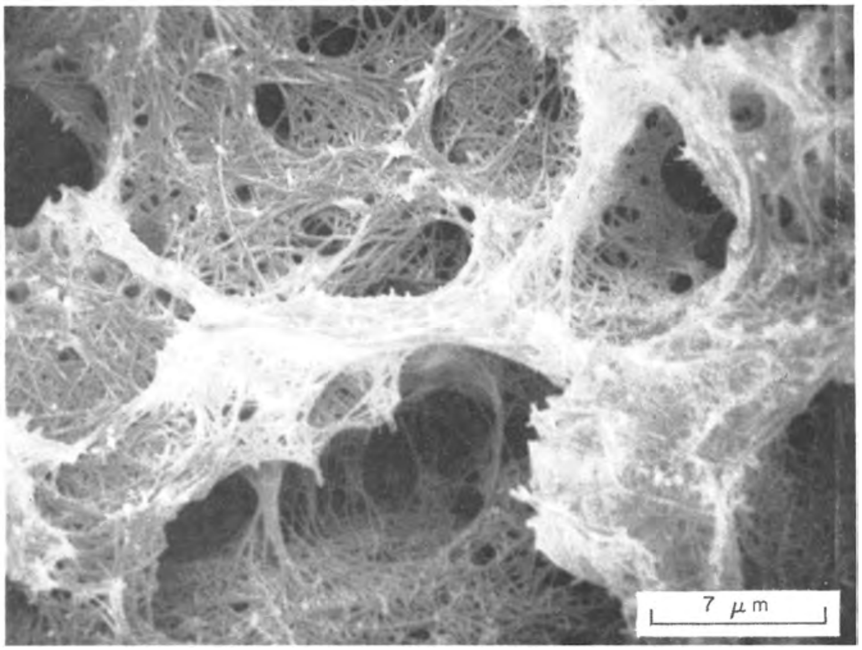

Figure 7-5.—Scanning electron micrograph of a mordenite-rich tuff from a Pliocene lacustrine deposit near Rome, Oregon, showing filiform mordenite. Electron micrograph by M. J. Pinel, U. S. Geological Survey.

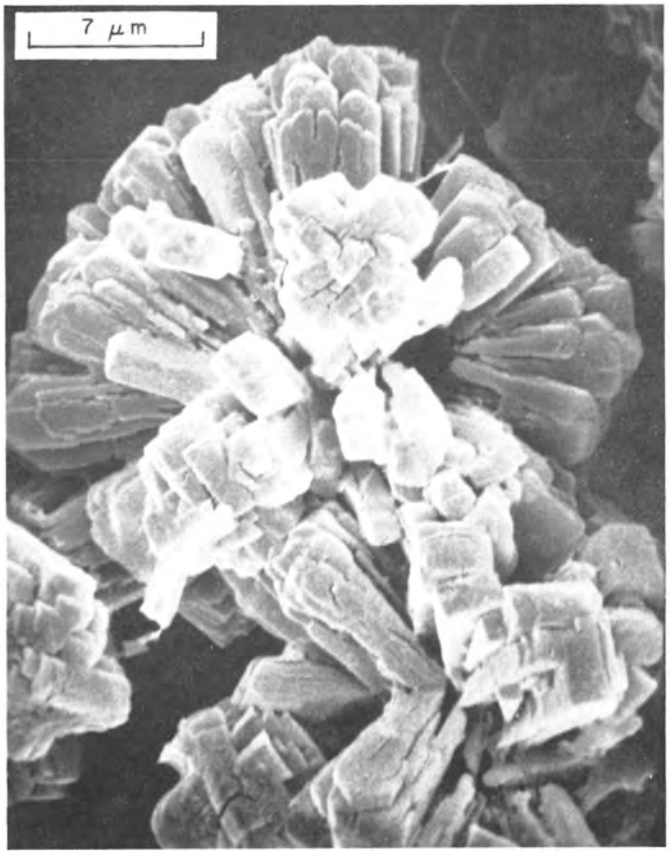

Figure 7-6.—Scanning electron micrograph of a phillipsite-rich tuff from a Pliocene lacustrine deposit near Durkee, Oregon, showing radial aggregates of prismatic phillipsite. Electron micrograph by M. J. Pinel, U. S. Geological Survey.

Table 7-2. –Occurrences of zeolites in sedimentary rocks of northwestern United States.

[Locality numbers are shown in Figure 7-7. Asterisk (*) indicates localities where beds are at least 1 foot thick and contain at least 75 percent zeolite.]

	Locality	Zeolites	Occurrence	Reference
			WASHINGTON	
1.	Near Renton, King County	Heulandite, clinoptilolite(?)	Sandstone and conglomerate in the Renton Formation and Lincoln Creek(?) Formation of late Eocene and early Oligocene age	Mullineaux (1970)
2.	Near Mt. Octopus, Jefferson County	Laumontite	Marine sandstone of Eocene to Miocene age	Stewart (1974)
3.	Backbone Ridge, Mount Rainier National Park, Lewis County	Laumontite, wairakite	Volcaniclastic rocks in the Ohanapecosh Formation of Oligocene age	Fiske and others (1963)
4.	Along Bear Creek, Skamania County	Heulandite, analcime, laumontite	Volcaniclastic rocks in the Ohanapecosh Formation of Oligocene age	Wise and Eugster (1964); Wise (1970)
5.	Near Ellensburg, Kittitas County	Clinoptilolite	Sandstone in the Ellensburg Formation of Miocene and Pliocene age	Hans-Ulrich Schmincke (oral commun., 1969)
6.	Along Naselle River, Pacific County	Heulandite, analcime	Marine tuff and tuffaceous siltstone of Eocene age	Wolfe and McKee (1972)
7.	Near Elk Mountain, Wahkiakum County	Heulandite	Tuffaceous siltstone in the Lincoln Creek Formation of Eocene(?) to Miocene age	Wolfe and McKee (1972)
8.	Restoration Point, Kitsap County	Clinoptilolite	Marine volcaniclastic rocks in the Blakeley Formation of Oligocene to Miocene age	McLean (1968)
9.	Near Greenwater, Pierce County	Heulandite, laumontite	Volcaniclastic rocks in the Ohanapecosh Formation of Oligocene age and the Stevens Ridge and Fifes Peak Formations of Oligocene to Miocene age	Hartman (1973)
10.	Near Leavenworth, Chelan County	Clinoptilolite, laumontite	Sandstone and tuffaceous sandstone in the Swauk Formation of Paleocene age	Lupe (1971)
			OREGON	
11.	Near Bearbones Mountain, Lane County*	Clinoptilolite, mordenite	Tuff and lapilli tuff in the Little Butte Volcanic Series of Oligocene and Miocene age	Moore and Peck (1962, p. 188); Peck and others (1964, p. 15, 40)
12.	Near Steins Pillar, Crook County	Clinoptilolite, mordenite	Tuff in the John Day Formation of Oligocene and Miocene age	Waters (1966)
13.	Near Corvallis, Benton County	Analcime, thomsonite	Marine volcaniclastic sandstone in the Spencer Formation of Eocene age	Enlows and Oles (1966)
14.	Newberry Crater, Deschutes County	Chabazite, phillipsite	Mafic tuff of Quaternary age	Higgins and Waters (1967)
15.	Near the Painted Hills, Wheeler County*	Clinoptilolite	Tuff and claystone in the lower part of the John Day Formation of Oligocene and Miocene age	Hay (1962, 1963)
16.	Near Deep Creek, Wheeler County*	Clinoptilolite	Tuff in the lower part of the John Day Formation of Oligocene and Miocene age	Fisher (1962, 1963); Wilcox and Fisher (1966)
17.	Near Durkee, Baker County*	Chabazite, erionite, clinoptilolite, phillipsite, analcime, mordenite	Tuff in unnamed lacustrine rocks of Pliocene age	Staples and Gard (1959); Sheppard and Gude (1975)
18.	Sucker Creek, Malheur County*	Clinoptilolite	Tuff and tuffaceous sandstone in the Sucker Creek Formation of Miocene age	Kittleman and others (1965)
19.	Near Sheaville, Malheur County*	Clinoptilolite	Tuff probably equivalent to part of the Sucker Creek Formation of Miocene age	Sheppard and Walker (1969)
20.	Near Rome, Malheur County*	Mordenite, erionite, clinoptilolite, phillipsite	Tuff and tuffaceous sandstone in the Rome beds (an informal unit) of Pliocene age	Regis and Sand (1966); Sheppard and Gude (1969); Wolf and Ellison (1971)

Table 7-2. (Continued)

	Locality	Zeolites	Occurrence	Reference
			OREGON (Continued)	
21.	East face of Steens Mountain, Harney County	Clinoptilolite	Tuff in the Pike Creek Formation of Oligocene(?) and Miocene age	Walker and Repenning (1965)
22.	Near Harney Lake, Harney County*	Clinoptilolite, erionite, phillipsite	Tuff and tuffaceous sedimentary rocks in the Danforth Formation of Pliocene age	Walker and Swanson (1968a)
23.	West face of Hart Mountain, Lake County*	Clinoptilolite, mordenite, phillipsite	Tuff and tuffaceous sedimentary rocks of late Oligocene or early Miocene age	Walker and Swanson (1968b)
24.	Near Flagtail Mountain, Grant County	Laumontite	Tuffaceous rocks in the Aldrich Mountains Group of Late Triassic(?) to Early Jurassic age	Brown (1961); Brown and Thayer (1963, 1966)
25.	Along Lewis Creek, Grant County	Heulandite, laumontite	Tuffaceous rocks in the lower part of the Trowbridge Formation of Jurassic age	Dickinson (1962a, 1962b)
26.	Near Monument, Grant County	Chabazite	Tuff in the lower part of the John Day Formation of Oligocene and Miocene age	Sheppard and Gude (1970)
			IDAHO	
27.	Near Challis, Custer County	Clinoptilolite	Tuff and tuffaceous sandstone in the Germer Tuffaceous Member of the Challis Volcanics of Eocene or Oligocene age	David McIntyre (oral commun., 1974)
28.	Near Preston, Franklin County*	Clinoptilolite	Tuff in the Salt Lake Group of late Tertiary age	Deffeyes (1959)
29.	Near Twin Creek, Bear Lake County	Analcime	Tuff in the Twin Creek Limestone of Jurassic age	Gulbrandsen and Cressman (1960)
			MONTANA	
30.	Near Vaughn, Cascade County	Analcime, clinoptilolite, mordenite	Tuff and tuffaceous siltstone and sandstone in Taft Hill, Vaughn, and Bootlegger Members of the Blackleaf Formation of Cretaceous age	Cobban (1955); Fox (1966); R. E. Van Leonen (written commun., 1968)
31.	Near Big Sandy, Chouteau County	Clinoptilolite	Sandstone in the Wasatch Formation of Eocene age	Vine and Tourtelot (1970)
32.	Near Turner, Blaine County	Clinoptilolite	Bentonite in the Bearpaw Shale of Cretaceous age	Berg (1969)
33.	Near Harlem, Blaine County	Clinoptilolite	Bentonite in the Bearpaw Shale of Cretaceous age	Berg (1969)
34.	Near Antelope, Sheridan County	Clinoptilolite	Bentonite in the Fort Union Formation of Paleocene age	Berg (1969)
35.	Ekalaka Hills, Carter County	Analcime	Lignite in the Fort Union Formation of Paleocene age	Gill (1959, p. 174); Denson and Gill (1965, p. 50)
36.	Finger Buttes, Carter County	Analcime	Lignite in the Fort Union Formation of Paleocene age	Denson and Gill (1965, p. 49)
37.	Near Acton, Yellowstone County	Clinoptilolite	Bentonite in the Bearpaw Shale of Cretaceous age	Berg (1969)
38.	Near Joliet, Carbon County	Clinoptilolite	Bentonite in the Claggett Formation of Cretaceous age	Berg (1969)
39.	Near Bridger, Carbon County	Clinoptilolite	Bentonite in the Thermopolis Shale of Cretaceous age	Berg (1969)
40.	Near Dillon, Beaverhead County	Heulandite, mordenite	Tuff of Miocene age	Rose (1972)
41.	Ryan Canyon, Beaverhead County	Clinoptilolite	Tuff of Tertiary age	D. B. Hawkins (written commun., 1974)
42.	Badger Pass, Beaverhead County	Clinoptilolite	Tuff of Tertiary age	D. B. Hawkins (written commun., 1974)

Table 7-2. (Continued)

	Locality	Zeolites	Occurrence	Reference
			MONTANA (Continued)	
43.	Point of Rocks, Park County	Clinoptilolite	Tuff of Eocene age	R. A. Sheppard (unpub. data)
44.	Near Livingston, Park County	Heulandite	Volcaniclastic rocks in the Livingston Formation of Cretaceous age	Roberts (1963); Sims (1969)
45.	Near Wilsall, Park County	Clinoptilolite, laumontite, mordenite, stilbite	Volcaniclastic rocks of Cretaceous age	B. A. Skipp (written commun., 1975)
46.	Near Maudlow, Gallatin County	Clinoptilolite, mordenite, laumontite	Volcaniclastic rocks of Cretaceous age	B. A. Skipp (written commun., 1975)
			WYOMING	
47.	Near Pedro, Weston County *	Clinoptilolite	Bentonite in the Sharon Springs Member of the Pierre Shale of Cretaceous age	Bramlette and Posnjak (1933)
48.	Southeast flank of North Butte, Campbell County	Heulandite	Sandstone in the Wasatch Formation of Eocene age	Vine and Tourtelot (1973, p. 9)
49.	South Fork of the Powder River, Natrona County	Analcime	Bentonite in the Mowry Formation of Cretaceous age	Slaughter and Early (1965)
50.	Near Casper, Natrona County	Analcime	Bentonite in the Mowry Formation of Cretaceous age	Slaughter and Early (1965)
51.	Northwest of Independence Rock, Natrona County*	Clinoptilolite	Tuff in the Bug Formation of Pliocene or Pleistocene age	Surdam (1972)
52.	Near Moonstone Peak, Natrona County*	Clinoptilolite, erionite, phillipsite	Tuff in the Moonstone Formation of Pliocene age	Love (1970); Surdam (1972)
53.	Near Split Rock, Natrona County*	Clinoptilolite	Tuff in the Split Rock Formation of Miocene age	Surdam (1972)
54.	Near Hyattville, Big Horn County	Analcime	Bentonite in the Mowry Formation of Cretaceous age	Slaughter and Early (1965)
55.	Near Lovell, Big Horn County	Clinoptilolite	Bentonite in the Mowry Formation and Thermopolis Shale of Cretaceous age	C. A. Wolfbauer (oral commun., 1974)
56.	Near Saratoga, Carbon County*	Clinoptilolite, phillipsite	Tuff in the Browns Park Formation of Miocene age	Surdam (1972)
57.	Near Dubois, Fremont County	Analcime	Ocher oolitic beds in the Popo Agie Member of the Chugwater Formation of Triassic age	Keller (1952); High and Picard (1965)
58.	Near Lander, Fremont County	Analcime	Ocher oolitic beds in the Popo Agie Member of the Chugwater Formation of Triassic age	Keller (1952); High and Picard (1965)
59.	Beaver Divide, Fremont County*	Analcime, chabazite, clinoptilolite, erionite, phillipsite	Tuff in the Wagon Bed Formation of Eocene age	Van Houten (1964); Boles and Surdam (1971)
60.	Near Cameron Spring on Beaver Divide, Fremont County	Clinoptilolite	Tuffaceous sandstone in the White River Formation of Oligocene age	Van Houten (1964)
61.	Near Riverton, Fremont County	Clinoptilolite	Tuff in the Wind River Formation of Eocene age	Surdam (1972)
62.	Near Gros Ventre River, Teton County	Analcime	Ocher oolitic beds in the Popo Agie Member of the Chugwater Formation of Triassic age	Keller (1952)
63.	Black Sand Basin, Teton County	Clinoptilolite, analcime, mordenite, erionite	Volcaniclastic rocks of Pleistocene age	Fenner (1936); Honda and Muffler (1970)

Table 7-2. (Continued)

Locality	Zeolites	Occurrence	Reference
WYOMING (Continued)			
64. Near Thermopolis, Hot Springs County	Analcime	Purple and ocher units of the Popo Agie Member of the Chugwater Formation of Triassic age	High and Picard (1965)
65. Near Lysite Mountain, Hot Springs County*	Analcime, clinoptilolite, erionite, mordenite	Tuff in the Tepee Trail Formation of Eocene age	Bay (1969); Surdam (1972)
66. Snake River Canyon, Lincoln County	Heulandite	Shale in the Aspen Formation of Cretaceous age	Heinrich (1963)
67. Near La Barge, Lincoln County	Analcime	Sandstone in the Wasatch Formation of Eocene age	Vine and Tourtelot (1973, p. 7)
68. Near Twin Buttes, Sweetwater County*	Clinoptilolite	Tuff and tuffaceous sandstone in the Bridger Formation of Eocene age	Sheppard (1971)
69. Near Green River, Sweetwater County	Analcime, clinoptilolite, mordenite	Tuff and oil shale in the Green River Formation of Eocene age	Bradley (1964); Goodwin and Surdam (1967); Iijima and Hay (1968); Surdam and Parker (1972)
70. Firehole Basin, Sweetwater County	Analcime	Sandstone in the Wasatch Formation of Eocene age	Vine and Tourtelot (1973)
71. Kinney Rim in the Washakie Basin, Sweetwater County*	Analcime, clinoptilolite, mordenite	Tuff and oil shale in the Laney Shale Member of the Green River Formation of Eocene age	Roehler (1972)
72. Kinney Rim in the Washakie Basin, Sweetwater County*	Clinoptilolite	Tuff in the Adobe Town Member of the Washakie Formation of Eocene age	Roehler (1973)

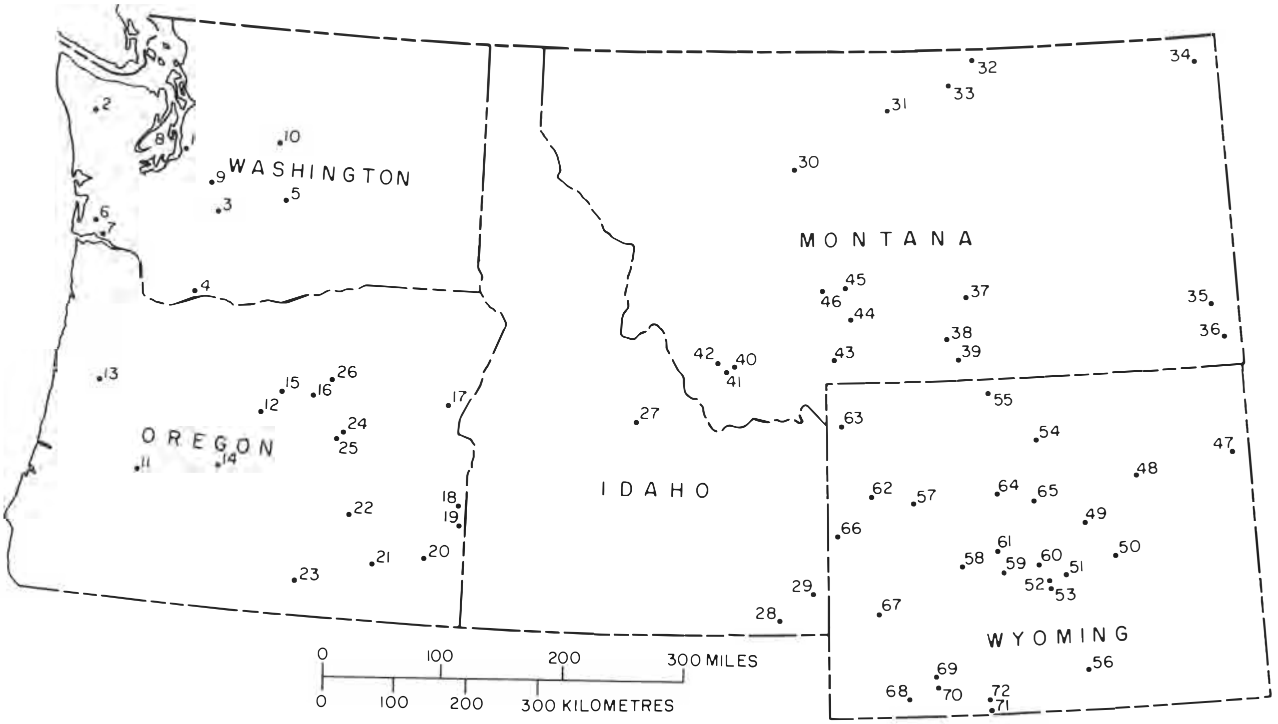

Figure 7-7.—Map showing occurrences of zeolites in sedimentary deposits of the Northwestern United States. Data for numbered localities are given in Table 7-2.

and Utah. Johannsen (1914), however, had earlier described unidentified zeolites in the Washakie Formation (Eocene) of Wyoming. Previously, Sinclair (1909) observed that vitroclastic grains in sandstone and tuff of the Washakie Formation showed "aggregate polarization" under the petrographic microscope. Finely crystalline zeolites probably produced the aggregate polarization.

Zeolitic tuffs generally are white or pastel shades of green, yellow, orange, or brown, relatively hard, and dull or earthy. The zeolitic tuffs commonly break with a blocky or conchoidal fracture. Unlike fresh volcanic ash, the zeolitic tuffs are resistant and ledge forming, particularly in arid areas (Fig. 7-8). Original textures and sedimentary structures, such as ripple marks (Fig. 7-9), are generally preserved in the zeolitic tuffs.

Most zeolites in sedimentary deposits formed after burial of the enclosing sediments by the reaction of aluminosilicate materials with the pore water. Silicic volcanic glass is the aluminosilicate material that most commonly served as a precursor for the zeolites, although materials such as clay minerals, feldspars, feldspathoids, and gels have also reacted locally to form zeolites. Hay (1966) showed that the formation of authigenic zeolites and associated silicate minerals can be correlated with the following factors: (1) composition, grain size, permeability, and age of the host rocks, (2) composition of the pore water, including pH, salinity, and proportion of dissolved ions, and (3) depth of burial of the host rock. Except for laumontite and possibly some heulandite, the common zeolites generally occur in tuffaceous sedimentary rocks that have not been deeply buried or exposed to hydrothermal solutions.

Classification of the diverse zeolitic sedimentary rocks is not settled, but the following tenuous classification is based on geologic setting: (1) hydrothermal, (2) burial metamorphic, (3) weathering, (4) open system, and (5) closed system. The hydrothermal type includes those zeolites associated with metallic deposits and especially with hot-spring deposits. A well-known example of the latter is at Yellowstone National Park, Wyoming (Fenner, 1936; Honda and Muffler, 1970). Zeolites of many geothermal areas show a vertical zonation, and the downward succession of mineral assemblages seems to correlate with an increase in temperature.

Zeolites of the burial metamorphic type were originally recognized by Coombs (1954) in Triassic sedimentary rocks of the Southland syncline, New Zealand. Coombs, Ellis, Fyfe, and Taylor (1959) demonstrated a vertical zonation of mineral assemblages that is characterized by a downward succession of clinoptilolite-heulandite-analcime, laumontite-albite, and then prehnite-pumpellyite-albite. The zeolites and associated silicate minerals of the burial metamorphic type commonly occur in marine volcaniclastic strata that are more than 10,000 feet thick and locally are as much as 40,000 feet thick. The vertical succession of mineral assemblages is one of decreasing hydration with depth and is generally thought to be temperature dependent, but chemical variables may prove to be equally important. Laumontite-bearing rocks of the burial metamorphic type occur in central Oregon (Dickinson, 1962b; Brown and Thayer, 1963) and in Mount Rainier National Park, Washington (Fiske and others, 1963).

Zeolites of the weathering type are volumetrically minor, but probably many deposits have been overlooked. Analcime was recently reported from alkaline saline soils of the eastern San Joaquin Valley, California (Baldar and Whittig, 1968).

The most voluminous and potentially valuable zeolite deposits belong to the open- and closed-system types. The terms "open system" and "closed system" are used in a hydrologic sense rather than in a thermodynamic sense. Deposits of the open-system type form by the reaction of volcanic glass with subsurface water that originated as meteoric water. The original volcanic material was deposited in marine or fluviatile environments or was air laid on the land surface. Deposits of the closed-system type form by the reaction of volcanic glass with the connate water trapped during sedimentation in a saline alkaline lake.

Deposits of the open-system type commonly form in thick tuffaceous strata and show a vertical zonation of authigenic silicate minerals. Hay (1963) proposed hydrolysis and solution of silicic glass by subsurface water to account for the formation of clinoptilolite in tuff and tuffaceous claystone in the lower part of the John Day Formation in central Oregon. The upper part of the formation contains unaltered glass or montmorillonite. Mineral zones of the open-system type commonly cut across stratigraphic boundaries.

Zeolite deposits of the closed-system type form during diagenesis in alkaline saline lakes, commonly of the sodium carbonate-bicarbonate variety. Brine of this composition generally has a pH greater than 9, which probably accounts for the relatively rapid solution of vitric material and precipitation of zeolites. The authigenic silicate mineralogy can be correlated with the salinity in deposits of the closed-system type. Vitric material is unaltered or partly altered to clay minerals in tuff deposited in fresh water near the lake shore and inlets;

Figure 7-8.—Natural exposure of zeolitic tuff in lower part of Pliocene lacustrine deposit, about 3 miles east of Durkee, Oregon. Tuffs consist chiefly of chabazite.

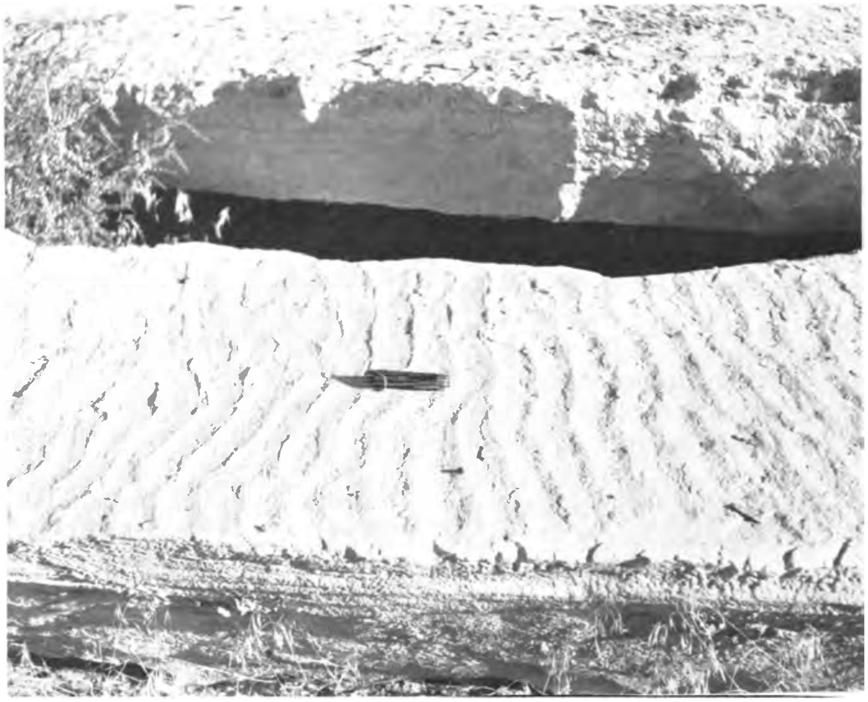

Figure 7-9.—Ripple marks preserved on a bed of zeolitic tuff from a Pliocene lacustrine deposit, about 2 miles southeast of Durkee, Oregon. Tuff consists of erionite and minor clinoptilolite.

the tuffs consist of zeolites where deposited in moderately saline water and of potassium feldspar where deposited in the highly saline and alkaline water of the central part of the basin. Examples of the closed-system type of zeolite deposits in the northwest are the Green River Formation (Eocene) of Wyoming (Surdam and Parker, 1972), the Wagon Bed Formation (Eocene) of Beaver Divide, Wyoming (Boles and Surdam, 1971), and the Rome beds (an informal unit) of Pliocene age in southeastern Oregon (Sheppard and Gude, 1969).

UTILIZATION OF ZEOLITES

The commercial utilization of natural zeolites in the United States is in its infancy, but the seemingly useful physical and chemical properties of zeolites, the high grade of many deposits, and the seemingly low cost of mining suggest greatly increased utilization in the near future. Synthetic zeolites have been used for nearly twenty years in diverse industrial applications, including applications as catalysts or catalyst supports, selective sorbents, and desiccants (Breck, 1974). The utilization and potential utilization of natural zeolites have recently been discussed by Mumpton (1973, 1975) and Munson and Sheppard (1974) and will be only briefly summarized here.

The earliest uses of zeolites and zeolitic tuff throughout the world were as pozzolanic raw material in cement (Mielenz, 1950) and as lightweight building stone. These early uses were, of course, made without knowing that the materials consisted chiefly of zeolites. Demand for zeolitic tuff for these uses in the United States is now almost nil. In central Europe, however, zeolitic tuff continues to be used in pozzolanic cement as it has been used for many centuries (Mumpton, 1973). Clinoptilolite is the most common constituent of tuff used as pozzolan, but analcime, chabazite, and phillipsite are major constituents in some. Zeolitic tuff is also quarried for building stone in Mexico, Japan, and many countries of central Europe.

Other potential uses of zeolitic tuff, made possible by the gross properties of the rock rather than the chemical or physical properties of the zeolite constituents, include fillers for paper and the production of lightweight aggregates. Because of low abrasion and high brightness of a clinoptilolite-rich tuff at Itaya, Japan, the material is used as a filler and whitening agent for paper (Minato and Utada, 1969). Experiments by Stojanovic (1968) have shown that clinoptilolite-rich tuff from several deposits in Yugoslavia can be expanded when heated and behaves similar to perlite. When calcined at temperatures of 1,220 to 1,400°C, the zeolitic tuff is transformed to a frothy, glassy material that has a density as low as 0.8 g/cm^3 and a porosity of about 65 percent.

Applications of zeolites in cation-exchange processes promise to utilize large tonnages of natural zeolites in the near future. Laboratory and pilot-plant studies using clinoptilolite demonstrated the removal of about 97 percent of the ammonia as ammonium ions from sewage streams (Mercer and others, 1970; Koon and Kaufman, 1971). This selective ion-exchange process has now been adapted to several municipal sewage-treatment plants in the United States. The clinoptilolite can be regenerated, and the ammonia is exhausted harmlessly to the atmosphere. Clinoptilolite has also been successfully used in the removal of Cs^{137} and Sr^{90} from atomic-energy waste effluent (Brown, 1962). Because of the growing use of nuclear energy, there is the increasing possibility of soil contamination by radionuclides at biological hazardous levels. Experiments by Nishita and Haug (1972) have shown that the addition of clinoptilolite to soils contaminated by Sr^{90} caused a marked reduction in the strontium uptake by plants.

Although zeolitic tuffs are widespread throughout the world, only the Japanese seem to be using them in agriculture. For more than a century, farmers in many parts of Japan have been adding crushed zeolitic tuff to their soil (Minato and Utada, 1969; Nishimura, 1973). The zeolites used in Japan as soil amendments are clinoptilolite and mordenite. Besides making available the exchangeable cations, the zeolites neutralize an acid soil. A related use of clinoptilolite is its addition to soils along with chemical fertilizers. For more than a decade, clinoptilolite has been used to improve the retention of nitrogen by the soil. The clinoptilolite apparently retains the ammonium nitrogen in the soil where the nitrogen is then utilized more effectively by the crops. The Japanese also spread crushed clinoptilolite-rich tuff on cattle feedlots. The zeolite picks up the nitrogen component from the wastes and is a more effective fertilizer when spread on the farmlands along with the manure. Crushed clinoptilolite-rich tuff is used in the raising of pigs and chickens to deodorize and dry the excrement of these animals. The spent zeolite-excrement mixture can then be used for fertilizer. Clinoptilolite is also used in Japan as a carrier for various insecticides and herbicides.

Successful experiments in Japan using clinoptilolite as a dietary supplement for pigs and chickens suggest increased demand for this zeolite. Test animals fed diets containing 5 to 10 percent clinoptilolite generally showed faster weight gain and required less feed than control animals (Kazuo Torii, oral commun., 1974). Severe cases of scours in pigs were also relieved by the addition of clinoptilolite to the pigs' diet.

Natural mordenite is used in Japan to separate oxygen and nitrogen from air. The process is based on the preferential adsorption of nitrogen by treated mordenite and is capable of producing oxygen at purities as great as 90 percent and nitrogen at purities as great as 99.95 percent (Koyo Kaihatsu Kabushiki Kaisha, 1971). Installations using this process are reported to be cheaper than air-liquefaction plants of the same capacity, and the power consumption is less than that of the air-liquefaction process. Installations of various sizes and mobilities have been constructed in Japan chiefly for the oxygen product, which is used in processes as diverse as the smelting of pig iron and the raising and transportation of fish (Hideo Minato, oral commun., 1974). If the underground gasification of coal progresses beyond the pilot-plant stage in the United States, natural mordenite could be used to produce relatively cheap oxygen. The use of oxygen rather than air in the gasification of coal would greatly enhance the production of useful fuel gases.

The adsorption selectivity of other zeolites has made them useful in the drying and purification of various gas streams. For example, chabazite from a deposit near Bowie, Arizona, is used to remove H_2O, CO_2, and H_2S from acidic natural gas. Chabazite is also used in a pilot plant near Los Angeles, California, to recover methane from a sanitary landfill (Mumpton, 1975). Erionite from a deposit in Jersey Valley, Nevada, is supposedly used in hydrocarbon separations (Mumpton, 1973).

Zeolites from the sedimentary deposits in the Northwest will undoubtedly find diverse applications in agriculture and industry. The potential applications of natural zeolites can be considerably increased by chemical and structural modifications of the natural material. Barrer and Makki (1964) demonstrated that a wide range of sorbents could be produced from clinoptilolite by treatment with hydrochloric acid.

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HELL BENT FOR BENTONITE

William B. Beatty*

ABSTRACT

Bentonitic clay is the alteration product of volcanic rocks and related ash. Deposits were formed in marine and lake waters in the Great Plains and Mississippi regions. Two-thirds of the United States reserves are in Montana and Wyoming and are of Cretaceous age. Many smaller deposits of Tertiary age are spread through the central and western states. Total domestic reserves are estimated at one billion short tons.

The swelling, binding, and absorptive properties of the bentonite clays give them a three-way advantage in several industrial applications, such as binding agents in foundry sands, an early and important continuing use. This binding ability has ensured an ever-growing market in the last twenty years in the taconite pelletizing industry, which is supplied in part from Montana and Wyoming deposits and processing plants. General "pit-run" bentonite clays have long been used in rotary drilling of oil wells. Here bentonite seals off porous strata, preventing loss of mud and fluid, and provides viscosity control to keep the barite suspended in heavily weighted mud, where mud weight may exceed 100 pounds per cubic foot.

Other uses include sealant in irrigation ditches and canals, additives in pelletized agricultural feeds, and adsorbants or filter media in many types of food processing. There is also a trend toward using bentonitic clay in the paper industry, a market long dominated by kaolin clay.

The outlook for the continued and rising expansion of the bentonite market is certainly healthy—tied as it is to unique applications to the accepted processes in the taconite iron, petroleum, and food industries. Generally speaking, as the Gross National Product goes, so goes bentonite!

INTRODUCTION

Bentonite clay is an alteration product of volcanic ash and tuff. It is characterized by colors ranging from greenish gray through yellow cream to near white on surface exposures. All bentonite has a waxy or soapy surface texture when moist; even a dry chip will become slick when moistened. The principal clay minerals in all bentonite are the several varieties of the montmorillonite family; most contain sodium, which gives water-swelling properties, or calcium, which is a low-swelling or non-swelling variety but which may be acid-activated for other uses. Magnesium, potassium, and lithium in other varieties give special properties to some of the family members.

Pure bentonite clay has a very large surface area, owing to the extremely fine particle size, which ranges down to colloidal in size. Silt- and sand-size particles of quartz, opal, calcite, unaltered ash, etc., are, in effect, impurities and are called grit. The crystal structure and large surface area give the clay a unique adsorbing capacity, either initially or when activated. This accounts for three principal capabilities:

Swelling	Adsorbing	Binding
drilling muds	decolorizers	agglomerating
sealants	carriers	foundry-sand binder
plasticizers	filters	
	fillers	pelletizing

These properties enable bentonite to find a wide variety of applications in the processing industries as well as in oil-well drilling, agriculture, and construction.

There are many specialty applications of bentonite, and many hundreds of patents have been issued covering unique uses. Bentonite enjoys a much wider spread across industrial uses than most of the members of the industrial mineral family.

GEOLOGY AND DISTRIBUTION

The rocks that have been altered into bentonite are of volcanic origin, mainly volcanic ash. The volcanic ash is air transported and is widespread over the Great Plains far to the east of presumed source vents in the Rocky Mountains. Alteration completely restructures and devitrifies the parent rock, and this may take place through submergence in a lake or sea, hydrothermal alteration, or slower ground-water percolation. Hot-springs action may contribute, as in the hectorite deposit in California's Mojave Desert.

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*Stanford Research Institute, Menlo Park, California.

Bentonite was first mined near Rock River, Wyoming, in 1888, but took its name from the Benton Shale, in which formation it was thought to be found. The type locality for the Benton Shale is well to the north at Fort Benton, Montana, at one time the head of navigation on the Missouri River. This western bentonite has become typed as "Wyoming-type high-swelling soda or sodium bentonite". It is mined extensively in Montana, Wyoming, and western South Dakota from Cretaceous beds, the oldest beds now mined for commercial-grade bentonite. Several western deposits are of Jurassic age, but they have not been developed. Elsewhere in the desert or interior side of the Pacific Slope there are scattered deposits of late Tertiary age. They are all of the nonswelling variety, but some have been long-time producers. The Cheto mine, in eastern Arizona, and a deposit in western Oklahoma are both Pliocene. A saponite deposit in the Ash Meadows district on the California-Nevada border has been mapped as Pleistocene in age, making this deposit virtually newborn. Table 8-1 shows the 1973 and 1974 production for the ten principal producing states; 1973 is the first 3-million-ton production year, and 1974 shows a 10 percent growth to 3.3 million tons.

Southern bentonite is classed as "calcium type" and occurs in Cretaceous and middle Tertiary formations. The southern states, Mississippi, Alabama, Oklahoma, Texas, and Louisiana, all produce bentonite, from three or four mines in a small district in each state. Georgia and adjacent Florida are also important suppliers of Fuller's earth, which is widely used for fillers, adsorbents, and drilling mud. Fuller's earth from these states occurs in a montmorillonite form, which can be used in place of either sodium or calcium bentonite, and also in the attapulgite form.

Table 8-1.–Bentonite sold or used by producers in the United States, by state (from Ampian, 1974).

	1973		1974	
State	Short tons	Value	Short tons	Value
Arizona	35,067	$ 394,588	32,803	$ 382,545
California	49,682	823,102	56,427	1,520,221
Colorado	1,012	6,525	4,124	37,688
Mississippi	286,135	3,606,934	333,533	4,599,118
Missouri	74,000	W	W	W
Montana	176,586	1,232,400	239,290	2,091,677
Oregon	875	10,495	1,119	13,423
Texas	84,620	802,182	68,575	881,065
Utah	4,880	64,880	3,153	49,172
Wyoming	2,106,369	23,529,610	2,295,248	28,882,276
Other states*	253,316	4,368,040	276,228	5,512,950
Total	3,072,542	$34,838,756	3,310,500	$43,970,135

W Withheld to avoid disclosing individual company confidential data; included with "Other states".

*Includes Alabama, Idaho (1973), Nevada, Oklahoma (1973), South Dakota, and data indicated by symbol W.

RESERVES

The deposits outlined above range in size from lenses covering but a few acres to formations miles in extent, such as the Mowry Shale of the Great Plains region, which can be traced in outcrop for tens of miles and which provides most of the high-swelling bentonite production at present. High-quality clay may be profitably mined from beds as thin as 1 foot, but most clay is obtained from larger deposits, ranging to 30 feet in thickness. Reserve figures for clays in general are based on stratigraphic and sedimentary geologic data as well as drilling and sampling.

Figures provided by the U. S. Bureau of Mines covering specialty clays estimate bentonite reserves at 800 million short tons, of which Montana and Wyoming together account for 500 million. The rest is divided mainly among eight other states. Similar deposits predicated in the plains provinces of Canada increase the total for North America to 1 billion tons available for future domestic requirements. As the total world reserves are approximated at 1.5 billion tons, North America is in good supply. It should be noted, however, that the U. S. Bureau of Mines' specific term is "Apparent Reserves".

INDUSTRY DEVELOPMENT PATTERN

Bentonite first was used for its swelling properties as a sealant and liner for irrigation ditches and reservoirs. In the early years of the century it was used as a cleaner and washing clay. In the 1920's foundry practice showed that bentonite made a superior binder in molding sands, and this discovery provided a great new market. Petroleum exploration during the 1930's saw the rapid development of deep oil-well drilling with a rotary bit and a circulating mud stream for lifting the cuttings. The thixotropic and lubrication properties of bentonite make heavily weighted drilling muds possible to pump, and the wall-building ability effectively cakes the wall and seals off permeable formations. These properties make bentonite indispensable to the oil industry.

The growth and wide diversification of the principal uses of bentonite are shown in Figure 8-1. A more specific listing of uses and related consumption figures for 1974 is provided in Table 8-2.

The development of the taconite pellet in the 1940's established a subindustry within the steel industry. In this application, a 1 percent content of bentonite in the mixture supplies agglomerating service in the raw stage and binding help when the pellet is fired. This development greatly increased the demand for the high-swelling Wyoming-type bentonite. As the taconite facilities were built in the Minnesota Iron Range, the steel companies acquired properties that became captive mines or they provided capitalization help by long-range buying contracts to assure their supply.

The three major industries noted here—foundry casting, oil-well drilling, and taconite pelletizing—con-

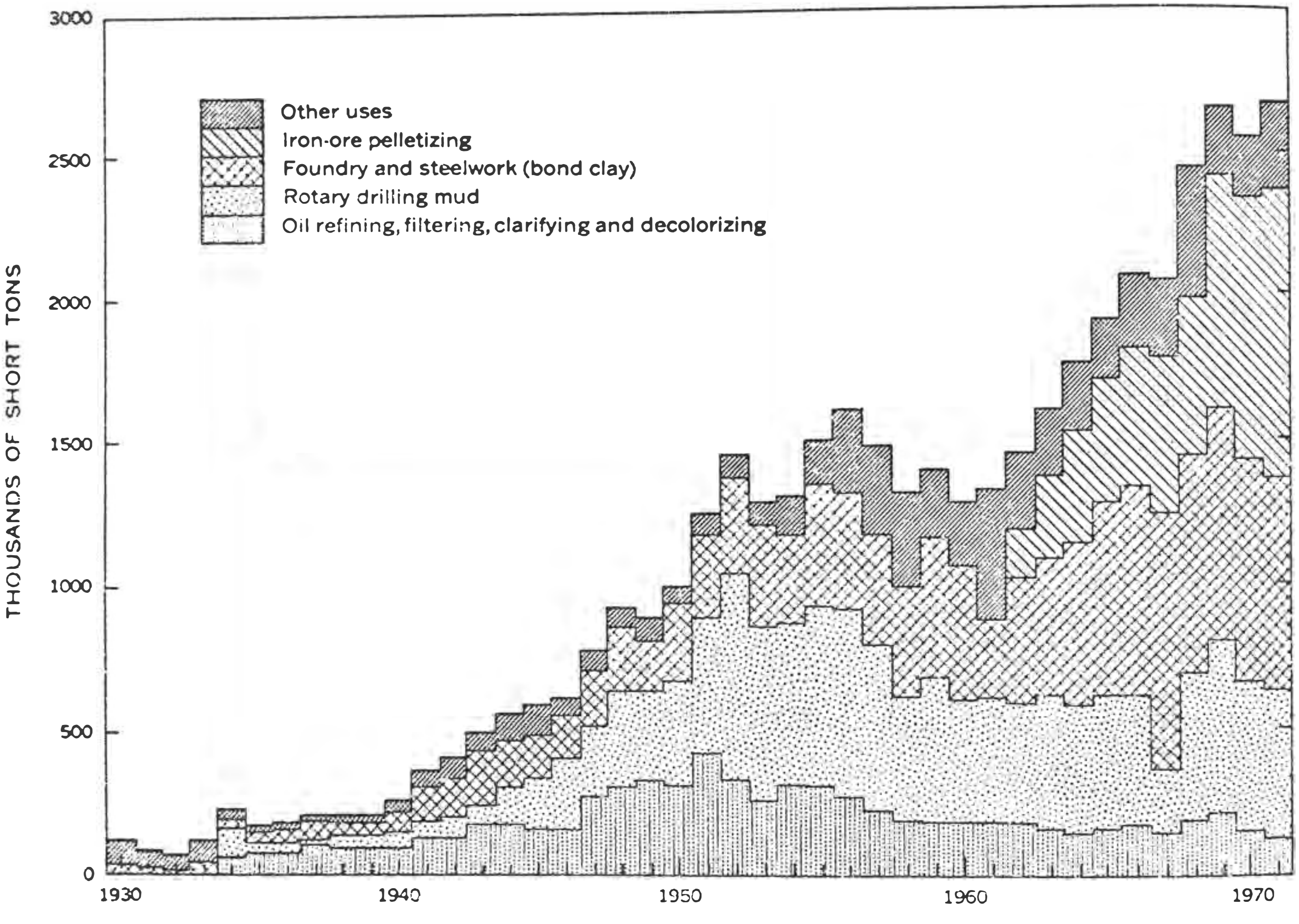

Figure 8-1.—Graph showing bentonite sold or used by producers for specified uses, 1930-1971, compiled from Minerals Yearbook, U. S. Bureau of Mines (Patterson and Murray, 1975, p. 524).

Table 8-2.–Bentonite sold or used by producers in the United States in 1974, by type and use, in short tons (from Ampian, 1974).

Use	Nonswelling	Swelling	Total
Domestic:			
Animal feed	46,532	129,174	175,706
Building brick, face	--	2,922	2,922
Catalysts (oil refining)	4,853	26	4,879
Cement, portland	--	459	459
Drilling mud	15,180	584,508	599,688
Fertilizers	6,490	--	6,490
Filtering, clarifying, and decolorizing:			
Animal oils and mineral oils and greases	83,535	8,269	91,804
Vegetable oils	71,290	--	71,290
Foundry sand	270,395	467,660	738,055
Glazes, glass, and enamels	--	209	209
Gypsum products	--	506	506
Medical, pharmaceutical, and cosmetic	200	14,678	14,878
Oil and grease absorbents	W	W	14,860
Paint	--	4,915	4,915
Pelletizing (iron ore)	--	870,464	870,464
Pesticides and related products	21,525	2,328	23,853
Pet absorbent	W	W	6,319
Pottery	307	--	307
Sewer pipe (vitrified)	100	--	100
Roofing tile	13,129	--	13,129
Waterproofing and sealing	1,407	84,888	86,295
Miscellaneous	27,060	54,348	60,229*
Total	562,003	2,225,354	2,787,357
Exports:			
Drilling mud	--	152,912	152,912
Foundry sand	16,781	215,142	231,923
Pelletizing (iron ore)	--	112,833	112,833
Other	4,458	21,017	25,475
Total	21,239	501,904	523,143
Grand total	583,242	2,727,258	3,310,500

W Withheld to avoid disclosing individual company confidential data; included in "Miscellaneous" uses.
*Incomplete total; remainder included in total for each specific use.

sumed 75 to 90 percent of total production in recent years. The rest is used in the multitude of specialties, most of which require special qualities but relatively small production lots. Some of these applications are in the agriculture, food and beverage processing, chemicals and pharmaceuticals, paint, and ceramic industries. Refer to Table 8-2 for the most important uses of bentonite.

MINING AND MILLING OPERATIONS

Most bentonite mines today are "open pit" developments. They are equipped with large and modern earth-moving equipment for mining and transport to the mill. Strip mining, disposal of waste tailings, and reclamation and restoration of mined areas all require a much greater input of management, planning, control, and labor and equipment time layout than in former times when "get it out and get it done" practices prevailed.

Milling and processing by the producer consists mainly of shipping a product that meets specifications related to size, lack of "grits" and impurities, and specific abilities, mostly physical, for the intended use. Standards and specifications are essentially *user-oriented* rather than industrywide. Essential processing at the mill, located at railhead of the mine-haulage road, includes drying, grinding, sizing by screens and cyclones, and possibly blending with other mine runs to ensure meeting specifications. All milling processes are carefully monitored for dust losses.

During the last decade, mining and related processing activities have been increasingly subject to scrutiny and restrictive regulations in areas where the "quality of the environment" would appear to be affected, either presently or potentially. These pressures come from bureaus and offices in all levels of government, from city and county to federal, as well as from groups of "concerned citizens", and they have effectively raised the cost of mining and processing all along the line. Open-pit mines and dusty processing plants—typical of the clay business—have been the most vulnerable to these regulatory pressures. On all sides one can see recently adopted "good housekeeping" rules which, in terms of cost effect, get passed on to the retail customer, who, from his standpoint, is likely to complain of inflation. Clay producers have formed their own self-supported organizations to protect their collective interests and to look out for regulatory laws or "cease and desist" controls. These groups include the Absorptive Minerals Institute recently set up in Chicago, the Bentonite Producers Association, organized in Casper, Wyoming, in 1971, and statewide mining associations established in Georgia and Texas in 1972. Most state associations represent all mining interests in general, and they have all added to their staffs and greatly increased their service level to keep their member companies informed and on top of regulatory legislation.

PAST PRODUCTION AND GROWTH PATTERN

Early-day bentonite production involved relatively small-scale mining operations, and the U. S. Bureau of Mines included available figures in "Miscellaneous Clays" until 1930, when it dignified bentonite as a statistical entity. Production grew slowly until increasing demand during and after World War II led to the first million-ton year in 1950. The impetus of the taconite pellet and its bentonite binder, which began in the late 1940's and boomed in the 1950's, helped production to reach the two-million-ton year in 1968. Production reached 3.3 million tons in 1974 (Tables 8-1 and 8-2).

In recent years taconite pelletizing plants have used one-third of the total production, supplied mainly from about two dozen producing mines in Montana, Wyoming, and South Dakota. The other two-thirds of annual production divides up somewhat evenly in the categories of oil-drilling mud, decolorizing agents, foundry sand binding agents, and specialty clays.

The U. S. Bureau of Mines has published statistical studies and forecasts (Cooper, 1970) of bentonite production in terms of demand for the year 2000 based on production and background consumption figures to the two-million-ton year 1968. The estimates in the thirty-year forecast are as follows: the low figure is 4.8 million tons per year, and the high estimate doubles that to 9.0 million tons per year. The Bureau's estimates are likely to be on the conservative side; the writer will readily subscribe to the higher 9.0 million ton figure as a reasonable target and suggests that it will likely be reached well ahead of the year 2000. This would require an industry rate higher than the Gross National Product projections, but as current reported production (1974) is 3.3 million tons, the 9.0 million figure should be a reasonable target. Reasons for this optimistic view are discussed hereafter in seeking trends in the principal uses of bentonite.

BENTONITE IN DRILLING MUD

As oil and gas well drilling practice developed during the 1930's and 1940's to depths in the 15,000-foot range, bentonitic mud became essential in aiding the pumping of heavily weighted mud and in sealing off porous strata to prevent water loss from the mud column. This provided a large and important market for bentonitic clay, and the supplying companies have developed supply depots in most of the petroleum-producing regions of the world. When salt strata or salt water inflows were encountered, bentonite did not stand up well, so attapulgite clay from Florida and Georgia was substituted. As drilling targets moved downward to the 20,000-foot range, high temperatures were encountered that also required this clay. In drilling from off-shore platforms, seawater and attapulgite clay are used for the mud column. In sum, drilling mud accounts for 10 percent of attapulgite output. If an off-shore well encounters strata that "steal" the mud, however, tank storage or stand-by barges provide fresh water and the well is drilled with a bentonite mud column.

Some advance the optimistic view that improved exploration techniques, such as better geological knowledge, more sophisticated geophysical interpretation, satellite imagery input, etc., will improve the successful discovery well ratio sharply and far fewer exploration wells will be drilled and abandoned in the overall exploratory effort, and far less bentonite would be required. This prediction is most unlikely to be fulfilled. If there is any trend at all, it would be more and deeper wildcat wells, requiring larger quantities of bentonite in the mud-circulating stream.

In 1973 the federal government launched its large energy program to make the United States independent of imported oil supplies by 1985. What has actually happened in two years' time? Very little. Most participants, especially in oil shale and coal, have backed away because of rapidly escalating project costs. Two of the three proposed oil shale processing plants are dormant because of costs, and the third has been scaled back to pilot-plant size. Other oil shale effort still in progress is an in situ burning recovery method, which has dubious prospects of evolving into a commercial process.

A deterrent to starting a 100,000-ton-per-day coal mine operation is the projected delivery date for the heavy equipment such as draglines, giant shovels, large trucks, and the accessory loaders, dozers, and power-supply packages. Because of the backlog already in line, a fleet of trucks ordered today might be delivered by 1980.

A recent U. S. Geological Survey review (Tooker, 1975) of the energy programs' estimated demands on domestic mineral resources for the period 1975-1990 is realistic about domestic oil, and it estimates the requirements for bentonite (drilling mud) at 11 million short tons for this fifteen-year period. This is an average of about 730,000 tons a year. Over a twenty-year period domestic mud requirements rounded off at 500,000 tons per year, but in 1974 the consumption went up to 600,000 tons (Table 8-2). The Survey figure would indicate an increase in consumption of mud by 21 percent. This increased demand can be readily met by increased production at present operations and by new mines brought into operation as the market expands.

BENTONITE IN TACONITE PELLETIZING

The development of the taconite iron ore pellet for blast furnace charging, which began in the midforties, has revolutionized the iron ore business. The inclusion of "a bit of bentonite" in each pellet provided an important and steady market for Wyoming-type high-swelling bentonite. Mines and milling facilities in Montana, Wyoming, and South Dakota have tripled as a result. Most pelletizing plants throughout the world add 1 percent bentonite to the raw mix, although some have cut this down to 0.5 percent (10 pounds per ton). The clay aids agglomeration in the moist mix and blends and vitrifies with the 5 to 6 percent slag (silica) content in the final firing stage.

Because of its unique physical characteristics, bentonite makes these major contributions to the pelletizing process:

Moisture control during balling
Green-ball strength
Resistance to deformation (green-ball stage)
Dry strength (above 250°F)
Resistance to decrepitation (250 to 750°F)
Preheat strength (about 1800°F)
Fired strength (about 2400°F)

Despite all these favorable factors, the added silica in the raw mix has to be fluxed out by lime in the final stage. Therefore, a great deal of attention has been paid to search for a binding agent that, having served its purpose along the way, would just leave in the stack gas of the blast furnace. Many organic products, especially starches, have been investigated, but they do not stand up in the beginning red heat of the induration period, and they burn out too soon in the grate-kiln operation.

Bentonite's position in the flow sheet might come to be threatened by any of several cold agglomeration processes that have been designed in Sweden (Hässler and Kihlstedt, 1975) or another variation developed in Germany. Here the red-heat kiln cycle, which involves a high cost in energy, is replaced by a steam curing period, at a greatly reduced energy charge. In general the pellet resulting from these processes lacks the tough ceramic hardness of the bentonite, does not travel as well, and does not stand up in the mass of the furnace charge. These alternative processes have been investigated by the steel companies but have not been adopted.

A recent trend to be noted is the growing supply of imported bentonite from Greece and Africa. This clay is used as a low-cost extender at the expense of the higher priced Wyoming-type bentonite. Although this substitution cuts into the domestic taconite market, it releases supplies for the higher priced specialty clay and drilling mud market.

A current review of the Great Lakes District's taconite pellet facilities shows that a "Billion-dollar expansion" (Guccione, 1975) is under way, consisting of major expansions of three present facilities and construction of two new plants in Michigan and Minnesota. The District's production of pellets will increase from 53 million tons in 1974 to 78 million tons by 1978, an increase of 50 percent. Annual bentonite shipments to pelletizing plants have averaged 900,000 tons a year (Fig. 8-1) for the last five years. Increased demand due to the outlined taconite expansions will raise this figure to 1,350,000 tons a year, a healthy 5 percent yearly increase from the 1974 figure of 3,300,000 tons total bentonite production.

BENTONITE AND THE PAPER INDUSTRY

Georgia and English kaolin clay have long dominated the paper coating (and to some extent, filling) market of the world despite penalizing freight costs and luxury prices. The high costs serve to attract the attention of owners of cheaper clay, who might enter the market and offer a competitive product. So far, relatively little inroad has been made. Most clay deposits in the western states have just enough swelling or gelling properties to make them unacceptable, and many contain dark minerals that discolor the finished sheet. A deposit at Ione, California, and another at Latah, near Lewiston, Idaho, however, have been shipping a suitable paper-weighting clay for the last 10 or 12 years. In both cases a considerable amount of processing research was done before an acceptable product was developed. Generally, strata that even look remotely like a clay deposit and are within three hundred miles of a finish paper mill will have been carefully scrutinized and sampled, in hope of providing a local or captive supply. But in the end, the mills remain true to that good white, unique Georgia kaolin, the Playboy centerfold viewer's best friend.

Bentonite is being used in several ways in paper making. A hectorite clay from the newly developed California deposit (see "Hectorite" hereafter) is said to be able to take the duty of quality kaolin, and the company has a large supply contract with a paper mill. This is a breakthrough and should help to set up a better market position with the paper industry in the western states. Bentonite is also a very good de-inking agent in reclaiming recycled pulp. Bentonite adds opacity to thin catalog papers, which is a large and continuing market. It makes a good carrier for the micro-encapsulated ink in "no-carbon" multiform invoice paper packets. And there are probably many other ways in which bentonite can and will capture an increasing share of the market and make a contribution to the paper business.

NOTES ON HECTORITE

Hectorite is a magnesium-bearing clay in the montmorillonite family and has greater lithium content than typical montmorillonite. This clay possesses certain unique characteristics in some of the processing applications that have been developed. The mineral takes its name from the railroad siding at Hector, California, in the central Mojave Desert. Although the deposit had been known for many years, it was first mined in 1931.

In the midfifties the mine was further developed and a processing plant was built at Newberry, California, to provide a specialty clay designed to meet filtering and flocculating requirements in the food and beverage industries. For many years the deposit was thought to be unique, and the several patented products ensured a very profitable operation.

The entire deposit occupies a few acres under a lava flow from the Pisgah Crater, which afforded protection from erosion. Volcanic ash deposited in an alkaline lake was altered to zeolites by a combination of the alkaline environment and hot-spring activity. The zeolites in turn were altered to the present set of hectorite layers. The deposits are in the form of white waxy lenses 6 to 8 feet thick. Chief impurities are calcite crystals, sand, ash, and glass remnants. The mine was an underground operation for years, but the present management stripped away the black Pisgah lava cover and made the mine into an open pit. The occurrence is no longer regarded as unique, as a large deposit of hectorite elsewhere in California has been brought into operation in the last two years, and other hectorite deposits are known at Amboy, California, and in Yavapai County, Arizona.

The large California hectorite deposit noted above is included in an extensive sequence of beds of calcium, sodium, and magnesium bentonites on the west flank of the Funeral Range in the Amargosa Valley region of California and Nevada. Three types of bentonite are found in extensive beds. These deposits are:

(1) Hectorite—Whiting clay deposit, which is in production and is being treated at a nearby plant.

(2) Sepiolite—This is equal to Georgia attapulgite clay, or Meerschaum, and is the only known deposit of this material in the Western Hemisphere. Sepiolite

is a hydrated magnesium silicate material sometimes known as "mineral soap".

(3) Saponite—This is a member of the montmorillonite family of clay minerals and is a hydrous magnesium aluminum silicate by definition. It matches Wyoming high-quality bentonite in performance.

These deposits have been drilled, sampled, and tested to establish reserves to supply bank-run open-pit production of various kinds of clay as may be required when markets are established. The mine output is processed at the nearby mill at a rate of 500 tons per day, one shift. The range of bentonites available for processing provides a wide selection of highly specialized clay products. Present markets include drilling mud, paper clay, fillers for paper and paint, and agricultural pellets. In addition to the deposits described above, older beds of a sodium-calcium bentonite mixture offer good market potential.

INDUSTRY OUTLOOK

The figures below, the writer's views fearlessly extended for the next five years, are based on the trends for drilling mud and taconite pellet requirements noted earlier. It should be remembered that the end figure of 9 million tons per year by 2000 represents the optimistic view of the U. S. Bureau of Mines, and should be reached much earlier. Space is left for the reader's own projections.

Annual growth rate for bentonite production, millions of short tons

1950	1968	1973	1976	1979	1981		2000
1	2	3	4	5	6	(USBM)	9
						WBB conjectural	20
				____	____		____

When a commodity is required in processing the basic stock of a major industry, iron ore, as bentonite is, or in drilling to find and produce petroleum, and when these uses have long resisted cheaper replacement, then the commodity becomes irreplaceable, and its future is tied to the stock market's favorite child, the Gross National Product! The rest of the good news is the domestic reserve picture—there is plenty on hand, and there are good exploration targets for more in Canada.

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This random array of "Basic Facts That You Should Know About Bentonite" has been made possible with the friendly help of data supplied from, and useful discussion with the managers, superintendents, and knowledgeable people who are the prime source, the bentonite producers, who should know. After all, they are on the ground floor. Up-to-date estimates and production data were supplied by the U. S. Geological Survey and the U. S. Bureau of Mines. The review of taconite pellet data by the staff of U. S. Steel's Research Laboratory at Coleraine, Minnesota, is very much appreciated. Without our friends, we wouldn't be in business.

SILICA ROCK IN THE NORTHWEST

P. M. Peterson*

ABSTRACT

The six western states of Montana, Idaho, Washington, Oregon, Nevada, and California, and the Canadian Province of British Columbia currently produce more than 65,000 tons a year of high-purity silica for metallurgical and decorative purposes. Potentially economic deposits must meet the strict requirements of chemical analyses, mining feasibility, transportation, and market specifications.

All consumers of high-purity silica rock in the northwest are in Oregon and Washington. Products include silicon metal, silicon carbide, silica manganese, and ferrosilicon.

Markets are predicted to expand, and technology is advancing toward the usage of lower-grade raw materials as existing and future high-purity sources are depleted.

INTRODUCTION

As part of locating new industry within Burlington Northern's service territory, the Raw Materials Division often searches for specific raw materials upon request by industry. In 1971, such a search for high-purity silica deposits was undertaken in the western states of Montana, Idaho, Washington, Oregon, Nevada, and California and in the southern part of British Columbia. This area represents one of the few places where there are scarce but suitable deposits (Fig. 9-1).

GEOLOGY

Evaluation of silica deposits was based on the following criteria:

1. Origin
2. Chemical analysis
3. Deposit size
4. Mining and processing

To date, quartzite and sandstone have not been technologically adequate in furnaces, thus only igneous silica bodies were evaluated for industrial use.

Of utmost importance in evaluating a silica deposit is the quality, as indicated by chemical analyses based on detailed surface sampling. Metallurgical specifications for any deposit demand a 99.5 percent SiO_2 content and less than .10 percent impurities consisting of Al_2O_3, Fe_2O_3, and CaO.

Deposit size is almost as important as quality. Producers of high-purity silica estimate that at least 50,000 tons of rock should be exposed at the surface and 150,000 tons indicated by drilling before a mining plan (including 30 percent loss) can be developed for a property.

To date, the most economical method of mining high-purity silica deposits, a low-value commodity, is open-pit bench mining, so topography also plays an important role in mine development. Benches 40 feet in height and 20 feet in width are standard for both safety and efficiency. Blasted quarry rock is processed by crushing, screening (for various markets), and washing (Fig. 9-2). Different product sizes are then loaded into railroad cars and shipped to various markets.

PRODUCTION

Currently, there are four producing silica deposits in the northwest, in Weiser, Idaho; Basin, Montana; Hawthorne, Nevada; and Galen, Montana (Fig. 9-3).

Serendip Industrial Minerals of Portland, Oregon, is producing silica rock from a deposit north of Weiser, Idaho. This deposit is a quartz plug encompassed by calcic granodiorite. On its west side, the silica is covered by a Tertiary basalt flow, so true dimensions and actual available reserves are obscured but are estimated at 600,000 tons. Producing a 99.78 percent SiO_2 product for the last two years, Serendip Minerals is utilizing open-pit bench mining methods to extract the silica rock for the metallurgical market.

At Basin, Montana, Pacific Silica, Inc., of Seattle, Washington, has produced a 99.5+ percent SiO_2 since 1964. The deposit consists of a quartz plug enclosed in

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*Burlington Northern Inc., Billings, Montana.

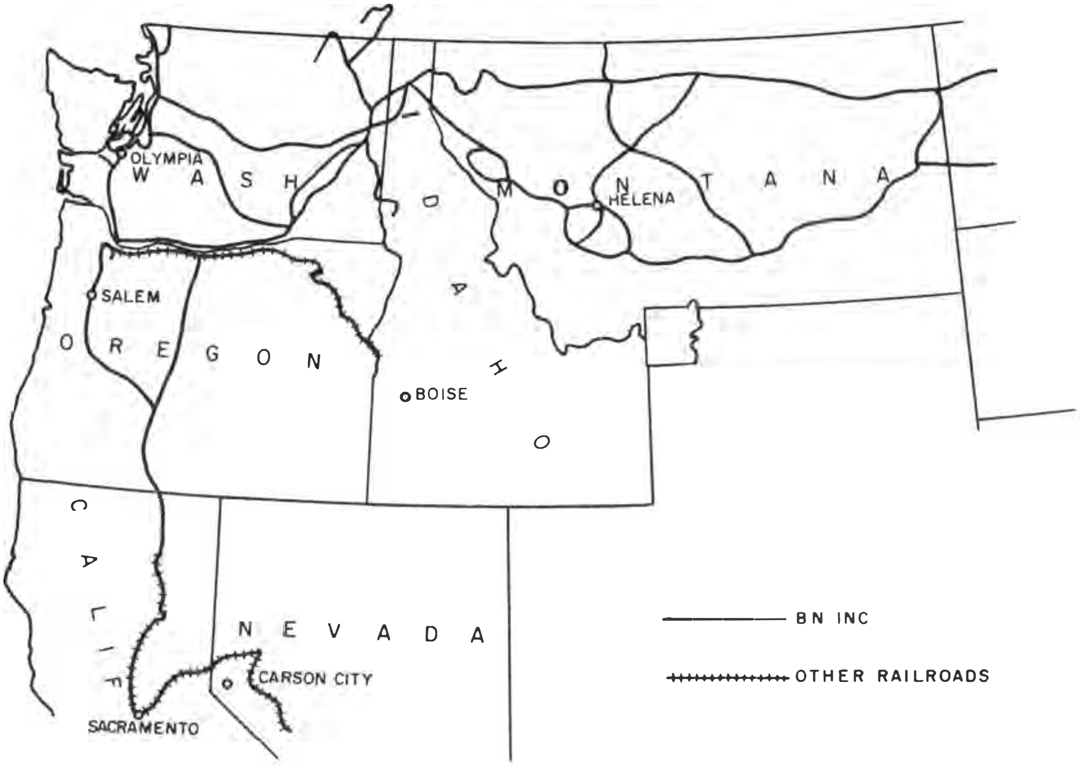

Figure 9-1.–Railroads that serve silica rock markets and deposits.

quartz monzonite. More than 250,000 tons of material has been removed for markets in the northwest. The material is blasted, loaded, and trucked to the crushing facility. Remaining reserves at this property are estimated at 100,000 to 150,000 tons.

Near Hawthorne, Nevada, Pacific Silica operates another open-pit quarry on the west flank of a huge vein of 99.89 percent SiO_2. Physical dimensions of this vein are a 1,400-foot length, 300-foot width, and 500-foot height. The deposit is enclosed in Jurassic granite and is separated into two parts by north-south faulting. Reserves at this location are estimated at three to four million tons. This deposit is the largest known in the northwest.

On a southwest slope of the Flint Creek Range west of Galen, Montana, Manufacturers Minerals of Renton, Washington, has a fairly small quarrying operation in a crystalline quartz body encompassed by limestone and quartzite of Precambrian age. Two facts suggest, but do not prove, an igneous origin for this body. No relict sedimentary texture is recognizable in thin section, and granitic dikes are abundant in the vicinity of the deposit. Manufacturers Minerals has in the past operated this quarry to produce decorative stone but is now beginning to ship this 99.81 percent SiO_2 for metallurgical use, to diversify their markets. Estimates of visible reserves range from 200,000 to 500,000 tons, and possible reserves exceed one million tons.

TRANSPORTATION

Transportation of this low-value commodity is also a vital factor, as all markets for high-purity silica rock are in Oregon and Washington, where low-cost electrical power is available for use in manufacturing various products.

All the silica rock being mined at present is transported to Oregon and Washington by rail in open-top gondola cars holding an average of 75 tons per car. The Burlington Northern alone moved about 50,000 tons in 1974.

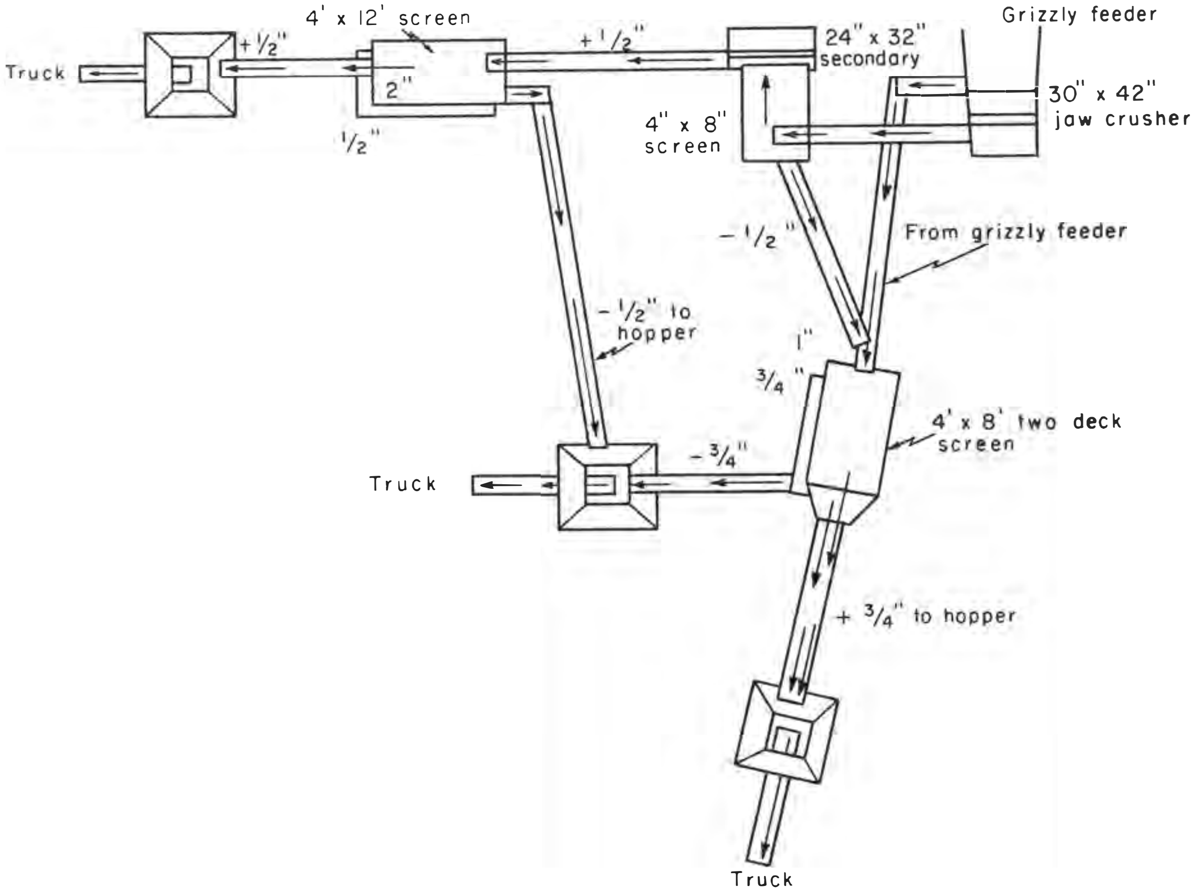

Figure 9-2.—Flow sheet for the Pacific Silica Co. mine at Basin, Montana.

MARKETS

The various metallurgical markets for silica rock are in Washington and Oregon because of cheap power and proximity to deposits. Crude high-purity silica is delivered to destinations in Oregon and Washington for use in the manufacture of silicon metal, ferrosilicon, silicon carbide, and silico-manganese (Fig. 9-4). These products play an important role as alloying agents, deoxidizers, or in electrical devices and diodes.

Hanna Mining Company operates a three-furnace silicon and ferrosilicon metal plant at Rock Island, Washington. Their consumption of silica raw materials is estimated at 50,000 tons a year; the material is obtained from the Weiser, Galen, and Basin deposits. The process raw materials include 50 percent quartz, 25 percent metallic iron, and 25 percent reductant (usually coke, charcoal, or wood chips). The products are used as deoxidizers for steel ingots and castings, alloying agents, diodes, and other electrical devices.

National Metallurgical in Springfield, Oregon, operates a four-furnace silicon metal plant, which consumes about 30,000 tons of silica a year. The silica is obtained from Hawthorne, Nevada. Processing procedures are similar to those of Hanna at Rock Island.

At Vancouver, Washington, Carborundum Company consumes approximately 30,000 tons of silica rock from Basin and Weiser to produce silicon carbide, a very hard abrasive for various uses. In Portland, Oregon, Union Carbide produces silicon metal and silico-manganese. The plant is not now receiving silica raw material as the stockpile material at the plant site is sufficient. Silico-manganese assists in the deoxidation of steel melts and also has alloying properties.

Consumers are now using about 85,000 tons of silica rock a year. In 1971, the consumption was estimated at 150,000 tons a year, but when Ohio Ferroalloys shut down its operation in Tacoma, Washington, and the steel industry market faltered, consumption dropped.

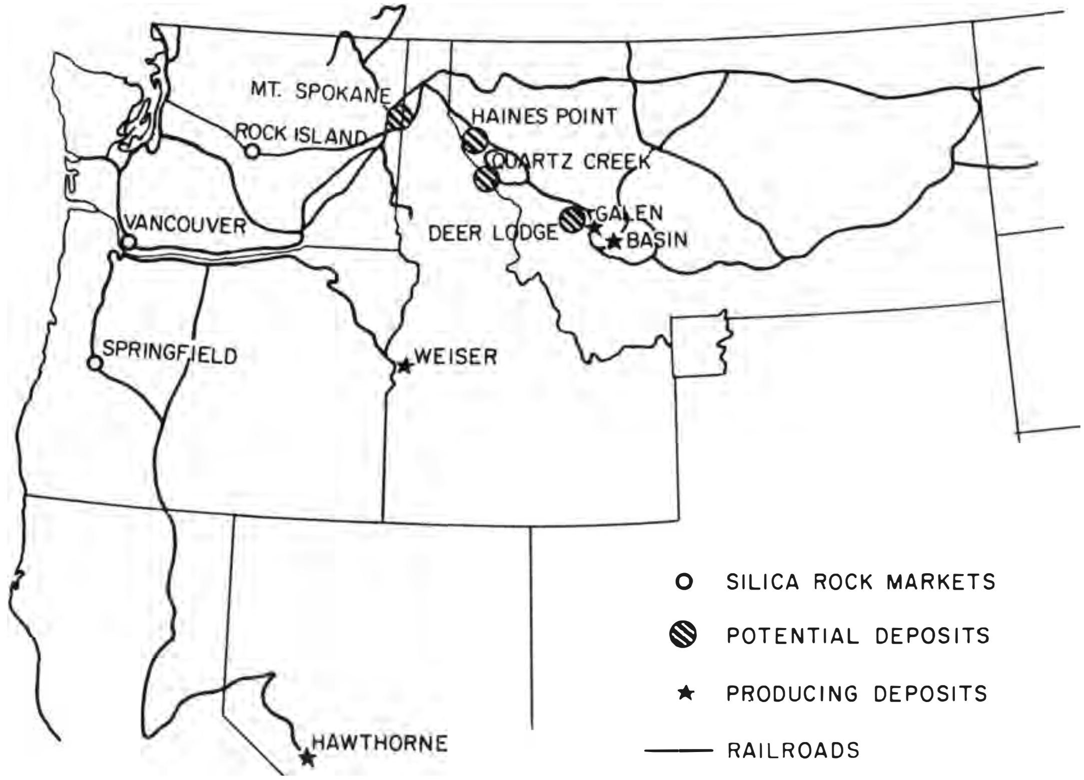

Figure 9-3.–Deposits of silica rock and their markets.

FUTURE

Market indications now predict increased consumption of silica rock for the future. These indications include such things as the doubling of plant capacity by National Metallurgical at Springfield, and construction of a magnesium plant by Alcoa at Addy, Washington.

The future of this unique market is positive, but at the projected consumption rate of 125,000 tons a year, some producing deposits will soon be exhausted. Additional deposits at Haines Point, Montana; Deer Lodge, Montana; Quartz Creek, Montana; Mt. Spokane, Washington; and Armstrong, B.C., may be developed, and may be adequate for the near future, but advances in technology by the consuming industry may make it more economical to use high-purity quartzite which is widespread in eastern Washington and western Montana. That technology has not yet been developed, however.

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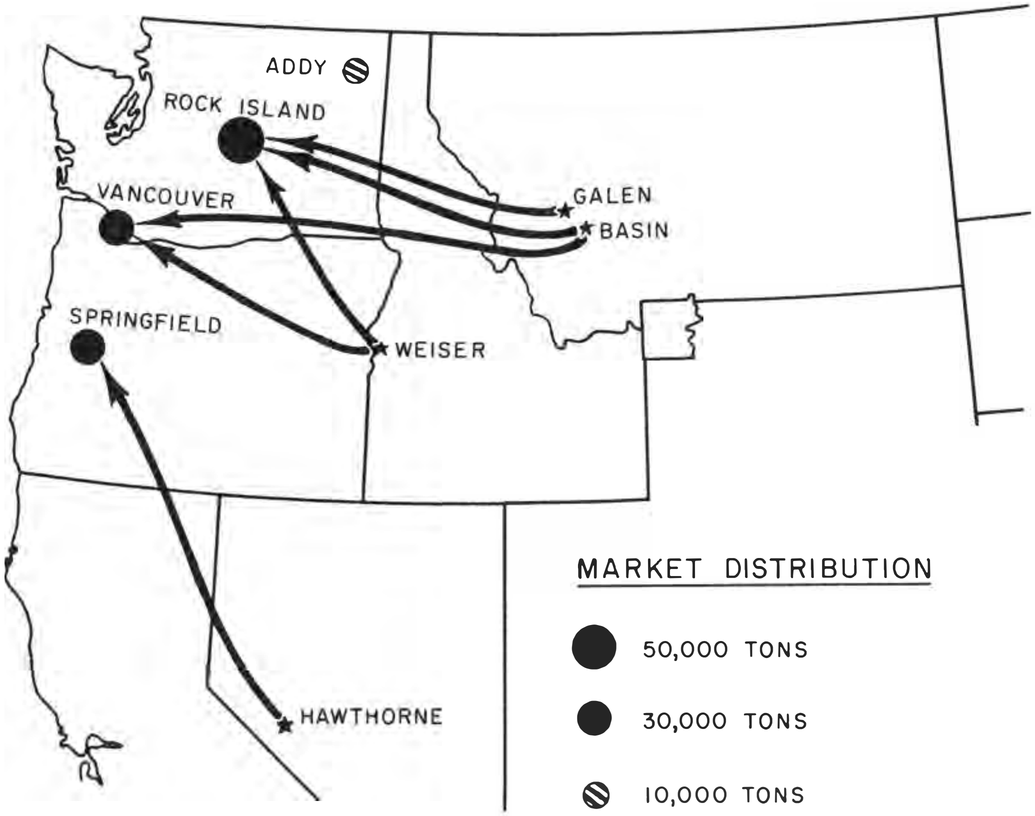

Figure 9-4.—Markets for silica rock.

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THE GEOLOGY OF MONTANA TALC DEPOSITS

Richard H. Olson*

ABSTRACT

Talc deposits in the Precambrian rocks of southwestern Montana (Beaverhead and Madison Counties) are unique within the U.S. in that large bodies of tremolite-free talc ore can be open-pit mined. All known deposits are in pre-Beltian dolomite units. The origin is suspected to be metasomatic, the siliceous component having been contributed by an intrusive body of Precambrian granite gneiss. Precambrian deformation was extreme and is characterized by multiple periods of folding and the flowage of less competent rocks, rather than by faulting. Post-Precambrian folding has been negligible; the characteristic Laramide structure is block faulting along northwest trends.

The talc is thought to have been formed in Precambrian time; the high-angle block faults have no significance with regard to the formation of the talc but do tend to complicate mining operations.

Tremolite-free talc ore bodies that have horizontal widths of more than 200 feet, vertical depths of several hundred feet, and strike lengths of as much as ½ mile are known in the Ruby and Gravelly Ranges. Where dolomite is interbedded with tremolite-free talc in the Gravelly Range the scale of this relationship permits the use of conventional open-pit mining methods with subsequent upgrading by hand-sorting techniques.

Underground mining has been used in the past, but all current Montana talc-mining operations are on the surface. The hand-sorted crude ore, some of which is shipped overseas, is finely ground or micronized in roller mills and fluid-energy mills. The products are distributed nationwide and abroad.

TALC-MINING INDUSTRY

The talc-mining industry, like that of many other industrial mineral commodities, has a complex and varied structure. This is necessitated by the fact that products made from such ores have a multitude of uses; literally hundreds of products, most of them manufactured from roughly similar ores, are currently on the market.

Talc, which has the composition $3MgO \cdot 4SiO_2 \cdot H_2O$, is a valid mineral species and has long been recognized as such by mineralogists. The term "talc", however, to talc miners, talc processors, talc salesmen, and talc consumers, covers a multitude of sins and when so used may pertain to material that contains little or none of the mineral talc. Among such persons, the term "talc" may be freely applied to any talc-like rock or mixture of such rocks that can be used to manufacture products acceptable to a customer.

Talc may be regarded as the pure end member of a series, soapstone being the impure end member of that series. Soapstone is a rock name, not a mineral name, and soapstone is generally composed predominantly of impure talc containing relatively minor amounts of chlorite, mica, and various amphibole and pyroxene minerals.

Tremolite, which has a theoretical chemical composition $2CaO \cdot 5MgO \cdot 8SiO_2 \cdot H_2O$, is, more commonly than not, the major component in "talc" ores, at the expense of the mineral talc itself, which may be of only minor volumetric importance. This relationship may hold throughout large talc-mining districts, e.g., the New York and California-Nevada districts.

Other talc-like minerals (i.e., chemically or physically similar) that may constitute various proportions of "talc" ores are anthophyllite, antigorite, chlorite, pyrophyllite, and serpentine.

The mechanics of the formation of talc bodies and the inherent compositions of the rocks from which such bodies have been formed dictate that some impurities will be present, even if none of the "talc-like" minerals are present; such indigenous impurities include calcite, dolomite, magnesite, and quartz. By "indigenous" is meant those materials that will be generated *in situ* by incomplete alteration to the mineral talc, i.e., the reconstitution of the pre-existing parent material without any appreciable addition of extraneous material.

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Many other impurities may also be introduced and modified during epigenetic processes of mineralization; the most common of these are calcite, dolomite, graphite, hematite, limonite, magnetite, pyrite, pyrolusite, quartz, and various sulfates.

"Steatite" is a much-abused name, which means, unfortunately, different things to different people. It was originally a mineralogical name used to denote massive talc or talcose rock. It has subsequently been used to designate a grade of talc ore that can be used to manufacture electronic insulators, thereby having primarily a physical connotation rather than mineralogical and chemical connotations. At one time the term was even synonymous with soapstone, but the present meanings of these two terms are far apart. In order to qualify as steatite-grade today, talc ore must contain less than 1.5% CaO, less than 1.5% Fe_2O_3, less than 4.0% Al_2O_3, and only minute quantities of "other impurities", and it must be suitable for the manufacture of high-frequency electrical insulators. Virtually all of this country's reserves of steatite-grade talc ore are in southwestern Montana. That grade of talc is present in several other districts, but those bodies are comparatively small, and most must be mined in conjunction with the lower-grade ores, the market for whose products dictates the rate at which the steatite-grade ores may be economically mined.

The term "steatite" will not be employed in this paper in the discussion of Montana's talc deposits. The term "talc" will be used in the mineralogical sense for ores that are predominantly composed of that mineral alone and contain little or none of the "talc-like" minerals. For those ores that contain measurable amounts of tremolite or other "talc-like" minerals, the term "talc-rock" will be used. This usage is not an attempt to establish nomenclatural rules but merely a desire to accentuate the difference in purity between Montana talc ores and the ores from the other five major talc-mining districts of North America.

High-purity talc ores, which can be mined as such without extracting other, lower grade ores and which can be used for the manufacture of high-purity talc products, are at present known in the United States only in southwesternmost North Carolina and southwestern Montana. Those in North Carolina are mined underground; only in Montana may such ores be mined by open-pit methods at relatively low cost.

The writer first became acquainted with Montana's talc deposits and their geology when Pfizer, Inc., by whom he was employed, purchased Southern California Minerals Company, which was then, as Pfizer is now, one of the two major producers of Montana talc ores and their products. It would not be possible to thank all of those Pfizer employees who willingly shared their knowledge, but Messrs. John V. Burk, Otto D. Rohlfs, Jr., Walter W. Weid, and L. R. Wood in particular worked in the field with the writer and their help and contributions and good company are herewith specifically acknowledged.

During his tenure with Pfizer the writer also had the privilege and the pleasure of working with Dr. Rudolph M. Hogberg and Mr. C. F. Joy, consultants, both of whom freely shared the results of their considerable prior experience in the Montana talc district and made numerous extremely helpful suggestions and contributions.

Also while with Pfizer the writer was privileged to participate in the supervision of two Ph.D. dissertations at Pennsylvania State University. Drs. John M. Garihan and Angelo F. Okuma studied the central and southern parts of the Ruby Range, respectively, particularly those specific areas that seem to have the greatest potential for the discovery of commercial talc deposits. Their work was a general areal study encompassing mainly stratigraphy, structure, and general geology; it was never intended that they, by themselves, solve the riddle of talc genesis. Their excellent contributions (Okuma, 1971; Garihan, 1973), however, serve as the firm background upon which all future work on the talc deposits of the Ruby Range will be based. Pfizer, Inc., deserves credit and sincere thanks for its generous support of these two investigations.

Messrs. Ed Stevens, James D. Mulryan, and Donald F. Kennedy of Cyprus Industrial Minerals Company have also shared their knowledge over the years and have extended the courtesy of conducting the writer on visits to their mines and mill in Montana.

Several geologists of the U.S. Geological Survey, particularly Mr. Kenneth L. Wier and Ms. Karen Shaw, have through years of dedicated effort and detailed mapping (much of it still unpublished) contributed to the knowledge of the extremely complicated pre-Beltian stratigraphy and structure of the southwestern part of the Ruby Range, particularly in the Christensen Ranch 7½-minute quadrangle. A particularly significant map (James, Wier, and Shaw, 1969) was open filed primarily in order to enhance the knowledge of potential talc-bearing areas for those economic geologists then involved in the search for new talc mines in the Ruby Range. For many most informative and constructive suggestions, as well as the benefits of numerous pleasant field excursions, the writer is fondly indebted to Mr. Wier and Ms. Shaw.

Mr. Walter K. Skeoch, formerly President and owner of Southern California Minerals Company, and Mr. James D. Mulryan of Cyprus Industrial Minerals Company have kindly supplied background information on the history of the growth and development of the Montana talc industry, which is incorporated into this paper.

Messrs. Tom McGovern and Bennett Owen of Dillon, Montana, have been involved in the prospecting for and the mining and processing of Montana talc for more than four decades between them. They have freely shared their considerable knowledge, have showed the writer several deposits of which he had not been aware, have pointed out features that he had not seen, and have described some that had been destroyed or mined out.

Little of the investigations documented in this paper could have been made without the cooperation of ranchers in the area, particularly Fred W. ("Buster") Brown and Art Christensen of Dillon, Montana. Both of these fine gentlemen not only allowed access to all of their large land holdings but also accompanied the writer on many field trips and pointed out several features that would otherwise have gone unknown to him.

Mr. Raymond Olson served as a most capable field assistant in 1974 and made many significant and meaningful contributions to this study.

TALC VS. TREMOLITE CONTROVERSY

Rightly or wrongly, in recent governmental investigations into health and safety matters tremolite has been likened to asbestos. The results of a symposium on the health hazards of respirable dust in the mining and milling of talc and "talc-like" ores, convened by the U.S. Bureau of Mines in Washington, D.C., on May 8, 1973, have recently been published (Goodwin, 1974). This and other such investigations have led many consumers to switch from products manufactured from tremolitic ores to those manufactured from high-purity talc ores, such as those mined in Montana. The production of talc ore in Montana has more than doubled in the period 1969-1974, and much of that sharp and relatively sudden increase must be attributed to that factor.

While "the jury is still out" on this controversial matter, the Montana talc-mining industry stands to benefit at the expense of all the other districts, with the possible exception of North Carolina.

USES

Talc products, whether manufactured from high-purity talc ores, tremolitic ores, or other types of "talc-like" ores, are numerous and have myriad uses and applications. These are well documented in the literature, particularly by Johnstone and Johnstone (1961), Cooper and Hartwell (1970), Olson (1970), Wells (1972), Patton (1973), and Roe (1975).

The natural color of Montana talc ores ranges from white or very pale green at the lightest to dark green, greenish gray, or even black at the darkest. In most of these ores, except for the darkest ones or the ones containing graphite, the color (whiteness) improves noticeably upon fine grinding (particularly in the 5-micron size). Blending of darker ores with some of the lightest ores can extend the life of ore bodies. Darker ores may be used in place of lighter ores if color is not a particularly important product specification.

The ceramics, paint, and paper industries consume more than half the dollar value of talc products currently sold in the United States, and it is in these three industries that virtually all of Montana's talc products are used. It is the development of high-quality pigment-grade products that has enhanced the rapid growth of Montana's talc industry in recent years, and these product lines have been brought about by the development of extremely fine grinding or "micronizing" techniques in "jet" or fluid-energy mills. Many of the Montana talc products currently sold by both present producers will have more than 50% of their weight in the −4 micron size, and almost all of them will have considerably more than 50% of their weight in the −10 micron size.

OTHER NORTH AMERICAN TALC DISTRICTS

Before embarking upon a description of Montana's talc deposits, it would be well to briefly describe the other five major talc-mining districts of North America and to cite similarities and differences, so that the reader will then have a background for comparison.

The geological settings of talc deposits in the United States and Canada are as varied and diverse as would be expected for any naturally occurring mineral commodity, but there are some broad similarities. First, talc is invariably a secondary mineral formed *in situ* from pre-existing or introduced material or both. Second, commercial bodies are generally tabular and concordant (at least in the overall sense, if not everywhere locally), being "molded" after the shape of the parent material, which is generally a sedimentary or metasedimentary rock unit. Third, most of the talc ore bodies occur within Precambrian rock units; the few that do not are in rock units no younger than Early Paleozoic age. Finally, in almost every deposit where genesis can either be firmly established or confidently inferred, the time of the talc formation is Precambrian as well.

The reasons for this almost total restriction of talc to the Precambrian in both space and time are unclear. It may be easier to understand in the case of ultramafic rocks, for they may be much more abundant in the Precambrian than in younger rocks. It is somewhat more difficult to understand with regard to dolomitic rocks, for they are certainly much more common in the Cambrian and younger systems than in the Precambrian. It may be that deep burial and the consequent conditions of dynamic metamorphism could have attained sufficient intensities only during the Precambrian; such a theory would perhaps explain the formation of talc in Montana and New York, for instance, but would probably not be applicable to some of the other districts, which have undergone deep burial but do not show conditions of extreme dynamic metamorphism and isoclinal structure, such as are common, for instance, in Montana and New York. It seems safe to say, however, that even though conditions of dynamic metamorphism have not necessarily been attained in all six districts, or at least cannot definitely be proved, conditions of burial beneath miles of rock cover have been attained in every district. The answers to what conditions have effected the origin of talc may well have to await solution by workers in academia, for few economic geologists have the time and the resources to devote to such problems.

Until such questions are answered it should suffice to say that if one wants to find talc in commercial quantities then one should restrict the search to Precambrian and possibly Early Paleozoic sequences in geosynclinal areas; in other words, stick to "elephant country"!

The six major talc-mining districts in the United States and Canada are: New York, Vermont-Quebec, North Carolina-Georgia-Alabama, Texas, California-Nevada, and Montana (Fig. 10-1). The history, geology, and several other aspects of the first five districts will be treated briefly below; Montana will then be described and discussed in detail.

NEW YORK

Talc was first produced and milled in the United States in northern New York in 1876 between the towns of Fowler and Balmat in St. Lawrence County. Before the turn of the century this operation became known as the International Pulp Company, which changed its name to the International Talc Company in 1944, and was acquired by the R. T. Vanderbilt Company in 1974. The Gouverneur Talc Company, a Vanderbilt subsidiary from the beginning, began operations near the zinc-mining town of Balmat in 1948. Prior to their acquisition of International Talc Company in 1974, Gouverneur shared with them in the New York talc district's annual production on an approximately 50-50 basis.

The New York talc district has long been and still may barely be the most important in the United States in terms of total annual production. It is most peculiar that this district, although dominant in production for the last century, and even more dominant in terms of proved and potential ore reserves, is the smallest in area of all six talc-mining districts in North America. All of the known commercial talc and talc-rock occurs within the Balmat-Edwards or Gouverneur mining district. A comprehensive study of talc in the United States by the U.S. Geological Survey (Chidester and others, 1964) indicated that New York then had almost 75 percent of this country's "measured and indicated" talc ore and about 40 percent of its "inferred" talc ore. All of the known talc and talc-rock lies within a narrow belt, which probably averages only 500 feet in width and is only about 8 miles long.

The bedrock complex of the Gouverneur mining district consists exclusively of metamorphic rocks of Precambrian age (the Grenville Series), but two specific types, namely, gneiss and marble, dominate. The gneiss is the older unit and is about 3,000 feet thick; the marble is the younger unit and has a maximum known thickness of about 2,000 feet. Thin sheets and lenses of amphibolite occur within both the marble and the gneiss but are minor in total volume. Brown and Engel (1956) subdivided the marble sequence into fifteen units, of which only Unit #13, the "talc unit", is known to contain commercial deposits of talc, tremolite, or zinc minerals. Unpublished geological investigations indicate that the composition of most of the marble in the district is relatively simple and probably does not and did not differ greatly along strike. The "talc unit", a dolomitic marble, shows evidence of being only 250 feet thick in its least contorted areas; greater thickness may be due to structural flowage.

The zinc and the talc ores occur within the same stratigraphic unit, but not together except at a few localities. Locally, the siliceous dolomite of Unit #13 has been converted to tremolite under conditions of dynamic metamorphism or metasomatism; subsequently, talc, anthophyllite, and serpentine have locally been formed from the tremolite. In the northeasternmost part of the district, anthophyllite may locally be the major constituent of the ores.

New York talc ores are commonly more than half tremolite. Tremolitic ores have been proven by underground workings to downdip depths of at least 1,100 feet and by core drilling (generally in the search for commercial zinc deposits) to downdip depths of more than 3,000 feet. Mineable bodies of almost tremolite-free talc (platy or "scaly" variety) have been discovered and recently exploited in mines near Talcville; these, however, are near the hanging-wall contact and are difficult to mine by themselves, so their scale of production tends to be directly related to that of the tremolitic ore being produced at the same time. Field mapping by U.S. Geological Survey workers has indicated that the tremolite and talc and associated minerals were formed prior to 1.0×10^9 years ago.

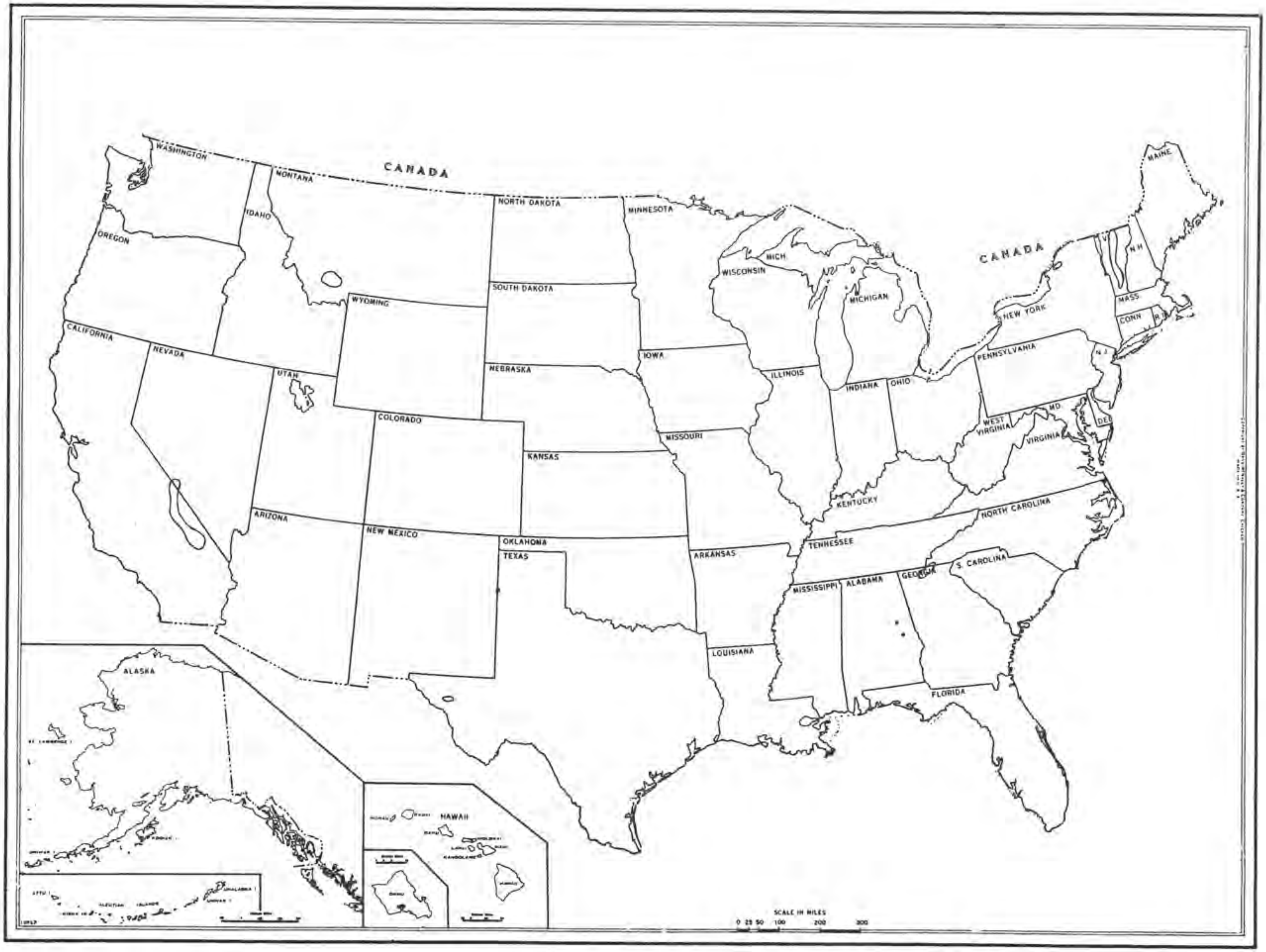

Fig. 10-1. –Major talc-mining districts of United States.

The zones of commercial talc-rock locally pinch and swell, but they are on the whole conformable to the dolomitic marble layers. The regional dip is about 45° to the northwest, and departures are only locally significant. Tight and contorted cross-folds superimposed upon the main talc belt have locally resulted in the thickening of the talc-rock sequence by at least 50 percent. All of the rocks are complexly folded, and metamorphism to the amphibolite facies is common, if indeed not ubiquitous.

Both open-pit and underground mining methods are employed. A large crushing facility is installed within one underground mine.

The deposits of the New York talc-mining district may well constitute the largest reserves of tremolitic-type ore in the world, for nothing described in the literature at the present time is of similar magnitude. In the late 1960's the total production of the New York talc-mining district was on the order of 225,000 tons annually. Although the most recent production figures issued by the U.S. Bureau of Mines group New York's production with that of several other states, it can be safely inferred that New York is now producing on the order of 250,000 tons annually.

New York talc ores are milled as is, i.e., without any beneficiation of any sort. Milling is accomplished in ball mills and in fluid-energy ("jet") mills and the product is then air-classified.

VERMONT-QUEBEC

The district that is commonly known as the Vermont talc-mining district runs through the central part of that state but also extends southward into Massachusetts and northward into Quebec.

Bodies of ultramafic rock have been intruded into a sequence of phyllite, schist, gneiss, greenstone, and amphibolite rocks; the ultramafic bodies have been locally serpentinized and partly converted into talc. These talc-rock deposits are commonly associated with dunite, peridotite, and serpentinite, which were probably the parent rock. These ultramafic rocks "form part of a belt more than 2,000 miles long, which extends from Alabama to Newfoundland" (Chidester and others, 1951). The talc-rock itself is more of a talc-carbonate complex, which locally grades into a carbonate complex rich in magnesite. The talc-rock is dark, gray to dark gray, has a schistose structure, and is relatively high in iron content. The mineral talc itself is minor in all the known deposits.

The ultramafic bodies are as much as 1 mile in width and as much as 3½ miles in length (Chidester and others, 1951). The commercial bodies, which occur in those ultramafic bodies known as the "verde antique" type, are zoned around cores of serpentinite. The talc-containing zone ("steatite zone") forms the outer shell or zone of the body; between it and the serpentinite core is the "grit zone", which is commonly several feet to several tens of feet thick. "Grit" is the miner's term for rock that is composed of talc and carbonate minerals only.

Although there are few masses of high-purity talc in the Vermont-Quebec district large enough to mine as such, tremolite is not known, and talc itself is the only talc-like mineral contained within the ultramafic bodies. The major problem hindering the production of pure talc is the fineness of its physical admixture with its contained impurities.

In northern Vermont, entire ultramafic bodies have been converted into grit and have widths on the order of 100 feet or so; in southern Vermont one similar body has a width of about 175 feet. In the state of Vermont alone at least 145 occurrences are known in an area having a strike length of about 150 miles and a width ranging from 5 to 25 miles. Homoclinal folding is the regional structure; isoclinal folding is thought to be uncommon, for little repetition by folding has been noted.

Few workers have attempted to date either the host rocks of the Vermont talc-mining district or the time of steatization, but studies by Christman (1959) and Christman and Secor (1961) suggested that the age of the parent rocks is Early Paleozoic, probably Ordovician.

Open-pit mining has been done in the past, but in recent years all production has come from underground workings, some of which extend to vertical depths of more than 1,000 feet.

The ore reserve situation in the Vermont-Quebec district has never been seriously investigated by anyone who would be at liberty to disclose the results of such a study. Proved ore reserves probably do not exist, for these producers seldom block out tonnage far ahead of the producing faces. Judging from the geographical distribution of the known bodies in Vermont alone, however, the reserves of talc-rock must be extremely large.

Producers have historically had the choice of grinding the talc-rock as mined and processing it for relatively low priced dusting compounds and fillers or of beneficiating the talc-rock by flotation or other means in order to derive high-value products containing major amounts of the mineral talc. If one wants to manufacture the most profitable product line in this district, he is faced with the necessity of employing wet-processing beneficiation techniques. The Eastern Magnesia Talc Company, Inc. (now Engelhard Minerals and Chemicals Corporation) has been using wet-beneficiation methods on ores near Johnson, Vermont, since 1937. The ore is subjected to froth flotation, then dewatered in a rotary vacuum drum filter. The filter cake is then dried, pulverized, and air-classified; Harrah (1956) has described this operation in detail. Eastern Magnesia Talc Company, Inc., established another, much more modern froth flotation plant at West Windsor, Vermont, in 1964; since 1972 this operation has been known as Windsor Minerals, Inc., a wholly owned subsidiary of the Johnson & Johnson Company. Trauffer (1964) has described this operation in detail.

The U.S. Bureau of Mines noted production of 251,087 tons of "talc, soapstone, and pyrophyllite" in Vermont in 1973.

QUEBEC

Deposits in the serpentine belt of the Eastern Townships of Quebec have been described as being altered from peridotite. These deposits are similar to those in Vermont and have been described by previous workers as "soapstone". Baker Talc Limited in Highwater, Quebec, used to mine such ore and dry-grind it for low-grade low-value fillers and dusting compounds. In the late 1960's wet-processing methods were introduced, particularly froth flotation and high-intensity wet magnetic separation; consequently, products now being manufactured from the same ores are being sold to the paint, cosmetic, and paper industries at considerably higher unit values.

NORTH CAROLINA-GEORGIA-ALABAMA

Although several deposits of talc and soapstone are known in the Appalachian Mountain province between Vermont and western North Carolina, none of them have such a history of past or present production, nor in the writer's opinion the future potential, to even suggest the possibility of their becoming major talc-mining districts. These occurrences in Massachusetts, Connecticut, Rhode Island, New Jersey, Pennsylvania, Maryland, and Virginia were described by Chidester and others (1964).

Several talc occurrences and ore deposits are known between Murphy in western North Carolina and Dadeville in eastern Alabama. Compared with those of the other major talc-mining districts, these are relatively small deposits, but some of them are important in that they are of high quality and serve specialized consumer needs.

NORTH CAROLINA

The Murphy talc district is about 85 miles long, extending from southwesternmost North Carolina into northern Georgia. Although talc is found in sedimentary rocks and also associated with ultramafic bodies in North Carolina, it is only those in sedimentary rocks that are of commercial interest at present. The host rock for these ore bodies is the Murphy Marble, which is generally more dolomitic than calcitic. Although the marble has been reported to be as thick as 400 feet or so, such thickness may be caused by structural deformation and therefore may be totally anomalous. The Murphy Marble in the vicinity of Murphy, North Carolina, has been divided into as many as eleven zones, only one of which (about 45 feet thick) is known to contain commercial talc deposits. Little information is available about the geology of the marble belt and its talc zone in areas away from mining activity, probably because climatic conditions cause outcrops to be few and far between.

Despite the relatively small size of the North Carolina talc deposits, the operations can be profitable because the purity and the color of the talc are extremely high and the products can compete with those manufactured from Montana talc ores as the only pure talc products of high color in North America that can be produced without the use of wet beneficiation methods. Tremolite is minor; indeed, even talc formed after tremolite, which is common in most other districts, is rare here.

The talc seems to have originated by "relatively simple metasomatic processes" (Chidester and others, 1964). Although the white talc-bearing zone in the Murphy area is dolomitic marble, which is locally "slightly sandy", Van Horn (1948) did not believe that the parent material contained sufficient magnesia and silica to permit the talc to form by dynamic metamorphism alone. Owens (1968), however, on the basis of a petrologic study of diamond drill cores, felt that the talc is of metamorphic origin. The age of the Murphy Marble has not yet been definitely determined. The general consensus, however, is that it is either latest Precambrian or Cambro-Ordovician.

Both open-pit and underground mining methods have been employed in the past, but recently the trend has been toward deeper underground mining. The developmental costs of shaft-sinking to relatively small ore bodies are among the highest such costs known to the writer, further testifying to the superior quality of these carbonate-derived ores.

Production figures for North Carolina talc are lumped together with those for pyrophyllite and soapstone by the U.S. Bureau of Mines in the Minerals Yearbook, making it difficult to determine the levels of talc production, but in recent years the total production of all three has ranged from 80,000 to 100,000 tons annually. Because North Carolina has in recent years been the only domestic producer of pyrophyllite, it is likely that North Carolina's talc production is less than 50,000 tons annually. North Carolina is at present the only domestic producer of talc crayons or welders pencils, a relatively minor but extremely lucrative product line.

Work being conducted by the North Carolina State Minerals Research Laboratory on the possibilities of beneficiating talc-rock from those deposits associated with ultramafic rocks is reportedly encouraging. Further advances in the wet beneficiation of talc-rock ores would increase the prospects that such deposits, which are similar to those in Vermont, would become of economic interest.

GEORGIA

A few occurrences of talc are known in the Canton area in northern Georgia, which is the southwesternmost part of the Murphy Marble Belt, but Georgia's principal talc deposits are in Murray County. Individual talc deposits may be tens of feet wide and several thousand feet long and may extend for several hundred feet downdip (Chidester and others, 1964). Furcron and others (1947), in the most detailed investigation to date, concluded that the talc has been formed by the alteration of dolomitic portions of the Cohutta Schist of Precambrian age; earlier workers, however, believed that it has been derived from peridotite. Needham (1972) thought that the soapstone and other talcose rocks of Murray County were formed by serpentinization, followed by metasomatism and metamorphism. Chidester and others (1964) stated that ultramafic bodies are not rare in Georgia, but no talc is known to be associated with them.

Talc in Murray County was discovered about 1872 and mining was begun shortly thereafter. Open-pit operations have historically been hampered by the presence of adverse surficial staining; mining operations are now conducted underground. The principal product lines have been crayons and finely ground products of both dark and light colors, but at the present time only the latter are being produced.

The U.S. Bureau of Mines stated (Minerals Yearbook) that the production of "talc, soapstone, and pyrophyllite" in Georgia in 1973 amounted to 38,000 tons.

ALABAMA

Pure white talc is mined near Winterboro in Talladega County, Alabama; as far as is known, all of this production goes to cosmetic and pharmaceutical uses. The parent rock is a carbonate sequence of probable Cambro-Ordovician age, which underlies the area, but the geological relationships are far from clear (McMurray and Bowles, 1941).

Talc and anthophyllite asbestos deposits, first noted in 1873, are present in Tallapoosa and Chambers Counties, Alabama, where they are associated with ultramafic bodies (Neathery, 1968). The talc content ranges from 3 to 26 percent, probably averaging 20 percent for the better deposits, and annual production is about 5,000 tons (Neathery, 1970). Neathery and others (1967) have described flotation-concentration feasibility studies, which show that "good-grade talc concentrates" can be made from these ores, but the economics of such an operation are yet to be proved.

TEXAS

Texas has two talc districts – the Llano district in the central part of the state and the Allamoore district northwest of Van Horn in the westernmost part of the state. The latter district, the more recently put into production, is now the only one of importance and is the only one that will be discussed here.

The Allamoore district extends about 20 miles east-west and is as much as 5 miles wide. Its ore deposits are in the Allamoore Formation, of Precambrian age, which consists of "thousands of feet" of carbonate rocks, volcanic rocks, and phyllite (King and Flawn, 1953). The talc is associated with dolomite, but it may be observed to intergrade with phyllite in certain parts of the district. The talc-rock deposits are large tabular masses, which pinch and swell to widths as great as 300 feet and may be several thousand feet long. The strata, which are in the lower plate below a large overthrust fault (the upper plate having been almost entirely eroded), are vertical or dip steeply to the south. No ore body of which the writer is aware has ever been "bottomed-out" by either drilling or mining. Large iron-oxide-stained "horses" of either carbonate rock or volcanic rock are fairly common but are generally easily eliminated by the use of selective mining methods. Talc is commonly found "from the grass roots down", and the soil cover is generally less than 1 foot thick. Caliche is abundant in the uppermost 5 feet or so of these dark ore bodies but seldom causes any problems at greater depths.

Petrographic and X-ray studies of the ores indicate that tremolite is not present to any significant degree but dolomite is so finely admixed with the talc as to make it extremely unlikely that pure talc can ever be produced from the known ore bodies by present beneficiation techniques. There is little indication of a hydrothermal origin for these ores. The talc ore (ceramic-type) is generally strongly foliated, the individual foliae ranging from paper-thin to as thick as ¼ inch. This dark Texas crude ore looks little like talc ore when one first visits the district, even to the trained observer. The first impression is to identify it as black shale or perlite or some other non-talc-bearing rock. Despite its dark or even black color and its "non-talc look", however, this talc-rock is a superior ceramic crude ore and has superior pressing qualities and excellent firing characteristics.

Flawn (1958) described the district in a stage of infancy, and King and Flawn (1953) described in detail the overall geology of the district and the surrounding areas. A more recent detailed study has been financed by the Texas Bureau of Economic Geology, but the results have not yet been compiled and made available.

All of the production has been from large open pits, with the exception of minor amounts of light-colored (generally pink to white) talc, which have been mined in small underground workings and then finely ground into filler and extender products. Almost all of the ore produced is shipped out of the district to the east, and even into Mexico, as crude unprocessed ore for use in the ceramic industry, particularly for the manufacture of wall tile.

Mining costs are probably the lowest anywhere for talc ores. Flawn (1958) gave the "costs of mining, transportation, and loading into cars" as ranging from \$1.75 to 3.00 per ton, and it is unlikely that these costs have subsequently increased more than would be expected from inflation and increased labor and equipment costs.

It is by far the youngest of all the major talc-mining districts of North America, for production commenced in 1952. The U.S. Bureau of Mines credited Texas with the production of 232,514 tons of ore in 1973.

CALIFORNIA-NEVADA

Of the major talc-mining districts of North America, the one that combines the largest area with the greatest number of productive commercial deposits is the one in southeastern California, which barely extends northward into Nevada. It is about 200 miles long and has an average width of 30 miles but is locally as much as 75 miles wide. Engel and Wright (1960) divided this long "belt" into three separate areas, each of which contains a slightly different characteristic type of deposit. This district is too large and its geology too complicated to be satisfactorily summarized within the scope of this paper. In general, however, all the deposits have been formed by the "metamorphism and hydrothermal replacement of siliceous and silicated magnesian marbles and limestones" (Engel and Wright, 1960).

The deposits come in all sizes. The Western-Acme mine complex near Tecopa in San Bernardino County, California, is more than 5,000 feet long (although locally severely complicated by cross-faulting) and as much as 80 feet wide and has been mined downdip for at least 350 feet. The deposits in the southern two areas occur in Precambrian sedimentary rocks, were probably formed in Precambrian time, and are spatially associated with a thick diabase sill intruded near the base of a widespread carbonate member. In the northernmost of the three areas, which has not been historically as important a producer as have the other two areas, deposits occur in Lower Paleozoic formations and are thought to have been formed by replacement processes, probably in Cretaceous or Tertiary time.

There are two main types of ore in this district: the "hard" ore of the miners is tremolitic, and the "soft" ore is talc schist. Many deposits contain both types, but their distribution is erratic and unpredictable. Most of the ore is markedly tremolitic, but there are some relatively small bodies of high-grade talc. The problem with these high-purity talc bodies, however, is that they generally cannot be mined by themselves, but must be extracted along with the tremolitic ores; therefore, the production of high-grade talc in California-Nevada today generally has to be a function of the production of tremolitic ores to supply the market for their products.

Most of the mining in the California-Nevada district has been done underground, relatively little mechanization is involved, and timbering costs are high. A small proportion of the district's production has been obtained by open-pit mining methods, but most such operations are decidedly sporadic.

In no other talc-mining district anywhere in North America are the mines so far from rail transportation as those in the California-Nevada district, but it serves mainly a special local market, especially southern California, and seemingly can meet and beat the current potential competition from other districts. Mills and other processing facilities are not located at or near the mines but in the Los Angeles area or at various points along the two railroad lines serving the Los Angeles area. Haulage routes to either a processing facility or the railroad are on the order of 50 miles or more.

Soapstone was mined from small deposits along the foothills of the western Sierra Nevada in the mid-1800's, but the current California-Nevada talc-mining district was established during World War I, when the area around Darwin in Inyo County, California, supplied block-grade steatite talc to compensate for the temporary elimination of foreign supplies. California production slacked off in the post-war period but was rejuvenated during World War II; since that time, however, California has not been a significant factor in the supply of steatite-grade talc. In the mid-1930's the use of California tremolitic ores for the manufacture of wall tile began to come into its own, and the ceramic industry became the major market, as it is today. The talc content of such ores is not critical, and a considerable amount of carbonate material can be tolerated, indeed may even be desirable.

HISTORY OF THE MONTANA TALC INDUSTRY

The only prior significant description of Montana talc deposits in the literature is that of Perry (1948). This excellent work, however, was compiled and published in the very early days of the Montana talc industry. In the almost thirty years since its publication that industry has undergone a period of amazing growth and development; therefore it is thought appropriate to present here some of the available background on the history of that period.

Much of the credit for the growth and development of the Montana talc industry belongs to two fine gentlemen who recognized, among other things, the unique quality of its ores and by their intelligent foresightedness, hard work, and perseverance paved the way for the current prominent position of Montana in North America's talc picture. Mr. Henry Mulryan (deceased, formerly President of Sierra Talc Company) and Mr. Walter K. Skeoch of Honolulu, Hawaii (formerly President of Southern California Minerals Company) began their involvement with Montana talc in the 1940's and are hereby acknowledged as the pioneers of that industry. Mr. Skeoch and one of Mr. Mulryan's sons have been so kind as to supply invaluable background information regarding the history of their contributions.

The following information concerning his part in the growth and development of the Montana talc industry has been supplied by Mr. Walter K. Skeoch . . .

"During the summer of 1942, the non-metallics division of the U.S. Bureau of Mines asked me to investigate and, if possible, develop a small outcrop of talc near Ennis, Montana. Samples from the Johnny Gulch outcrop and from a small exploratory pit were sent to several 'steatite ceramic' manufacturers who were then trying to find an American source for block talc. They insisted this was necessary for the supply of spacers or dividers used in radio filament lamps. They were dependent on imported material called 'Wonderstone' from Africa, which was satisfactory for gas lite tubes but could not withstand the high-intensity shock required for other products.

The samples were interesting but almost all had fine hair cracks when sawed into shape. The open pit proved hazardous, so a shaft was sunk and exploratory drifts driven. The market was for 2" x 2" x 8" blocks and we were offered 8¢ to 10¢ per pound for blocks sawed to size and delivered to railhead. The Vermont talc suppliers could supply such products, but the iron content was too high. The manufacturers refused to buy the ground material so we were obliged to cancel our lease when the owner, a Mr. Clark, would not sell the property. Sierra Talc was later successful in purchasing the property – now known as the Yellowstone Mine.

From that experience we learned of an outcrop of talc southeast of Dillon, Montana. No work had been done upon this property, and we purchased the mineral rights from a rancher, Mr. Clyde Smith. The original purchase of 40 acres was located in Axes Canyon. Originally we explored underground by vertical shaft and laterals and later by open-cut methods. This property, the Smith-Dillon Mine, produced a very pure talc that was much in demand as a steatite ceramic material. The U.S. Government stockpiled forty carloads of it for emergency use. The property was worked continuously from 1943 until the late 1960's, after the sale of Southern California Minerals Company to Pfizer, Inc. A second 40 acres was purchased from Mr. Smith about 1960 but did not prove productive.

Our Ogden, Utah, mill was completed in 1944. At first only a Raymond roller mill was installed, then later a high-speed Raymond hammer mill; still later Fine Pigments Corporation produced the extremely low-micron talc '399' at this facility.

The Barratts,* Montana, crushing plant was installed in 1943. The intention was to blend the Montana talcs at Ogden, Utah, with much whiter California ore – this was done successfully for the paint and paper trade. Then better talc was developed from the Stone Creek claims (Treasure State Mine) purchased from Mr. Claude Brown in 1952. The Barratts mill was completed in December 1954 with a large Raymond roller mill, a high-speed Raymond hammer mill, and a large Kidwell mill for Fine Pigments Corporation. At that time, starting in 1947 and lasting until 1965, Fine Pigments Corporation was owned 60% by Tri State Minerals Company (a division of Southern California Minerals Company) and 40% by Whittaker, Clark and Daniels Company, then of New York City. Tri State Minerals Company purchased the W.C.D. interest in 1965. The Ogden mill was closed and most of that equipment was moved to Barratts, but some of the equipment was moved to a new modern mill built at Dunn Siding, California (on the Union Pacific) in 1964-65 by Southern California Minerals Company.

Several other talc claims in Montana were purchased during the period 1946-1966. The largest, and the only one of these mined, is the Keystone-Regal, east of Dillon, Montana, purchased in 1947. The property was explored by a vertical shaft 110 feet deep and 100-foot long tunnels driven in all four directions – *all in talc*! This may be the largest body of talc on record. The quality is excellent, but not of such a good color as are the Stone Creek grades (Treasure Chest Mine).

The color on all the Montana grades was very much improved by the installation of sorting belts and vibrating-screen sizing devices and magnetic separators. An electric sorting table was installed but was discarded, as the manual maintenance work required was to great."

In February 1966 Mr. Walter K. Skeoch sold Southern California Minerals Company to Pfizer, Inc. of New York City. Its Montana talc mines and mill have been operated since then by the Minerals, Pigments, and Metals Division of that firm.

Mr. Henry T. ("Joe") Mulryan is President of Cyprus Industrial Minerals Company, the successor of Sierra Talc Company. His brother, Mr. James D. Mulryan, is Western Area Production Manager of Cyprus Industrial Minerals Company and is in charge of that firm's Montana talc operations, based at Three Forks, Montana, and has supplied the following information concerning, among other things, his father's part in the development and growth of the Montana talc industry.

"The original name of the Yellowstone Mine was the Mountain Talc Mine. Sierra Talc, largely through my father's efforts, acquired the property in 1948. The mine was renamed the Yellowstone Mine at that time and the story behind this is that Henry Mulryan and Otis Booth, both of Sierra Talc, were driving to Montana to look over the property after having acquired it. One commented to the other that since they had now bought the mine, they ought to figure out some sort of a name for it. About that time, there was occasion for a panic-type stop in the car they were driving, and a bottle of Yellowstone whiskey, which had been under the front seat, rolled out and hit the passenger on the foot. They felt that this must have been an omen of some sort, and the mine was named Yellowstone Mine. It is therefore named for the Yellowstone whiskey, in spite of the fact it is only about 50 miles from West Yellowstone, Montana. Cyprus took over the mine in late 1964 when they acquired Sierra Talc.

The Beaverhead Mine was discovered by a group including Bennett Owen and Bob Dutton. This property was nothing more than a prospect and was purchased by Sierra on a lease option in the early 1950's. Here again, Cyprus took over this property in 1964 when they acquired Sierra Talc.

The Yellowstone Mine began with Mr. L. F. Teutsch's operations as a small underground glory-holing type of operation. The talc was being mined primarily in the block lava area where there was a high percentage of manganese dendrites. This material was being used in the electronics industry for the manufacture of non-fired ceramic pieces, such as insulator bases for high-frequency electronic tubes. In the late 1940's, when Sierra took over, there was some extensive underground work primarily to try to delineate the deposit and to find out whether open-pit mining was feasible and also to get some larger samples than we had had in the past to work with in our lab to determine what could be done with the talc. In the early 1950's the mine was opened up as an open pit and there has been no underground work since.

At the Beaverhead Mine the previous owners had done very little, if anything, other than assessment work. In the mid-1950's, when Sierra took over, some exploratory underground work was done. In the early 1960's assessment work was being done in the form of stripping, with the idea of eventually opening up the deposit. By the late 1960's the mine was opened up for open-pit operations and all underground work ceased. This mine operates on a seasonal basis normally because of the altitude and weather conditions at that altitude.

At the Yellowstone Mine all of the talc shipped from the mine is hand sorted. The first sorting shed was installed in either the late 1940's or early 1950's. In this shed the waste is picked from the talc by the sorters. A new sorting shed was built in 1958-59 and the reason for this was to improve the facilities as well as to increase the capacity. In 1971 we installed a pit sorter, as we call it, into which the lower-yield material is fed and the talc is picked from the waste. Basically, this is the processing history of the Yellowstone Mine at the mine site.

At the Beaverhead Mine there were no facilities of this type until 1974, at which time we put in a pilot-size pit sorter, which differs from the Yellowstone pit sorter in that basically the need to pick waste is lower at the Beaverhead than it is at the Yellowstone; therefore, the process more resembles the sorting shed at the latter than it does the pit sorter. Certain difficulties with the Beaverhead ore required, however, that it be washed prior to sorting; the nearest point at which this could reasonably be done was Alder, Montana. In the late 1960's or early 1970's a wash plant was installed at Alder, and the crushed ore was run through a log washer and the waste was then picked from the washed material. This system has remained basically unchanged since it was installed, except that occasionally we have found that the need to wash the ore has decreased with materials from certain areas of the pit.

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*Spelled Barretts on Dillon West 7½-minute quadrangle

The Three Forks, Montana, grinding plant was built in 1960-61 with one roller mill and one Double Eighty-eight fluid-energy mill. A second such fluid-energy mill was added in 1963. A pellet system was added in 1970, and we have undergone a major expansion in 1973-74 in which we have added a third such fluid-energy mill, storage silos, etc., plus pneumatic conveying systems. We have also added a Stedman mill for the preparation of feed for the fluid-energy mills.

The Grand Island, Nebraska, grinding plant was built, I believe, in 1952 with only one roller mill. We put in the first fluid-energy mill, which was a single mill rather than a double mill, in 1955. The second one was installed about 1958. The plant was generally remodelled in 1962 and the two single fluid-energy mills were replaced by one Double Eighty-eight, and improvements were made in the packaging system. A second roller mill was added in 1969.

The basic difference in the two fluid-energy plants is the fact that Three Forks has a pelletizing system and a more sophisticated materials handling system, whereas Grand Island has only the basic necessities of such an operation. The flow sheet at Grand Island would be basically a crude-unloading and storage area, a jaw crusher, one of two roller mills, either of which can feed a packer bin or a feed bin for the fluid-energy mills, which in turn feed a second packaging system.

At Three Forks we have essentially the same system through the jaw crusher, but then we split to either a roller mill or a Stedman cage mill. Basically, the Stedman mill feeds the fluid-energy circuits, and the roller mill feeds the packer bin. The fluid-energy mills then feed silos from which material can be reclaimed to go either into the second packer bin directly or into the pelletizing feed system, from which it then goes to a third packaging station. Finished products are then loaded out as in any normal operation.

The sales in Europe of our fluid-energy-mill products from plants in the United States reached the point where we could justify the building of a plant in Europe. Gent, Belgium, was the site selected. This plant was constructed in 1965-66 and was basically comparable to the original Three Forks setup. We have installed a pellet mill and a second fluid-energy mill plus silos and pneumatic conveying since the plant was built. The products made in Europe are manufactured in large part from crude ore from the Yellowstone Mine; this has been the basic raw material used in the Belgium operation. Periodically we accumulate between 15,000 and 20,000 tons of crude ore and make single shipments of this size as needed in order to keep the Gent plant supplied with mill feed.

As indicated above, we originally used only Yellowstone crude in Europe, but as the Beaverhead crude became available we began to ship smaller quantities of it to Europe. When we established a working agreement with a talc producer in Australia, we began shipping crude talc from that country to Gent for grinding. The basic supplies of ores used at Gent, however, are still those from Montana.

Generally speaking, we started at the Montana operations in the steatite talc business for the ceramics market. Later, we began to produce material for the control of pitch in paper-pulp mills. This has become the predominant market for our Three Forks plant, the ceramic and paint industries being secondary. We have also begun recently to move into the synthetic rubber and plastics industries with our Montana talc products. Over the years the shifts in our product line have by and large been gradual."

GEOLOGY OF MONTANA TALC

The geology of Montana talc deposits has been described extensively in only one prior publication (Perry, 1948) but has been described briefly in three other publications (Heinrich, 1960; Heinrich and Rabbitt, 1960; Chidester and others, 1964).

High-purity talc deposits in southwestern Montana are *totally* restricted to dolomitic marble of the pre-Beltian sequence of "Cherry Creek-type rocks". The talc occurs as generally conformable lenses and stringers within the marble. If they are anywhere discordant, it is commonly at relatively low angles. Talc is invariably localized within a narrow stratigraphic range. Structural control, in the strictest sense, has not been recognized, but there is an *apparent* restriction of talc mineralization to that part of the marble that is spatially close to large bodies of the Dillon Granite Gneiss. The complete restriction of the talc mineralization to the marble *only* must indicate that the aqueous solutions that contributed to the deposition of talc were amenable to doing so in the *dolomite only*. Winkler (1974) gave the following reaction:

$$3 \text{ dolomite} + 4 \text{ quartz} + 1 \text{ H}_2\text{O} = 1 \text{ talc} + 3 \text{ calcite} + 3 \text{ CO}_2$$

This seems to be the most likely reaction to account for the formation of Montana talc deposits; inasmuch as the host dolomite is not notably siliceous adjacent to the talc, it is likely that most of the silica required was metasomatically introduced, probably along with the water.

In the Ruby Range the Dillon Granite Gneiss *may* have been emplaced before the talc was formed, but if this be the case, then the close spatial relationship between the talc and the granite gneiss suggests the probability of a relationship that must be explained in some manner. Garihan (1973) has noted that finer-grained dolomite and thin-bedded marble "are notably barren of talc" and his studies suggest that high-purity talc has invariably been formed as a replacement of pure coarsely crystalline dolomite marble. Furthermore, he concluded that "with the exception of one occurrence, talc mineralization in marble above the main mass of Dillon Gneiss is confined to one stratigraphic unit, the Regal marble". The Regal (Keystone) Mine and the Treasure Mines all occur within the Regal marble of Garihan (1973), who further concluded that "In general, talc is associated with tight folds, fractures, marble breccia zones, bedding planes and faults" and that all of these factors, along with texture and compositional and chemical factors, are important in localizing the formation of the talc.

Both Okuma (1971) and Garihan (1973) believed that the talc is genetically associated with the north northwest to northwest high-angle fault system. The writer disagrees, on the basis of his study of producing mines during the late 1960's, in which no evidence was found of differing composition, mineralogy, texture, etc., in areas proximal to such fault surfaces. It would seem that if those faults have been a factor in the formation of the talc, such changes and lateral variations would be readily recognized within the ore bodies – unless, of course, they have been masked by subsequent retrograde metamorphism.

It is peculiar that although tremolite has been noted by many workers near high-purity talc in southwestern Montana, all of the ores mined at present and in the past are and have been, to the writer's knowledge, totally free of detectable tremolite. Most chemical analyses of Montana talc ores express CaO as being present only in "trace" amounts, rather than as a definitive quantitative value. Of dozens of such samples collected by the writer and subjected to X-ray diffraction analysis, not a single one has shown a detectable amount of tremolite. The purity of Montana talc ores is shown in Table 10-1, as modified from Chidester and others (1964).

In the discussions of the individual Montana talc mines, deposits, and prospects, the term "talc-zone" will be used to denote that stratigraphic zone that is susceptible to the formation of talc. All of this zone may be converted to talc, or none of it, or any part between these two extremes.

In large areas of numerous talc occurrences and considerable future talc potential, such as the area of the southern Ruby Range between Timber Gulch and Stone Creek and the area between Johnny Gulch and Cherry Creek along the eastern flank of the Gravelly Range, overlying soil cover is either completely absent or extremely thin. It would be most unusual over much of these areas to find soils (particularly in the low ground beneath timber stands) that are more than 1 foot thick. Indeed, at the Regal (Keystone) Mine, soil cover over the talc and dolomite bedrock is generally completely absent. In the high country north of Gordon Peak in the Ruby Range and in the central part

Table 10-1. –Chemical analyses of talc ore from the Dillon-Ennis district, Montana.

	Bozo Group mine[1]	Key-stone mine[2]	Smith-Dillon mine					Sweet water mine[1]	Treas-ure mine[2]	Yellowstone mine	
			Stea-tite[2]	SD-1[3]	SD-2[4]	SD-3[5]	SD-S[6]			Stea-tite[7]	Y-1[8]
SiO_2	58.2	57.72	58.46	62.25	62.06	61.78	62.37	61.0	60.40	62.65	62.73
Al_2O_3	1.50	1.13	1.90	.27	.50	.57	.50	.90	1.91	.31	.10
Fe_2O_3	.51	.48	.84	.71	.67	.75	.63	.10	.27	1.51	1.45
CaO	.20	1.34	.30	$<.05$	$<.05$	$<.05$	$<.05$	.20	.80	Trace	$<.05$
MgO	31.0	30.72	31.78	31.13	31.12	31.06	31.32	31.7	30.81	30.23	30.32
K_2O	. . . .	Trace	Trace	.02	.01	.02	.01	. . . .	.14	.05	.01
Na_2O	. . . .	Trace	Trace	.06	.07	.08	.07	. . . .	.20	.15	.03
H_2O-				.14	.18	.17	.10			.08	.27
H_2O+	5.8	5.94	6.22	5.03	5.09	5.17	4.90	5.6	5.15	4.87	5.14
CO_2				Nil	Nil	Nil	Nil			.27	Nil

[1] Analyst unknown. Data from S. W. Stockdale, American Chemet Corp.

[2] Analysis by Raymond G. Osborne Laboratories, Inc.

[3] Massive white to pale-green opaque to translucent fine-grained to dense talc rock with intermixed splotches and veinlets of gray and darker green talc. Contains scattered tiny flakes of graphite and a few dendrites of manganese oxide. Analysis by Leonard Shapiro, U.S. Geological Survey.

[4] White to pale-green or cream-colored massive talc rock, predominantly fine grained but with variable proportion of disseminated medium-sized folia or plates of talc. Analysis by Leonard Shapiro.

[5] Fine-scale intermixture of types SD-1 and SD-2. Analysis by Leonard Shapiro.

[6] Material representative of whiter and denser parts of sample SD-1. Analysis by Leonard Shapiro.

[7] Analysis by A. J. MacArthur, Sierra Talc and Clay Co.

[8] Dense pale-green talc. Analysis by Leonard Shapiro.

of that range to the north of Stone Creek thicker soils are developed, however, particularly in stands of timber. It is in such areas that a geochemical approach to ore-finding, should such prove feasible, would prove invaluable for the discovery of concealed talc deposits – the normal system of "float-prospecting" does not work well in such areas.

Over large areas of the northwesternmost part of the southwestern flank of the Ruby Range the bedrock has been sharply pedimented and major parts of large acreages have bedrock actually exposed or have "bedrock-at-the-grassroots". The area between Carter Creek and the divide between Hoffman Creek and Winnipeg Creek, from the Regal (Keystone) Mine northwesterly to the floor of the Beaverhead Valley is an excellent example.

Along the southwest edge of the Ruby Range, thick alluvial terrace deposits conceal vast areas of bedrock that could contain talc, but it is unlikely that methods will ever be found to assess whether or not talc deposits may be present there at depth. Going downhill to the northwest from the range divide, one comes into the pedimented area, then into the terraced area, and finally into the alluvial fill of the Beaverhead Valley.

The crucial reason that we have not attained a better and more nearly complete understanding of the geology of Montana talc deposits is that no geologist has ever "lived with" a Montana talc deposit or mine from the time of its discovery through its developmental stages and on into its period of mining activity. Any field geologist who has attempted to decipher geological relationships in trenches dug long ago in talcose rocks knows what an exercise in frustration it can be! The talc exploration geologist should be afforded the opportunity to map and sample while the bulldozer is there. Talc producers generally feel that talc mines can be operated without geological control or advice. Until daily geological studies are made upon such deposits, it stands to reason that they will continue to remain enigmas!

ORIGIN OF TALC IN MONTANA

Commercial talc ores in Montana have formed *only* in dolomitic marble of pre-Beltian age. Although talc in other districts has formed through the alteration of ultramafic rocks, no such origin is known to the writer for any commercial deposit in Montana.

Garihan (1973) has recognized that many marble layers in the Ruby Range that have been host to the formation of talc deposits are not quartzose nor do they contain interbeds of metaquartzite; therefore, he believed that the silica needed for the formation of the talc had to be introduced. The writer has made several similar observations and fully agrees with Garihan's conclusion. Garihan (1973) also stated that "the talc was derived chiefly from low-grade regional metamorphism of dolomitic marbles, through the action of hydrothermal solutions containing silica and perhaps magnesia". Retrograde metamorphism of tremolite to form talc, so common and important in other districts, is thought not to have been a factor in the Ruby Range because tremolite is not known to be present in Montana talc ores.

Okuma (1971) thought that some of the talc in the Ruby Range may have been formed as the result of the replacement of serpentine and tremolite. The writer does not dispute this possibility but stresses that *all* of the known *commercial* talc bodies have been formed from dolomitic marble *only*. It seems very unlikely that such ore bodies have been invariably *completely* altered to talc, leaving no contained tremolite or serpentine remaining whatsoever; many such ore bodies, however, do contain large "horses" of unaltered dolomite, which are either mined around or thrown to waste.

All of the pre-Cherry Creek rocks and the "Cherry Creek-type rocks" and most of the rock types of the Dillon Granite Gneiss have been subjected to upper amphibolite grades of regional metamorphism, a long-lived metamorphic event of pre-Beltian time, which included the development of intense isoclinal deformation. It is unlikely that the talc was formed during the period of upper amphibolite regional metamorphism, but it could well have been formed during the period of regional metamorphism of greenschist grade, which post-dated the amphibolite period and predated the intrusion of the diabase dikes. If the age of the dikes is Precambrian, which although not absolutely proved is very likely, then the talc was almost certainly formed in Precambrian time. This age of formation seems most likely, for were the talc to have been formed in Cambrian or later time it would be extremely unlikely that no talc at all would have been formed in the thick dolomite units of the Cambro-Ordovician Systems in the northern third of the Ruby Range (Tysdal, 1970). Garihan (1973) noted that talc has not been found in those Paleozoic dolomite strata in the northern third of the range, yet talc has been formed in the pre-Beltian dolomites at many localities very near the Paleozoic outcrops. This, plus the fact that the Paleozoic rocks are completely unmetamorphosed, led him to conclude that the age of the talc mineralization was Precambrian. Okuma (1971) also thought that the most likely age of the talc mineralization was Precambrian. Although the writer has no firm proof one way or the other, he concurs fully with this age assignment for the formation of the talc. Okuma (1971) stated that "The talc bodies result from the replacement of dolomitic marbles by aqueous solutions rich in silica" and he further stressed that "Areas of retrograde metamorphism may be of special significance in talc prospecting".

Van Horn (1948) has studied in detail the talc deposits of the Murphy Marble Belt in southwesternmost North Carolina. It is interesting that the geology of this district is similar in many ways to that of Montana and that many of his conclusions concerning the genesis of the Murphy talc ores are also appropriate for the genesis of Montana talc ores. Van Horn thought that simple dynamic metamorphism could not, by itself, have accounted for the formation of the Murphy talc ores because of the lack of silica and magnesia in the original marble, but he believed that such metamorphism might have formed zones of weakness in the marble. The subsequent introduction of hot aqueous solutions may have partly silicified the dolomite and at about the same time, or possibly somewhat later, may have formed talc bodies in such zones of weakness.

The writer believes that the mechanism of formation of Montana talc bodies was probably extremely similar to that postulated by Van Horn (1948) for the Murphy, North Carolina, talc ores. The dynamic metamorphism of the earlier upper amphibolite period may have formed zones of weakness and allowed the introduction of siliceous material (probably from the Dillon Granite Gneiss) and possibly some magnesia also (probably remobilized from amphibolite and other ultramafic rocks). After this metasomatic event had afforded the opportunity for the introduction of all the constituents necessary for the formation of the talc, it is thought that the talc itself could have been formed during the retrograde metamorphism; i.e., the event of greenschist grade that Okuma (1971) and Garihan (1973) judged to have been widespread over both of their areas. This theory of origin can neither be proved nor disproved at this time; the final solution must await detailed studies of paragenesis by workers who can follow the mining of these talc ore bodies over sufficiently lengthy periods of time.

GEOGRAPHICAL DISTRIBUTION OF MONTANA TALC

All commercial Montana talc deposits of which the writer is aware are contained within pre-Beltian metasedimentary strata. They are also geographically restricted to a relatively small area in southwesternmost Montana (Fig. 10-2) bounded by the Beaverhead-Jefferson, Madison, and Red Rock Rivers; more specifically to parts of the Ruby Range, the Greenhorn Range, and the Gravelly Range. Talc occurrences are known in adjacent ranges, especially in the Tobacco Root Mountains, but these have not yet produced any ore.

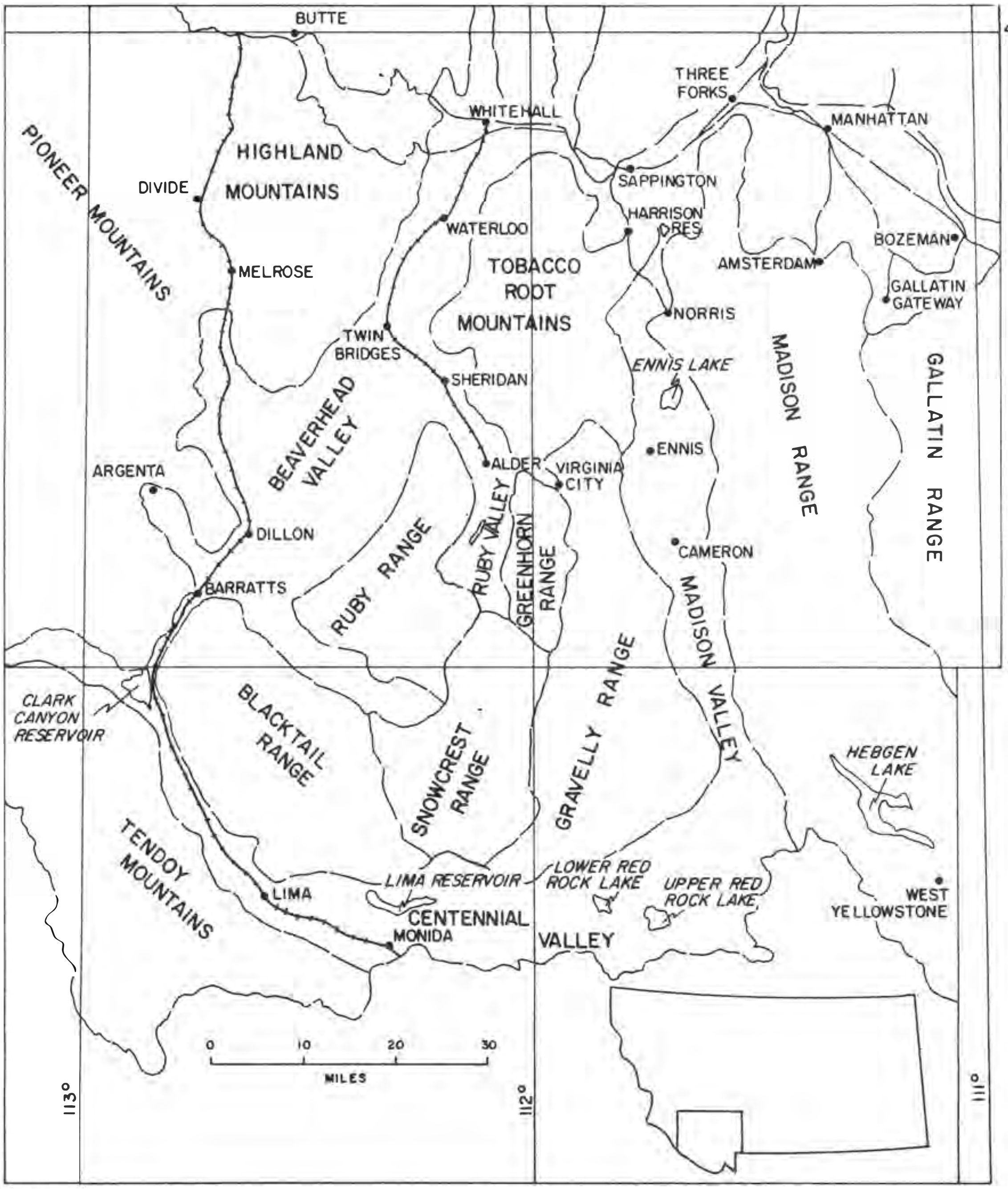
The talc has invariably been developed within dolomite marble of pre-Beltian age. These marble and associated metasedimentary strata are known as the Cherry Creek Group and were originally studied and described by Peale (1896) south of Ennis, Montana. The Pony Series, as described by Tansley and others (1933) in the Tobacco Root Mountains, is not known to occur with the dolomitic marble of the Cherry Creek in any area where the latter contains commercial talc deposits. The Dillon Granite Gneiss is younger than the dolomitic marble but still pre-Beltian in age.

Ross and others (1955) have mapped the unit in which all of the known commercial talc occurs as "Pre-Belt gneiss, schist, and related rocks" and it constitutes significant portions of an area about 180 miles long in an east-west direction (Red Lodge to Bannack) and 85 miles wide (Three Forks to the Idaho-Montana line near Upper Red Rock Lake). The unit is a conspicuous and predominant one over this area of 15,000 square miles and locally makes up single homogeneous blocks of several hundred square miles each. The dolomitic marble, however, is not an integral part of this unit over its entire extent. As known today, admittedly from fragmental and incomplete information, the dolomitic marble is probably significant only in the Ruby Range, the Greenhorn Range, the Gravelly Range, the Tobacco Root Mountains, and possibly in part of the Madison Range.

Perry (1948) has described several talc deposits in the Ruby Range, the Gravelly Range, and the Greenhorn Range, and his work is of interest in that it describes the Montana talc-mining district and its deposits in their early productive stages. Much mining and prospecting have been accomplished since then, however, and it is one of the purposes of this paper to update Perry's work.

The two ranges that contain all of the large Montana talc deposits, namely the Ruby and Gravelly Ranges, will be the ones dealt with at most length in this paper. They have the most obvious present potential and may well have the best future potential. The other areas and ranges mentioned above are, at the present time, still strictly wildcat areas.

The areal geology of the Greenhorn Range has never been published. The Ruby Range has been described in reconnaissance fashion by Klepper (1950). The entire Ruby Range has been mapped in recent years by student investigators, but the results of this work have not yet been published. Tysdal (1970) mapped the northern third of the Ruby Range, which



10-2. –Index map of southwestern Montana.

consists for the most part of Paleozoic strata. Garihan (1973) in the central part of the Ruby Range and Okuma (1971) in the southern part, in a joint study that was subsidized by Pfizer, Inc., mapped all of that range that has, in the writer's opinion, any significant chance of containing commercial talc deposits.

Mann (1954, 1960) mapped much of the Gravelly Range, including significant amounts of pre-Beltian rocks, but did not differentiate them into separate units. Hadley (1969a, 1969b) mapped key areas along the eastern flank of the Gravelly Range, which give considerable insight into the talc potential of that area. Student investigators are currently working in and mapping portions of the Gravelly Range, but it will be some time before that work is reported.

It is difficult to discard a stratigraphic name such as "Cherry Creek", because of its longevity and widespread usage, but the writer chooses not to use it without qualification (except at its type area), for there is no way to be certain that one is always referring to sequences of the same age when widely scattered outcrops of pre-Beltian dolomitic marble are being considered. The Cherry Creek Group, as defined by Peale (1896) south of Ennis, Montana, consists of more than 7,000 feet of interlaminated gneiss, mica schist, marble, crystalline limestone, and quartzite. Heinrich and Rabbitt (1960) restudied the type area and characterized the Cherry Creek Group as containing the following major classes of rock types:

1. Marble, calc-schist, and lime-silicate gneiss
2. Quartzite and quartz schist
3. Phyllite
4. Mica schist
5. Kyanite schist and kyanite-staurolite schist
6. Sillimanite schist and gneiss
7. Magnetite schist and related rocks ("iron formation")
8. Amphibole gneiss, schist, and amphibolite
9. Quartz-feldspar gneiss, granitic gneiss, biotite, and injection gneiss

The marble layers form the thickest and the most persistent of the units within the group at this locality, and individual marble layers as much as 1,500 feet thick have been noted. Quartzite units as thick as 550 feet have also been noted. The "total minimum thickness of the Cherry Creek group in its type area is estimated to be about 30,000 feet" (Heinrich and Rabbitt, 1960).

Heinrich (1960) studied the Cherry Creek Group in the Ruby Range and reported the following as the characteristic rock types:

1. Marble and calcium-magnesium-silicate gneiss
2. Quartzite and conglomeratic quartzite
3. Muscovite and biotite schist, some garnetiferous
4. Biotite gneiss, some containing various amounts of garnet
5. Sillimanite schist and gneiss, some garnetiferous
6. Hypersthene-magnetite schist
7. Pyroxene schist and gneiss
8. Chlorite schist
9. Corundum schist
10. Hornblende gneiss, amphibolite, and schist
11. Anthophyllitic gneiss and schist

The marble units are the most conspicuous; individual units as thick as 1,600 feet have been noted, but such thicknesses may not be original. They may have resulted from flowage that occurred during the epochs of intense folding in Precambrian time.

In the Tobacco Root Mountains, Tansley and others (1933) described the Cherry Creek Group as consisting of "quartzites, limestones, schists, and gneisses whose sedimentary origin is unquestionable, whereas the Pony group possesses features common to both sedimentary and igneous rocks. No limestone or true quartzite occurs in the Pony group".

"Cherry Creek-type rocks" will be discussed and described below in detail; the use of the foregoing terminology will allude to the fact that the term Cherry Creek Group, as used in the past for occurrences outside the type locality area, should not necessarily imply stratigraphic correlation or time equivalence. Therefore, except for the type locality in the Gravelly Range, the term "Cherry Creek-type rocks" will be used in this paper to denote a series of pre-Beltian strata of unquestionable sedimentary origin, characterized by marble and quartzite and containing abundant schist and minor gneiss, with no implication whatsoever that any of the geographically isolated sequences can be correlated stratigraphically with any other.

GEOLOGY OF THE RUBY RANGE

The Ruby Range is elongate in the general direction of N. 40° E., being about 30 miles long and having a width of 10 to 15 miles. Altitudes along the base of the range are generally 6,000 feet or so above sea level; the highest peaks are in the northern third of the range, Ruby Peak at 9,391 feet above sea level being the highest point in the range. The Ruby Range may be divided into several geological blocks, each having certain unifying characteristics.

A generalized geological map (Fig. 10-3) has been compiled by the writer from his own field work and from unpublished maps by James, Wier, and Shaw (1969), Tysdal (1970), Okuma (1971), and Garihan (1973). These four unpublished maps cover the entire Ruby Range except for a very small triangular segment at its southeasternmost extremity. Six geological units are shown on Figure 10-3; three of Precambrian age, one "mixed" Precambrian-Paleozoic, one almost entirely Paleozoic, and one Tertiary-Quaternary. The second oldest unit is that one along the southwestern flank of the range that contains "Cherry Creek-type rocks". Virtually all of the known dolomitic marble in the range is within the boundaries of this unit; those that are not are contained within the undifferentiated Precambrian portions of the "mixed" Precambrian-Paleozoic unit. The granite gneiss unit along the southeastern flank of the range is the one that previous workers have called the "Dillon Granite Gneiss". The distribution of this unit on Figure 10-3 has been delineated so as to exclude all known marble units. The "mixed" Precambrian-Paleozoic unit has been established because it covers an area where the relationships between the intensely folded Precambrian units and the homoclinal Paleozoic formations have been complicated by Laramide block faulting, resulting in a mosaic-like complex of the two very different sequences. The Paleozoic block consists almost entirely of Cambrian-Pennsylvanian formations, but has some scattered and relatively minor outcrops of Cretaceous, Tertiary, and Quaternary units. A Tertiary-Quaternary block is shown along the central portion of the eastern flank of the range where units of such ages are so widespread that they can readily be shown, even on the scale of Figure 10-3.

ROCK UNITS

PRE-CHERRY CREEK ROCKS

Both Okuma (1971) and Garihan (1973) recognized the presence of rocks pre-dating "Cherry Creek-type rocks" along the southern margin and the eastern margin, respectively, of the Ruby Range. Okuma listed the main rock types of this group as:

Biotite-garnet-quartz-feldspar gneiss
Biotite-garnet gneiss
Amphibolite and hornblende gneiss

and stated that most of these rocks are coarse grained and banded. He believed that the discontinuous nature of some of the amphibolite bodies indicates their origin as mafic sills and provides evidence for an intrusive origin. Okuma mapped this group as being confined to the southeasternmost part of his area and described it as being composed of metasedimentray, meta-igneous, and migmatitic units.

Garihan (1973) described "a belt two kilometers wide between Sage and Mormon Creeks" of pre-Cherry Creek rocks along the central part of the eastern flank of the range, but the area that is so exposed is too small to allow the establishment of firm and reliable relationships to other lithologic sequences in the range. This group of pre-Cherry Creek rocks includes gneiss, schist, amphibolite, and migmatite – but no marble or metaquartzite.

Heinrich (1960) described rocks of the "pre-Cherry Creek group" in the Ruby Range as "gneissic, banded, and coarse-grained" and noted the absence of distinctive laterally persistent units. Schist was noted as markedly subordinate to gneiss.

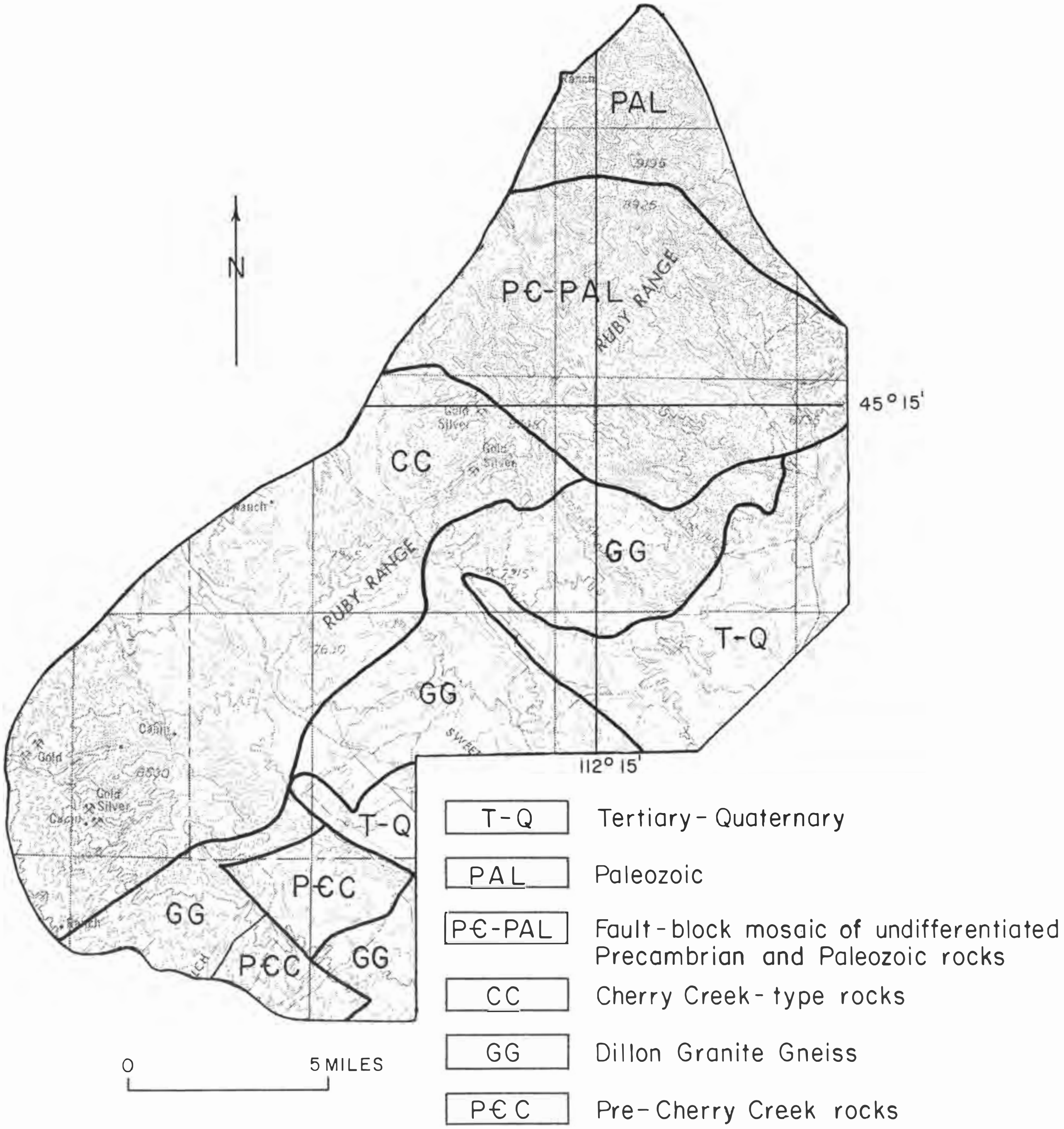
"CHERRY CREEK-TYPE ROCKS"

Particular attention was paid to the "Cherry Creek-type rocks" by both Okuma (1971) and Garihan (1973) because a good deal of their attention was devoted toward talc occurrences, and *all* of the known commercial deposits of talc in the Ruby Range, and all of Montana for that matter, are found within the boundaries of dolomitic marble units of the "Cherry Creek-type rocks".

Okuma (1971) listed the following as the distinctive rock types of his "Cherry Creek Group":

1. Marble
2. Quartzite
3. Calcium-magnesium schist and quartzite
4. Amphibolite and hornblende gneiss
5. Mica schist
6. Sillimanite schist and sillimanite gneiss
7. Magnetite schist (Iron Formation)
8. Other rock types (not mapped separately)

The marble layers are conspicuous and invaluable as structural marker units and have been mapped as 30 to several hundred feet thick. They are generally well-bedded, individual layers ranging from 6 inches to 4 feet in thickness. The dolomite generally crops out



10-3. –Generalized geologic map of Ruby Range, Beaverhead and Madison Counties.

better than its enclosing units, but is further sharply delineated by dense growths of greasewood and the presence of a light-orange lichen, which seemingly grows only upon the dolomite rock. The dolomite is generally white to light gray in fresh color. Actinolite and tremolite occur locally in the marble, but generally only near contacts with the ultramafic rocks; both minerals are unknown within commercial talc bodies. Garnets are also locally developed within the marble. Quartzite layers range from 15 to 180 feet in thickness, and although they are decidedly subordinate in volume compared to the marble, they do make excellent structural marker units. Amphibolite and hornblende gneiss are decidedly important volumetrically, and these units range from 6 inches to 1,500 feet in thickness. Most of the "Cherry Creek Group" is of sedimentary origin, according to Okuma (1971), but the amphibolite bodies probably were originally igneous dikes and sills.

Garihan (1973) stated that in the southern part of the Ruby Range the rocks of the "Cherry Creek Group" trend uniformly northeasterly, but in the central part of the range, especially along Stone Creek, they bend easterly and then southeasterly, and then continue in a general easterly direction into the Greenhorn Range in the vicinity of Ruby Dam. He recognized the following lithologic subdivisions of the "Cherry Creek Group":

1. Marble
2. Calc-silicate rock
3. Metaquartzite
4. Sillimanite schist
5. Biotite gneiss and schist
6. Chlorite schist and related rocks
7. Actinolite schist
8. "Iron Formation"
9. Amphibolite and related rocks
10. Anthophyllite gneiss and related rocks

and further specified that this order of listing does not in any way connote stratigraphic succession. He mapped marble layers 100 feet to approximately 1,500 feet thick and noted the presence of both calcitic and dolomitic marble; the calcitic variety is finer grained than the dolomitic variety, which is only locally fine grained and sugary textured as is the calcitic marble. Garihan (1973) stated that the marble commonly grades into calc-silicate rock and diopsidic marble, which is much more common than tremolitic marble. The calc-silicate rock, a relatively minor rock type, may or may not contain carbonate and is relatively rare in the central part of the range; it is much more widespread, however, in the southern part, where it has been used as marker beds for mapping. Sillimanite schist constitutes only 8 percent of Garihan's measured section along Stone Creek on the western flank of the range. This rock type is easily eroded, and several valleys, such as Mine Gulch, have been cut from it. It can be mapped locally by the micaceous soil formed upon it. Amphibolite constitutes more than 20 percent of the thickness of the "Cherry Creek Group" according to Garihan (1973) and is thus one of its more important lithologic units. He recognized one such unit as being about 1,000 feet thick and stated that some of these units can be traced "for several kilometers" laterally. Anthophyllitic amphibolite is common. Anthophyllite is also found in the gneiss and schist, as is cummingtonite; the two minerals are indistinguishable in the field but were not found together in thin section. Garihan (1973) also noted the occurrence of cordierite-anthophyllite gneiss, which is associated with amphibolite. There seems little doubt that these metamorphic units originally formed a sedimentary sequence.

Heinrich (1960) made a petrographic study of some of the marble in the "Cherry Creek Group" of the Ruby Range and by the use of staining techniques he found that dolomitic marble is about twice as abundant as calcitic marble.

The Carter Creek iron deposit, which bridges the Beaverhead-Madison County line southeast of Dillon, is in "Cherry Creek-type rocks". A detailed geological map of this deposit has been published (James and Wier, 1972).

DILLON GRANITE GNEISS

The Dillon Granite Gneiss of southwestern Montana has been described by Heinrich (1953, 1960).

The major rock types in the Dillon Granite Gneiss in the southern part of the Ruby Range, according to Okuma (1971) are:

1. Reddish-brown quartz feldspar gneiss
2. Foliated, light-colored pegmatitic gneiss
3. Coarse-grained biotite-feldspar-quartz gneiss
4. Olive-gray granite gneiss
5. Epidote-rich gneiss

The Dillon Granite Gneiss is generally conformable with those metasedimentary rocks that it has intruded (here the "Cherry Creek-type rocks"), and any cross-cutting relationships are generally minor in degree and angularity. Okuma (1971) favored a magmatic origin but recognized that this is not the only plausible genetic model.

In the central part of the Ruby Range, Garihan (1973) recognized three major rock types in the Dillon Granite Gneiss:

Biotite-hornblende-garnet gneiss
Pegmatitic Dillon Granite Gneiss
Chloritic Dillon Granite Gneiss

and stated that the Dillon Granite Gneiss is concordant with the "Cherry Creek-type rocks". All of those workers who have published major contributions upon the pre-Beltian rocks of the Ruby Range view the Dillon Granite Gneiss as a large tabular intrusive body, of batholithic proportion, which is in regional concordance with its enclosing rocks. Other alternatives, however, must be considered, such as granitization and the regional metamorphism of sedimentary sequences. Garihan (1973) provided detailed petrographic descriptions of the various types of rocks within the Dillon Granite Gneiss in his area.

Heinrich (1960) described "non-foliated pegmatites, which commonly are zoned", which transgress the grain of the country rock that includes them. These pegmatite bodies are not abundant, and although Heinrich judged them to be genetically related to the Dillon Granite Gneiss, he recognized that they may be much younger, possibly even of Laramide age. Unfortunately they are not known to come into contact anywhere with rocks younger than Dillon Granite Gneiss, and thus can be dated only as post-Dillon and probably pre-Tobacco Root batholith in age.

ULTRAMAFIC ROCKS

Ultramafic rock units, which Okuma (1971) referred to as peridotite, intrude the pre-Cherry Creek rocks, the "Cherry Creek Group", and the Dillon Granite Gneiss in the southwestern part of the Ruby Range. They are fifteen feet to several hundred feet wide.

Similarly, in the central part of the Ruby Range, Garihan (1973) described the pre-Cherry Creek rocks, the "Cherry Creek Group", and the Dillon Granite Gneiss as all playing host to ultramafic bodies. For the most part, he stated, the ultramafic bodies are concordant, i.e., parallel to the regional foliation, but they are locally discordant. The three major types of ultramafic rocks are metaperidotite, metapyroxenite, and serpentinite. Garihan (1973) thought that the ultramafic rocks were probably introduced at least as early as the complex isoclinal folding and upper amphibolite metamorphic event.

Heinrich (1960) described these ultramafic intrusive bodies as "unmetamorphosed" and noted that they are cut by the younger diabase bodies and also by the master faults of the Ruby Range (northwest system).

GRANULITES

Granulite rocks have been recognized by Garihan (1973) only in the northern part of the Mine Gulch 7½-minute quadrangle. In the field they are difficult to distinguish from amphibolite, and their outcrops are generally poor, but they have been recognized as granulites after thin-section study. They are common in terranes underlain by the Dillon Granite Gneiss, less common in those underlain by the "Cherry Creek Group", and are of interest because of their proximity to at least two talc-bearing marble units.

DIABASE DIKES

Diabase dikes, with preferred orientation in the north-northwest octant, are common along the southern two-thirds of the western flank of the Ruby Range. Okuma (1971) described them as ranging from 5 to 500 feet in width and extending as much as 5 miles. They commonly occupy long and relatively narrow distinctly depressed swales, which are generally free of all vegetation except grass and contain few or no outcrops. Their intrusion has had little or no effect upon the older country rocks, except for the marble, which may locally have had small amounts of serpentine developed. These dikes have not been subjected to the high-grade amphibolite metamorphic event, but have been metamorphosed to the greenschist facies. Okuma (1971) speculated about the age of these diabase dikes – as to whether they are of Precambrian, Paleozoic, or Tertiary age – and concluded that they are *probably* Precambrian.

Garihan (1973) stated that such diabase dikes are also common in the central part of the Ruby Range and that they may be as wide as 100 feet and as long as 1 mile, possibly more. They are easily recognized and traced upon aerial photographs. They generally cut the foliation of the enclosing pre-Beltian rocks at high angles and are not folded as are those older rocks. They are vertical or subvertical, as judged by the linear nature of their traces over extremely rugged topography, and they are decidedly less metamorphosed (generally only to the greenschist facies stage) than the enclosing rocks. Their lack of folding and foliation suggests that they were emplaced later than the phases of shearing and recrystallization that are associated with the ultramafic rocks and the other older pre-Beltian rocks. The mapping by Garihan (1973) and Tysdal (1970) suggests that these dikes have no intrusive relationship whatsoever with the Paleozoic strata of the northern third of the Ruby Range, despite their locally close proximity to those strata. If this inference is correct, the diabase dikes are of Precambrian age and are possibly the youngest Precambrian unit in the range.

A large diabase dike cuts what may well be the largest single talc deposit in the Ruby Range, the Regal (Keystone) Mine in sec. 2, T. 8 S., R. 7 W., Madison County. This dike is more than 200 feet wide at the mine and, with two other similar bodies along approximately the same strike, can be traced for about 4 miles in a north to north-northwest direction. It is probably vertical, or at least very close to vertical, as deduced from its almost linear trace over rugged topographic relief.

Heinrich (1960) described one diabase dike in Axes Canyon near the southwesternmost extremity of the Ruby Range as being 600 feet wide and 6 miles long. He stated that these bodies are generally intruded along faults, particularly the master fault set of the range (north to northwest system).

UNDIFFERENTIATED PRECAMBRIAN

Tysdal (1970) has mapped large areas of Precambrian rocks in the northern third of the Ruby Range but has not differentiated them into separate lithologic units or groups. He mentioned "metadolomite" as one of the five dominant rock types, however, so it is likely that "Cherry Creek-type rocks" are present.

PALEOZOIC

Tysdal (1970) described the Precambrian-Cambrian unconformity in the northern third of the Ruby Range as a nearly planar contact, and he mapped and measured Cambrian, Devonian, Mississippian, and Pennsylvanian formations that have an aggregate thickness of about 5,300 feet, of which approximately 1,500 feet (mostly Cambrian and Devonian) is dolomite or markedly dolomitic. No talc is known to have been formed in these younger dolomite beds.

CRETACEOUS-TERTIARY

Tysdal (1970, p. 94) asserted that the Beaverhead Formation, of Cretaceous-Tertiary age, contains quartzite clasts that have been eroded from Beltian rocks. Belt strata, completely absent from the Ruby Range, are known in the Pioneer Mountains to the west; this was probably the source.

TERTIARY-QUATERNARY

Late Tertiary and Quaternary strata are present in the Ruby Range, especially in its northern third along the lowermost flanks.

METAMORPHISM

All pre-Cherry Creek rocks, the "Cherry Creek Group", and most of the rock types of the Dillon Granite Gneiss have been subjected to upper amphibolite grades of metamorphism, according to Garihan (1973), "as part of a prolonged pre-Beltian episode which included isoclinal deformation and subsequent intrusion of basic dikes". He thought that the available information strongly suggests that the pre-Cherry Creek rocks may date back to 3.1×10^9 years ago and that the Dillon Granite Gneiss is on the order of 1.6×10^9 years old. He further inferred a second regional metamorphism of greenschist grade of an undetermined (but certainly Precambrian) absolute age.

Okuma (1971) also agreed that the Precambrian rocks of the Ruby Range have been subjected to regional metamorphism of the upper amphibolite facies and further observed that garnet is ubiquitous in rocks of the Ruby Range. He saw no clear evidence to suggest multiple metamorphism, i.e., multiple metamorphism of the highest rank achieved (upper amphibolite facies). His study of thin sections indicated that the later retrograde metamorphism of the greenschist facies was widespread and that the formation of the talc may well be related to this later metamorphism.

STRUCTURAL GEOLOGY

According to Okuma (1971) "the southwestern portion of the Ruby Range has remained relatively stable since its intense deformation in late Precambrian time". Almost throughout his area the foliation is "invariably parallel to the formational contacts of the different rock types". Isoclinal folds are characterized by parallel or near-parallel limbs, and Okuma recognized three phases of Precambrian folding. The prominent northwest- and north-northwest-trending master faults, which are readily recognized locally by the abrupt juxtaposition of radically different rock types, have essentially no topographic expression whatsoever, despite their large displacements. The Elk Creek Fault, trending N. 40° W., displaces the "Cherry Creek Group" – Dillon

Granite Gneiss contact a horizontal distance of 2 miles; the Red Canyon Fault displaces it about 1 mile. Okuma (1971) thought that the age of the high-angle faulting could be Laramide; if the strikes of the diabase dikes indicate Precambrian lines of weakness, however, then these faults could have originated in Precambrian time and been reactivated in the Tertiary. Okuma suggested that the pre-Cherry Creek rocks, the "Cherry Creek Group", and the Dillon Granite Gneiss were deformed contemporaneously. According to him, Precambrian structural deformation "was primarily by a combination of flexural-flow, slip or shear along schistosity, and plastic flow".

Those investigating in detail the pre-Beltian rocks of the Ruby Range recognize either two, three, or four phases of folding in Precambrian time. Tight isoclinal folding is common in such rocks throughout this area. The master northwest-trending faults, which are post-folding in age, are superimposed throughout the range at approximately right angles to the strike of the Precambrian foliation. This faulting is probably much more pervasive and important in scale than is presently recognized; the faults can be easily recognized where they cut the Precambrian-Paleozoic unconformity, but they may be extremely difficult to trace where areally confined to the Precambrian sequences. The range-bounding faults in the central part of the eastern flank of the range have an overall trend of about N. 50° E., but in the northern part of the eastern flank they trend north-northwest. The age of this high-angle faulting is difficult to ascertain. Garihan (1973) thought that the northwest-trending faults may have been initiated in Precambrian time, if one considers that the diabase dikes represent the establishment of weakness surfaces in the north-northwest octant in Precambrian time. He favored the theory of recurrent movement on these faults in Precambrian, Laramide, and post-Laramide times; the writer agrees that this is most plausible.

Tysdal (1970) described the Ruby Range as being on the western edge of the foreland of the Rocky Mountains in a structural setting that is characterized by:

a) high-angle faults cutting basement rocks.
b) extensive exposures of Precambrian metamorphic rocks in the cores of mountain uplifts.
c) relatively thin cover of Paleozoic and Mesozoic sedimentary rocks.

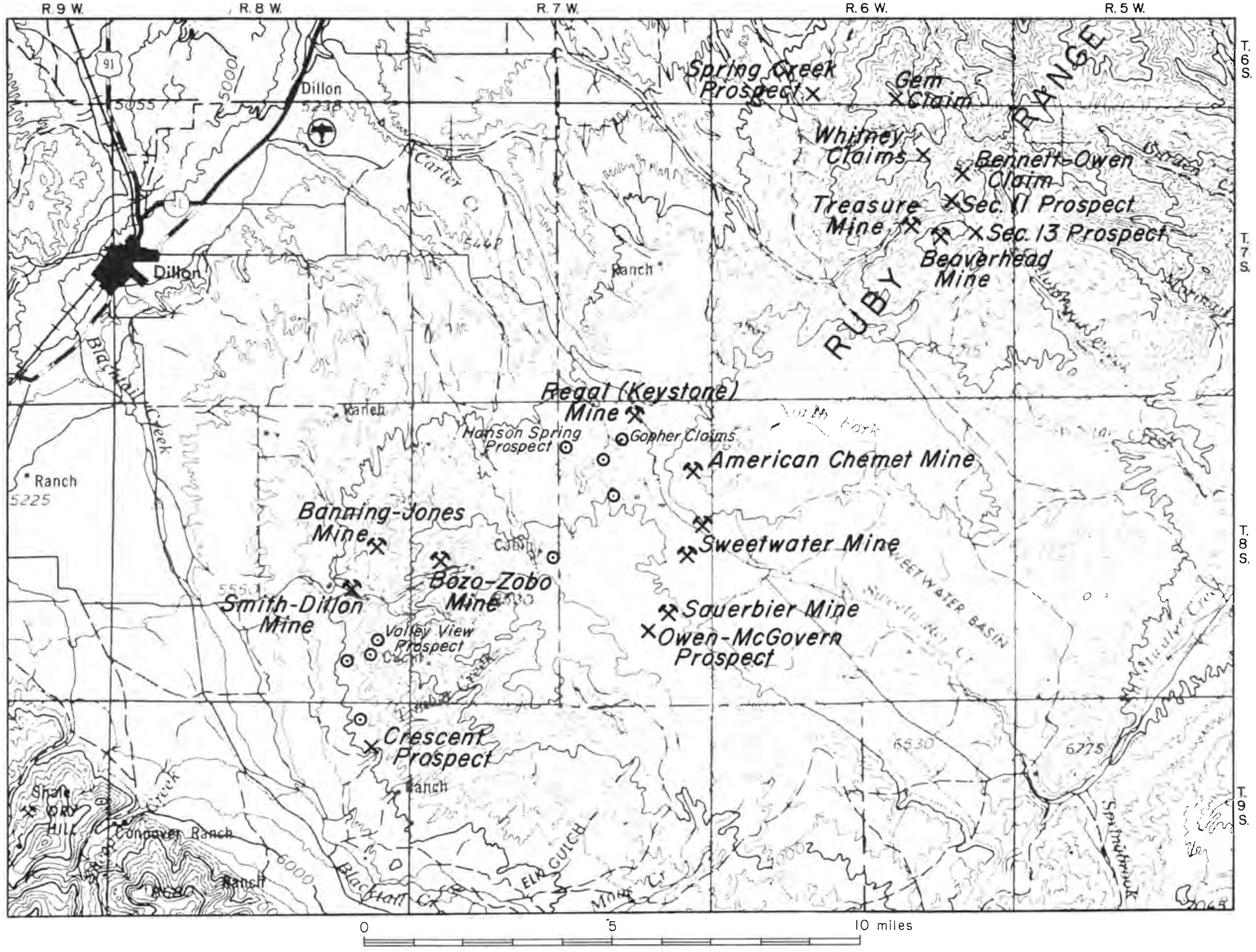
The Paleozoic and Mesozoic strata in the Ruby Range had an aggregate thickness of about 10,000 feet or less during deformation in the Late Cretaceous-early Tertiary, according to Tysdal (1970). Major normal faults border the western, northern, and much of the eastern sides of the range in Tysdal's area. He showed seven major fault blocks within the range, all delineated by en echelon northwest-trending high-angle faults; all except one of these faults are downthrown on the southwestern side and upthrown on the northeastern side. These basement blocks have been tilted to the northeast and plunge to the northwest. Tysdal (1970) described the northwest to north-northwest master faults in his area as having throws of 6,000 to 7,000 feet and stated that they generally truncate the northeast-trending faults, which are relatively minor in magnitude and importance. He has mapped broad anticlinal folds involving Cambrian formations, referring to them as flexural flow folds, but these structures are totally different than the tight isoclinal folds developed in the pre-Beltian rocks. He has also mapped synclinal folds, whose limbs locally become vertical and overturned. These anticlinal and synclinal folds are closely associated with the northwest to north-northwest master faults and were most likely formed as a consequence of their proximity to those major faults.

ACTIVE TALC MINES IN THE RUBY RANGE

TREASURE CHEST MINE

The Treasure Chest Mine, near the head of the Left Fork of Stone Creek in the north-central part of the Ruby Range, is owned by Pfizer, Inc. It is and has long been the most important producer in that range. The Treasure State Mine, which has not produced any talc ore for more than a decade, lies a few hundred feet downhill and to the west of the Treasure Chest Mine. The two are believed to be faulted-off segments of what was once a single ore body, and the writer has named the structure that separates them as the Treasure Fault (Fig. 10-4).

The Treasure Chest Mine lies midway on the south hillslope of the Left Fork of Stone Creek in the NW¼ sec. 14, T. 7 S., R. 6 W., Madison County, Montana (Mine Gulch 7½-minute quadrangle). This large tabular ore body has a strike length of about 1,000 feet (of which 700 feet of strike length on the western end has the greatest commercial potential) and horizontal width as great as 120 feet, and has been mined to a vertical depth of about 250 feet. Its strike ranges from east to N. 60° E., and the dip averages 55° northerly. The actual local strike must be determined by close scrutiny of the outcrops, for an intricate system of right-lateral faults has imparted an overall trend to the entire ore body of somewhat south of east.



10-4.–Talc mines and prospects, Ruby Range, Beaverhead and Madison Counties.

The Treasure Chest Mine is unusual among talc deposits in the Ruby Range in that throughout parts of its lateral extent a thick dolomitic marble unit has been completely converted to talc. The footwall is dark biotite schist, called "The Blackwall" by miners, and the hanging wall is Dillon Granite Gneiss, which is generally chloritic. The footwall schist is locally garnetiferous and extensively serpentinized and chloritized. The extensive alteration has resulted in a crumbly and relatively incoherent mass, which renders much of this schist susceptible to widespread and unpredictable sloughing into the pit. The presence of numerous but generally unmappable undulatory fault surfaces is indicated by the abundance of slickensides on fresh surfaces. The alteration and the faulting, plus the fact that the talc generally has been formed and is therefore mined right up to the vein-schist contact, all combine to constitute an extremely difficult safety problem. Several slides of schist footwall blocks have occurred during periods of mining activity; as the pit goes deeper, attaining a satisfactory amount of stability of the steep footwall will become an increasingly difficult problem.

The hanging wall is a medium- to coarse-grained variety of Dillon Granite Gneiss, which contains biotite and garnet. Individual beds are well layered, and the gneiss is concordant with both the talc-containing marble and the footwall schist.

The Treasure Chest Mine is situated along the nose of the major broad structural arch of the Ruby Range as mapped by Garihan (1973, Plate I). In the general vicinity of the mine the strata generally strike east to N. 60° E. and although the dips may range from 25° northerly to vertical, the common range is 45° to 65° northerly. Along with this regional dip, the major structural features include a strongly developed en echelon set of high-angle to vertical right-lateral faults striking N. 20° W. These faults may be as closely spaced horizontally as 100 feet or so, but the spacing is generally wider than this. The southwestern block has moved relatively upward along each one of the faults that has been recognized to date. The Treasure Fault is the most important of these within the mine area; it has displaced the Treasure ore body in right-lateral direction 150 to 200 feet. Present evidence within the mine area does not conclusively indicate whether the formation of the talc preceded or post-dated the faulting. The writer's work in the late 1960's suggested that the talc was formed prior to the faulting, but this conclusion is still unproved. The character of the "talc-zone" was nowhere observed to change appreciably, near or adjacent to the fault surfaces, and it is generally uniform within each individual fault-block. Geological relationships observed during the writer's investigations of this mine suggest that the alteration of dolomitic marble to talc within the "talc-zone" occurred first, and that subsequent high-angle block faulting jostled individual fault blocks around so that rocks of different lithology were directly juxtaposed.

The presence of the right-lateral faults went unrecognized for many years during the early operation of this open pit. This is understandable, for little if any structure can be observed within the "talc-zone", which reacts plastically to deformative forces. A further complication is that lithologic contacts must generally be observed during the mining operations; even only a few days after they have been originally unearthed, and certainly at the end of the mining season, such relationships have generally become totally obscured by the movement of mining machinery, by slumping, or by concealment under waste material. During the plane-table-and-alidade mapping performed by the writer in 1969 it was even necessary to call upon earth-moving machines equipped with ripper teeth in order to locate lithologic contacts within the pit floor, so pervasive and obscuring were the huge amounts of dust generated by the mining activity. The extent of the faulting cannot be accurately mapped nor truly understood until one works in the footwall schist or the hanging-wall granite gneiss in areas close to the "talc-zone" itself.

The westernmost block of the Treasure Chest Mine, between the Treasure and Pit Faults, (see Garihan, 1973, Fig. 42, p. 150) has not over the years contained appreciable amounts of the highest-grade talc ore. Chloritic material and white quartz veinlets have been locally so abundant that no ore whatsoever could be recovered from this portion of the "talc-zone", and it has thus either gone to waste or has been left. The area between the Pit Fault and the westernmost exposure of the Dolomite Fault has contained the best ore mined on this property. During the late 1960's the "talc-zone" between the footwall schist and the hanging-wall gneiss was composed entirely of the highest-grade talc over a horizontal width of 120 feet (true vein width of about 95 feet). From the Dolomite Fault eastward, the quality of the ore within the "talc-zone" becomes lower and lower, and the talc is contaminated by large "horses" of dolomite and dolomitic talc as well as by large "knobs" of silicified material. Where these contaminants are present in large masses they can easily be mined around and left or can be sorted out and sent to waste by the use of mining machinery, but inasmuch as hand-sorting methods are not employed at this mine, much material containing appreciable quantities of pure talc is thrown to waste from areas where contamination by waste is intimate and on a small scale. In recent years efforts have been made to extend the Treasure Chest Mine to the east, but present exposures indicate that these attempts have met with little success. Much high-grade talc is present in the easternmost reaches of the present mine area, but its recovery will require the use of sorting methods rather than large earth-moving machinery alone, which is the present method of operation.

In the mid-1960's the waste:ore ratio was on the order of 3:1 or 4:1, but it is now on the order of 15:1 and will soon be at least as great as 20:1. Present mining costs may be approaching the point that would justify considering the alternative of underground mining. Even if the operating costs of the latter were greater, the improved safety that would result from eliminating the high-standing dangerous "Blackwall" might help to offset them. In addition to the recent large increases in the waste:ore ratio, it is now necessary to transport waste greater and greater distances from the mine area.

The highest grade talc from the Treasure Chest Mine must rank with the purest grades of talc known throughout the world. Large blocks have been mined (consisting of several thousand tons each) that are either white or pale greenish and are homogeneously cryptocrystalline and massive pure talc. Garihan (1973) has petrographically identified minor amounts of apatite, chlorite, graphite, limonite, and rutile in the talc ores of this mine, but these impurities have not commonly been abundant enough to render the talc unsuitable for the mill. Talc that is darker green than usual is termed "#2 ore" by the miners, but compositional differences between it and the lighter-colored "#1 ore" are slight; it is the color that is the important difference.

All of the marble that has been observed within the mine area by the writer is dolomitic, not calcitic. The Treasure Chest Mine does not have enough recorded history to indicate whether the "talc-zone" is thinning or thickening with depth, i.e., are we within the upper half or the lower half of a lenticular body? The most easterly of the right-lateral high-angle to vertical faults that has been recognized within the mine area lies about 400 feet east of the easternmost recognizable part of the Dolomite Fault. If the ore body or indeed even the "talc-zone" is present east of this unnamed fault, and if the pattern of right-lateral displacement *only* persists, then the talc would have to be uphill from and southeast of the present mine area. Efforts to locate such an easterly extension by bulldozing and drilling have thus far been, to the writer's best knowledge, unsuccessful.

Talc ore from the Treasure Chest Mine is trucked 30 miles or so to the Pfizer mill at Barratts Siding on the Union Pacific Railroad about 8 miles southwest of Dillon.

TREASURE STATE MINE

The Treasure State Mine was in operation long before the presence of talc ore in the Treasure Chest Mine area was even known. Shortly after the latter mine was opened, the Treasure State Mine was closed; it has been inactive ever since, although much high-grade pure talc ore obviously remains in this lower deposit. It is situated in the NW¼ sec. 14, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle), downhill and to the west across the Treasure Fault from the Treasure Chest Mine.

The Treasure State Mine is obviously a faulted-off extension of the same ore body as that which produces at the Treasure Chest Mine. Its offset has been right lateral, the same direction of relative movement as is shown along all of the known faults within the Treasure Chest Mine area. The geology of the two mines is almost identical. Talc in the Treasure State Mine has been proved to have a strike length of at least 400 feet and a horizontal width of 75 to 100 feet and has been mined down dip to a depth of about 200 feet. The writer did not have the opportunity to observe this mine during its operation, but it is likely that blocks of high-purity talc without dolomitic or siliceous "horses" were not as large here as those in the Treasure Chest Mine. This grade factor plus the greater length and width of the latter deposit were probably the principal reasons that the Treasure State Mine was abandoned in favor of the Treasure Chest Mine; nevertheless, it is certainly true that much recoverable ore-grade talc remains in the Treasure State Mine, awaiting the day when its cost of recovery will become compettitive with then-present sources. In the last days of its operation this mine was certainly "high-graded"; before it can be reactivated some of the sins of the past must be redeemed and paid for.

As in the "talc-zone" of the Treasure Chest Mine, talc in the Treasure State Mine may locally extend from the footwall schist to the hanging-wall granite gneiss. Garihan (1973), however, has described some interesting relationships in this mine that are not well shown in the Treasure Chest Mine. He described a four-fold division of rock types from south (footwall) to north (hanging wall): schist, pale-green talc, a dark blue-green talcose-rock zone with gneissic foliation, and finally less-altered varieties of Dillon Granite Gneiss.

He further described the talcose-rock zone as being "probably highly altered Dillon Gneiss". The presence of a "transitional zone" between the "talc-zone" and the hanging wall in the Treasure Chest Mine has been locally noted by the writer, but it is either not nearly as well developed there as in the Treasure State Mine or else it may be present but a lack of exposures does not allow its widespread recognition in this active mining area.

Any westward extension of the talc of the Treasure State Mine is presently enigmatic. Poorly developed evidence suggests that it might be faulted uphill by a totally anomalous left-lateral fault, but such a possibility would have to be proved with the bulldozer or the drill. It is extremely unlikely, however, that the present westernmost exposures of this ore body are identical with its actual westernmost extent.

Both the Treasure Chest Mine and the Treasure State Mine are owned by the Minerals, Pigments and Metals Division of Pfizer, Inc., which obtained them through the acquisition of the assets of Southern California Minerals Company in 1966.

BEAVERHEAD MINE

The Beaverhead Mine, owned and operated by Cyprus Industrial Minerals Company, lies southeast of the Treasure Chest and Treasure State Mines and over the crest of an east-west ridge from them. Present operations are within the NW¼ SE¼ sec. 14, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle). The mine lies high on a steep hillslope north of the head of the Middle Fork of Stone Creek, only 2,000 feet or so southeast of Pfizer's Treasure Chest Mine.

The geology of this mine is similar to that of the Pfizer mines to the north, except for the strong possibility that the strata of the Beaverhead Mine have been overturned with respect to the strata of the Pfizer mines. At the Beaverhead Mine we have essentially a single body of talc that has at least 800 feet of strike length, and is offset by relatively minor lateral faults. It ranges in horizontal width from 25 to 100 feet (probably averaging near 75 feet), and has locally been mined to a vertical depth of 150 feet. The strata dip homoclinally north 35° to 70°; the average dip is probably close to 45°. The strike ranges from east to slightly north of east.

The footwall is dolomitic, and the hanging wall is composed of schist and gneiss. This relationship is exactly the opposite to that of the Treasure Mines; coupled with the fact that the dips are about the same, this suggests the possibility that the Beaverhead Mine may be on the same isoclinal fold as the Treasure Mines but on the opposite limb. Field mapping by Garihan (1973) and the writer, however, has not been able to prove or disprove this possibility. As contrasted with the Treasure Mines, the "talc-zone" of the Beaverhead Mine is only locally a single homogeneous talc body from the footwall to the hanging wall; almost everywhere it contains numerous large "horses" of non-talc rock, especially dolomite that has not been altered to talc. Seemingly the dolomite is more abundant in the lower half (southern part) of the "talc-zone" than in the upper half (northern part), and the purest talc occurs along the hanging-wall contact.

The footwall of the "talc-zone" is well-layered granite gneiss, which is very similar to that which forms the hanging wall of both Treasure Mines. Between this gneiss and the talc ore is a dolomitic zone, suggesting that for some reason the "talc-zone" was not entirely converted to talc ore, as it was at places in the Treasure Mines. The hanging-wall rock adjacent to the "talc-zone" is biotite schist, which is in turn overlain by well-layered granite gneiss, which has been locally chloritized. Garihan (1973) stated that the hanging-wall country rock is similar to the footwall material of the Treasure Chest, and the writer fully agrees. In this mine, in both of the Treasure Mines, and in the Smith-Dillon Mine there is the suggestion that the best talc lies along the contact of the "talc-zone" with biotite schist, suggesting that this sharp contact may have represented a pronounced permeability barrier and thus may have locally channelized and impounded the mineralizing solutions.

The present exposures of the Beaverhead Mine probably constitute its full possible extent, for it is likely that the western and eastern extremities are "pinch-outs" rather than faults. If the Treasure Fault extends this far south, the Beaverhead Mine probably lies entirely east of it. Several small high-angle to vertical northwest-trending right-lateral faults are present within the mine area, but their offsets seem to be even less than those of analogous faults in the Treasure Chest Mine. All of these faults that have been recognized in the Beaverhead Mine have their southwestern side thrown upwards, as is also true of all those in the Treasure Mines.

Whereas topography is the friend of the miner at the Treasure Mines, where the talc is dipping in the same direction as the hillslope, topography is the firm enemy of the miner at the Beaverhead Mine. Stripping ratios, at present probably similar to those at the Treasure Chest Mine, will become pronouncedly greater and at a faster rate for similar rates of production than they will at the Treasure Mines. The Beaverhead Mine has yielded most of its production in less than the last decade. Garihan (1973) noted that the mine area tripled in size during the period 1968-73, and a massive 1974-75 stripping operation has increased the mine area even further.

Ore produced from the Beaverhead Mine is trucked southeast down the Cottonwood Road to the Ruby drainage and thence to a small washing plant at the terminus of a Burlington Northern spur at Alder, Montana. From this plant it may go to Belgium for processing there for European markets, or to Cyprus' domestic mills in Grand Island, Nebraska, or Three Forks, Montana.

REGAL (KEYSTONE) MINE

The Regal (Keystone) Mine is situated alongside the Sweetwater Road in the NW¼ NE¼ and NE¼ NW¼ sec. 2, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle). It is owned by Pfizer, Inc., having been acquired by them in 1966 along with all other assets of Southern California Minerals Company.

Okuma (1971) described the mine as occurring close to the core of a tightly refolded synform. The ore body is complex in that there are many large lenses of talc enclosed within a large body of dolomitic marble; this relationship has been further complicated by widespread faulting. Except for intrusive diabase, rock types other than talc and marble are rare upon this fairly large property. The marble strikes N. 45° E. to S. 80° E. and dips 30° to 75° north; although the structural geology in the area around the mine is extremely complex, this uniform attitude holds throughout the exposed extent of talc on the surface. A diabase dike more than 200 feet wide, seemingly vertical to subvertical, cuts the foliation of the marble almost at right angles along the western edge of the best exposures of the talc. Okuma (1971) has observed that at many places where the diabase has intruded the marble, no talc has been formed along the contact, but rather the dolomitic marble has been contact-metamorphosed to calcite and fine-grained serpentine.

Bedrock talc is exposed at the Regal Mine along more than 750 feet of strike length and over a horizontal width of more than 300 feet perpendicular to strike. A small open-pit mine has been developed along the southern margin of the Regal talc deposit. It is about 450 feet long (approximately along strike) and 50 to 100 feet wide, and the vertical depth is 20 to 30 feet. Perry (1948) described a shaft 60 feet deep and 300 feet of drifts off the bottom of the shaft, all of which are in talc, but these workings have been inaccessible for many years.

The Regal Mine is of particular interest geomorphologically. It is a true "pedimented" talc deposit, for over several acres bedrock talc appears in large outcrops right at the surface without any grass or soil cover whatsoever.

Talc-marble contacts are abrupt and have been locally faulted, as shown by numerous small lateral offsets. Talc float is locally so abundant that one's boot can hardly be placed upon the ground surface without touching some of it.

A conjugate fracture set may be observed along the north wall of the open pit on the southern side of the Regal Mine area; these fractures are vertical or subvertical and strike N. 60° W. and N. 30° E., the former being apparently better developed. The bedrock faults that displace talc-marble contacts so spectacularly at many places on the ground surface have the same azimuth traces as the aforementioned fractures, and similarly the northwesterly ones are better developed; however, the existing exposed relationships do not allow even a well-educated guess as to the relative directions of movement along these presumably minor faults.

The Regal Mine could well be the largest single mass of talc in the entire Ruby Range. Unfortunately, its operation has thus far been controlled strictly by sales considerations; i.e., the talc at the surface makes relatively poor products (mainly because of the dark color) and consequently low sales and profit figures do not result in the generation of sufficient funds to explore its potential at depth. This is a common failing in the industrial-minerals field and is certainly not restricted to talc alone! As the Regal talc ores are known now, it is true that the color is bad, owing to the presence of graphite and limonite (altered from contained pyrite), but the character of the talc at depth is almost completely unknown.

SAUERBIER MINE

The Sauerbier Mine is the newest talc mine in the Ruby Range, having been established upon almost virgin ground in 1973. It is situated in the NW¼ NW¼ sec. 25, T. 8 S., R. 7 W., Madison County (Elk Gulch 7½-minute quadrangle). It lies just south of a major fault zone developed along the southwestern edge of the flats south of the Sweetwater Road; the Carter Creek Fault may connect with this zone. It is unlikely that any large commercial talc ore bodies will be found east of this property, for it is seemingly the easternmost extent of the marble in this general vicinity.

The talc has been developed within a marble zone, which strikes N. 35° E. and dips from vertical to an estimated 70° southeast. Downhill northward from the mine toward the valley of Sweetwater Creek, shallower southeast dips (as flat as 30° or so) may be locally observed. The east and southeast dips in sec. 25 contrast with west and northwest dips in sec. 26 and over much of the Owen-McGovern Prospect and indicate the degree of local structural complexity, which is probably due to the proximity of the aforementioned major fault zone. The talc is more sporadic and erratic in its distribution within this "talc-zone" than in that of any other Montana talc deposit of which the writer is aware. Hand sorting has been necessary at this mine from the beginning, and unless pronounced changes in the geological relationships are encountered, it will probably always be so.

The American Talc Company, of Summit, New Jersey, has mined this property under lease from Mr. Karl L. Sauerbier of Alder, Montana. The hand-sorted ore is trucked along the Sweetwater-Ruby Road to Alder, where it is stockpiled on concrete pads for shipment by rail to mills in South Plainfield, New Jersey, and Alpine, Alabama.

INACTIVE TALC MINES IN THE RUBY RANGE

AMERICAN CHEMET MINE

The American Chemet Mine is situated in the NE¼ sec. 12, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle). It was once operated by the American Chemet Corporation of Chicago, Illinois. The workings consist of three open pits and several minor bulldozer trenches.

The talc is contained within "a complexly folded northeast-trending belt of marble" (Okuma, 1971), which is isolated within large expanses of Dillon Granite Gneiss extending both northwest and southeast.

BANNING-JONES MINE

A talc deposit in the SW¼ sec. 13, T. 8 S., R. 8 W., Beaverhead County (Dillon East 7½-minute quadrangle) was leased by the State of Montana in 1964 to Messrs. Wallace Banning and Lester Jones, both of Dillon, Montana (Geach, 1972). It is situated within the same belt of marble as is the Smith-Dillon Mine, which lies along strike from it about 1 mile to the southwest.

Talc has formed within a marble zone as much as 100 feet wide, but the widest zone of talc known (without included marble bodies) is only about 10 feet wide, and few such dolomite-free talc bodies are more than 5 feet wide. The talc is exposed on both sides of a major north-flowing gully and has seemingly been displaced at least 100 feet laterally by a right-lateral fault, which has determined the course of the gully.

Small amounts of talc were mined here, hand sorted, and trucked to Sheridan, Montana, where they were purchased by American Chemet Corporation.

BOZO-ZOBO MINE

The Bozo-Zobo Mine lies in the NE¼ sec. 19, T. 8 S., R. 7 W., Beaverhead County (Dillon East 7½-minute quadrangle) on the northern wall of Axes Canyon near its head. The strata here strike N. 50° E. and dip 80° northwest. The best exposures are in a large open cut near the southwest edge of the property, where the talc is 25 to 30 feet wide and has been mined to an estimated maximum depth of 50 feet or so. Seemingly less than half of the mineralized zone was converted into talc, as shown in this cut, rendering selective mining difficult and hand sorting probably absolutely necessary.

The occurrence of talc at several different levels along the north wall of Axes Canyon may indicate either the presence of several veins or the repetition of a single vein by tight isoclinal folding or faulting, but this puzzle will be solved only by careful mapping, aided by the results of the previous drilling program. Manganese oxides have locally stained the talc so intensely as to render it useless.

The Bozo-Zobo Mine lies roughly along strike from a similar prospect in the SW¼ NW¼ sec. 19, which is described elsewhere in this article. The two may represent the same stratigraphic zone and therefore a potential strike length of talc of 3,000 feet or so, but such a possibility, of course, would have to be proved by detailed mapping of this relatively small area.

The property was drilled by R. T. Vanderbilt Company in 1962-63 under the direction of Mr. L. R. Moretti; four core holes and at least 23 rotary drill holes were sunk during the course of that exploration program.

American Chemet Corporation of Chicago, Illinois, reportedly shipped approximately 8,000 tons of ore from this property in the mid-1960's.

SMITH-DILLON MINE

The Smith-Dillon Mine, topographically the lowest talc mine in the Ruby Range, is situated almost at the mouth of Axes Canyon near the southwestern corner of the range in the W½ sec. 23, T. 8 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle). Although this mine was an important producer of high-grade ore in the early days of the Montana talc district, it has been inactive for several years now. Originally an underground operation, it was open-pitted in its last days.

The marble unit in which the talc occurs is about 1,300 feet thick according to Okuma (1971). The regional strike is N. 30° to 40° E. and the dip is 60° to 70° northwest. Although all of the talc occurs in dolomitic marble, relatively little of the "talc-zone" has been converted into talc. Marble ribs, locally veined with white quartz, are common within the talc bodies and have long created a problem in the mining of this deposit. Okuma (1971) also noted the presence of small thin folded "stringers" of talc within the marble of the "talc-zone". The footwall in the mine area is dark mica schist, which is extensively slickensided, as in the footwalls of the two Treasure Mines.

The talc, as proved thus far by the open-pit mining, occurs over a strike length of about 750 feet and has an average horizontal width of about 50 feet; it has been mined to down-dip depths of about 125 feet in the open pit, and according to Perry (1948), to depths of more than 200 feet underground. The talc has been abruptly truncated at the northern end of the pit by an east-west fault, which dips 55° to 60° south. Left-lateral displacement along this fault is on the order of 70 feet.

It is probable that the talc exposed in shallow diggings at the Crown Mine, about 700 feet to the northeast, represents the same zone as that at the Smith-Dillon Mine, but to the writer's best knowledge this has yet to be proved by exploration. The presence of abundant talc float over the concealed area between these two properties, however, suggests that they may represent the same ore zone and that there may be a fair degree of lateral continuity of talc mineralization.

Although it is obvious that talc would have to be mined much more selectively upon this property than upon other Pfizer properties – indeed, hand-sorting may even be an absolute necessity here – much of the talc on the Smith-Dillon and adjacent properties is pure and of good light color.

Mining rights on this and adjacent properties are owned by the Minerals, Pigments and Metals Division of Pfizer, Inc., which obtained them through their acquisition in 1966 of the assets of Southern California Minerals Company.

SWEETWATER MINE

Numerous workings along the Sweetwater Road about 16 miles southeast of Dillon are collectively known as the Sweetwater Mine (Okuma, 1971). These workings are situated in the E½ sec. 13 and NE¼ sec. 24, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle).

The talc lies completely within a marble unit, which is about 460 feet wide, strikes N. 20° to 30° E. and dips 50° northwest (Okuma 1971). The marble is a relatively thin unit completely isolated within a large mass of Dillon Granite Gneiss, similar to the situation at the American Chemet Mine only a mile or so to the north. Okuma (1971) cited convincing evidence that, in this particular deposit at least, the talc has definitely formed from dolomitic marble and not by the alteration of ultramafic rocks.

TALC PROSPECTS IN THE RUBY RANGE

BENNETT OWEN CLAIM

The Bennett Owen Claim is located near the head of Cottonwood Creek in the NW¼ sec. 12, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle). The strata here strike N. 70° E. and dip 55° north. Talc is shown in place by bulldozer cuts over a strike length of at least 80 feet and a width of at least 20 feet. Although the exposed talc is everywhere dark green, it powders surprisingly to white or near-white colors. Garihan (1973) described this as the largest body of uniformly dark green, low-purity talc known to him in the central part of the Ruby Range. His petrographic work has shown the presence of opaque minerals and minor chlorite in the talc. The footwall rock is dolomitic marble and the hanging-wall rock is either dolomitic marble or reddish Dillon Granite Gneiss, depending upon the location; therefore, the geology is similar to that of the Treasure and Beaverhead Mines a mile or so to the southwest.

CRESCENT PROSPECT

The Crescent Prospect was acquired by Pfizer, Inc., when they obtained the assets of Southern California Minerals Company in 1966. It has not been mined, chiefly because of its graphite content and the presence of dark staining throughout the talc. This deposit is situated in the SW¼ sec. 1, T. 9 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle). The talc occurs within marble layers 10 to 15 feet thick, which have been intruded by pegmatite and granite gneiss bodies. The marble strikes northeasterly, dips northwest at 50° or so, and is locally so decomposed that it is friable. Perry (1948) described talc float as having an extent of 800 to 1,000 feet along strike. A shaft and some small workings have proved the talc to a depth of at least 20 feet.

GEM CLAIM

Two small bulldozer cuts in the SE¼ sec. 34, T. 6 S., R. 6 W., Madison County (Beaverhead Rock SE 7½-minute quadrangle) have exposed small bodies of dark-green talc, which are not of economic interest, as exposed, because of their small size and dark color. These showings are on the Gem Claim, which is owned by Pfizer, Inc.

OWEN-McGOVERN PROSPECT

The Owen-McGovern Prospect is covered by the Badger #1-8 mining claims in the SE¼ sec. 23 and the E½ sec. 26, T. 8 S., R. 7 W., Madison County (Elk Gulch 7½-minute quadrangle). Although the geology of these deposits is not yet satisfactorily understood, it is apparent that they are a continuation of the talc at the Sauerbier Mine, which is to the northeast. Several bodies of dolomitic marble are present upon this property, and all of the known talc occurs within such rock. There is no talc deposit in Montana known to the writer whose geological relationships are so difficult to decipher as this one! The dolomite bodies have been intruded by pegmatite, amphibolite, and diabase dikes. The soil and tree cover are thick and exposures are rare. The regional strike of the strata is N. 20° E. and the dip ranges from 50° to 80° northwest. Okuma (1971) stated that this property has "now been thoroughly investigated", but the writer strongly disagrees. No detailed geological map has ever been made of this complex area, and the relatively minor amount of excavations and drilling cannot rule out the possibility of ore bodies within this large area.

SECTION 11, T. 7 S., R. 6 W.

Bulldozer cuts in the S½ sec. 11, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle) just north of the Left Fork of Stone Creek have exposed several showings of talc. The strata in this area strike roughly east-west and dip 50° to 60° north. These talc bodies, which are developed within dolomitic marble, are as thick as 10 feet and have lengths of as much as 80 feet. Minor amounts of the talc are of the light-colored variety sought for commercial uses, but most of it is somewhat darker; furthermore, the common presence of limonite and graphite renders that talc which is exposed of minimal economic interest.

SECTION 13, T. 7 S., R. 6 W.

Cyprus Industrial Minerals Company has cut a small prospect pit into the same marble unit as that of the Treasure Mines. This pit is located about 4,000 feet southeast of the Treasure Chest Mine and is in the W½ sec. 13, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle). The relationships of the talc bodies are poorly exposed, this being an old pit, but the largest talc body is less than 5 feet wide. The strike is roughly east-west and the dip is 50° to 60° north. Graphite is locally present, and most of the talc is dark green, but minor quantities have the light-green commercial color.

SPRING CREEK PROSPECT

Talc in dolomitic marble is exposed along the north side of Spring Creek in the SE¼ SE¼ sec. 32, T. 6 S., R. 6 W., Madison County (Beaverhead Rock SE 7½-minute quadrangle). This same zone of talc extends (seemingly continuously) southwestward into the NE¼ sec. 5, T. 7 S., R. 6 W. and northeastward into the central part of sec. 33, T. 6 S., R. 6 W., where it seemingly extends underneath the Cambrian strata. This zone, which extends for about 6,000 feet in a northeasterly direction, shows the longest single strike length of talc known to the writer in the Ruby Range or anywhere else in Montana. Talc widths of more than 20 feet and continuous lengths of 100 feet or more are exposed in the old workings along the north side of Spring Creek. The marble unit, which contains all of the known talc showings on this property, strikes N. 50° E., dips 60° to 70° northwest, and has a horizontal width of about 1,500 feet over most of its strike length; Garihan (1973) called this unit the "Regal Marble", the same dolomitic marble unit as that which contains the Regal (Keystone) Mine, and he stated that it may be traced to the south from this prospect for a distance of about 10 miles.

Much of the talc exposed upon the Spring Creek Prospect is darker than that now being used (except for that of the Regal Mine), and this deposit contains more different colors of talc than any known to the writer in Montana; nevertheless, the presence of some suitable-colored talc plus the extremely large size of this prospect make it worthy of a serious exploration effort.

WHITNEY CLAIMS

The Whitney Claims were acquired by Pfizer, Inc., when it obtained the assets of Southern California Minerals Company in 1966. They lie to the north of the Treasure Mines on the steep hillslope north of the Left Fork of Stone Creek in and around the SW¼ sec. 2, T. 7 S. R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle).

As at the nearby Treasure Mines of Pfizer and the Beaverhead Mine of Cyprus, the strike is roughly east-west and the dip is to the north or northwest, in this area about 50° or so. The talc is entirely enclosed within dolomitic marble, and much of it is light green and cryptocrystalline, as are the best commercial talc ores elsewhere in the Ruby Range. Its quality and desirability, however, are downgraded by the presence of pyrite and limonite, by the intense shearing to which it has been subjected, and by the presence of bodies of quartz and dolomite within the talc bodies.

Southwest of the main Whitney Claim, some small cuts in the SE¼ sec. 3, T. 7 S., R. 6 W., Madison County (Mine Gulch 7½-minute quadrangle) have exposed small quantities of green graphitic talc in fractures within dolomitic marble. This talc body is as much as 15 feet thick. Other cuts below the timber line have exposed additional talc occurrences, one of which is more than 20 feet wide. These talc bodies, which are in the westernmost exposure of the marble of the Whitney Claims, are contaminated by the presence of marble "horses" and locally abundant graphite.

MISCELLANEOUS PROSPECTS IN THE CENTRAL RUBY RANGE

Garihan (1973) has noted the occurrence of talc bodies in dolomite in the SW¼ sec. 17, T. 7 S., R. 6 W., and the presence of talc float in the SW¼ sec. 18, T. 7 S., R. 5 W., and in the SW¼ sec. 11, T. 7 S., R. 6 W., all in Madison County and all on the Mine Gulch 7½-minute quadrangle. These do not seem to be of interest in themselves as exposed, but they may well indicate areas worthy of further investigation.

MISCELLANEOUS PROSPECTS IN THE SOUTHWESTERN RUBY RANGE

Talc occurrences are numerous throughout the southwestern part of the Ruby Range, especially upon the Benson Ranch which, to the writer's best knowledge, has never been thoroughly prospected or studied. The writer has never done any field work on the Benson Ranch, but from oral descriptions given by others, it is obvious that it would take some time for any worker to even visit, let alone inspect and study these occurrences. None of the prospects described below are on the Benson Ranch.

Talc in place is exposed fairly continuously for about 1,350 feet of strike length along the crest of the northern wall of Axes Canyon in sec. 19, T. 8 S., R. 7 W., Beaverhead County (Ashbough Canyon and Dillon East 7½-minute quadrangles). The strata here strike N. 55° E. and dip 55° northwest. Most of this talc is in the SW¼ NW¼ sec. 19. This talc, for the most part, is much darker than any currently being mined in Montana, indeed some of it is black – but the large size of this showing would seem to render it worthy of further exploration.

Several talc prospects in the southwestern part of the Ruby Range, discovered and developed by Messrs. Tom McGovern and Bennett Owen of Dillon, Montana, are now under lease to J. M. Huber Corporation of Atlanta, Georgia. The remaining properties discussed in this section all belong to this group.

Talc in place may be traced fairly continuously over a strike length of about 900 feet in the W½ NE¼ sec. 35, T. 8 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle). The strata strike N. 55° E. at this locality and dip 70° north to vertical. At least three clearly separate stratigraphic zones contain talc, and solid widths of at least 10 feet have been locally proved by shallow trenches. The talc is light green and at depth could probably be as good as most of that which is now being mined in Montana, assuming that impurities such as pyrite and graphite were absent.

Bulldozer cuts have exposed talc in place at two localities in the NW¼ NW¼ sec. 36, T. 8 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle). The talc exposed is generally dark green. Mining rights are owned by the State of Montana.

The Valley View Prospect, in the SW¼ sec. 25, T. 8 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle) is, with the exception of the

Regal (Keystone) Mine, the largest body of dark talc known to the writer in the southwestern part of the Ruby Range. Bulldozer excavations have exposed a probable horizontal width of talc of about 90 feet, and the talc may be traced for at least 150 feet along strike. The strata at this locality strike N. 50° E. and dip 55° northwest.

Green talc, somewhat resembling that of the Regal (Keystone) Mine, occurs in place along a ridge crest for several hundred feet and has horizontal widths of 5 to 30 feet in the SE¼ SE¼ NE¼ sec. 26, T. 8 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle). The enclosing dolomite strata are essentially vertical. This showing and other isolated outcrops to the southwest and northeast make up a total strike length of at least 1,200 feet in sec. 26 and adjacent sec. 25. This talc is megascopically very similar to that of the Valley View Prospect.

In sec. 1 and 2, T. 9 S., R. 8 W., Beaverhead County (Ashbough Canyon 7½-minute quadrangle) a well-developed zone of talcose rocks may be traced for 5,000 feet along strike (east northeast) from the Brown Ranch Road along the base of the range in the SE¼ SW¼ sec. 2 on into the SE¼ NW¼ sec. 1. Talc ore, per se, has never been observed upon the surface by the writer, but the extent of the talcose development in rocks in place certainly warrants further exploration of this large and long zone.

Talc float of high purity and light-green color has been traced continuously along relatively horizontal land over more than 600 feet of strike length to the southwest of Hanson Spring in the SW¼ SW¼ sec. 3, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle). The horizontal width of the talc zone perpendicular to the strike is locally as much as 325 feet. The strata here strike N. 30° E. and dip 70° to 75° northwest. Outcrops are rare, but the host rock can clearly be observed to be dolomitic marble. Darker talc crops out in higher stratigraphic positions to the northwest over a stratigraphic thickness of about 200 feet and along strike lengths of at least 300 feet.

In the writer's opinion, one of the most attractive talc exploration targets in Montana occupies an estimated 480 acres in sec. 10 and an estimated 220 acres in sec. 11, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle). Along the northern boundary of this area, talc is exposed both in place and as abundant float in several separate stratigraphic zones over about 7,000 feet of strike length before being truncated on the eastern end by the Carter Creek Fault. In the SW¼ NE¼ sec. 10, abundant talc float has been traced along a 650-foot strike length and over at least 170 feet of horizontal width in an area where the enclosing dolomite strata strike N. 50° E. and dip 80° northwest.

High-purity talc lying in a gentle swale on the Gopher #1-3 mining claims in the SW¼ NW¼ sec. 2, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle) probably represents a southwestward extension of the talc of the Regal Mine, owned by Pfizer, Inc. The light-colored talc float, which may be traced over about 200 feet of strike length and a horizontal width of 100 feet, is probably the equal in quality of any talc being mined in the Ruby Range.

Talc float is abundant along both sides of a ridge of dolomitic marble that extends from the NE¼ sec. 15 on into the SW¼ sec. 11, T. 8 S., R. 7 W., Madison County (Christensen Ranch 7½-minute quadrangle). Sporadic talc float has been detected by brief reconnaissance studies over a strike length of 4,000 feet or so; but a puzzling riddle lies in the fact that there are so few outcrops of talc compared to the large abundance of float. Most of the talc observed is green, somewhat darker than the grades that are being mined in Montana. This long ridge of dolomitic marble has the structure of a synform, its axis striking N. 30° E. and dips averaging 50° or so on both the northwest and southeast limbs. The dolomite strata seemingly wrap around the southwestern nose of the ridge, giving structural closure there, but on the northeastern end the dolomite is truncated by the Carter Creek Fault.

A large thick band of dolomitic marble north of Gordon Peak in sec. 21 and 22, T. 8 S., R. 7 W., Beaverhead and Madison Counties (Christensen Ranch 7½-minute quadrangle) contains several talc prospects in dolomite strata, which strike east-west and dip 40° to 65° north. This large belt of predominantly dolomitic rock averages about 2,500 feet in width over almost 3 miles of strike length. One talc zone in the NE¼ NE¼ NE¼ sec. 21 extends for about 500 feet along strike.

GENERAL GEOLOGY OF THE GRAVELLY RANGE

The name "Cherry Creek" was first used by Peale (1896) for rocks in an area 15 to 20 miles south of Ennis, Montana, along the base of the eastern flank of the Gravelly Range. He stated that "The Cherry Creek beds consist of a series of marbles, or crystalline limestones, and interlaminated mica-schists, quartzites, and gneisses" and that "They are all highly inclined and are perfectly conformable to one another occupying an area of 30 to 40 square miles." Their total thickness, according to Peale, "is certainly not less than several thousand feet" and in his columnar section he showed a thickness of 7,000 feet or more for the "Cherry Creek" portion of the Precambrian section.

The most detailed study of the type area of the Cherry Creek Group has been made by Heinrich and Rabbitt (1960). In general the grade of the metamorphism increases slightly as one goes northward, but it is puzzling how rocks of different metamorphic grades can exist together in the same area, e.g., phyllite, mica schist, and kyanite schist along the Cherry Creek drainage. Heinrich and Rabbitt (1960) recognized the following major classes of rocks in the type area of the Cherry Creek Group:

1. Marble, calc-schist, and lime-silicate gneiss
2. Quartzite and quartz schist
3. Phyllite
4. Mica schist
5. Kyanite schist and kyanite-staurolite schist
6. Sillimanite schist and gneiss
7. Magnetite schist and related rocks ("iron formation")
8. Amphibole gneiss, schist, and amphibolite
9. Quartz-feldspar gneiss, granitic gneiss, biotite, and injection gneiss

The marble layers are the thickest and the most laterally persistent of these rock types. Heinrich and Rabbitt reported one dolomitic marble as nearly 6,000 feet thick, but later workers and the writer believe that much of this thickness is likely due to structural flowage during folding and to repetitions caused by tight folding. Heinrich and Rabbitt also noted the relatively rare presence of tremolitic marble in the area, but the ores produced thus far from the Johnny Gulch area have characteristically contained no detectable tremolite. It may be readily seen from a comparison with the rock types mapped as "Cherry Creek-type rocks" in the Ruby Range by Okuma (1971) and Garihan (1973) that the sequences there and in the Gravelly Range are very much alike. One of the most striking differences involves the amphibolite rocks, for Heinrich and Rabbitt (1960) stated that "dark-colored amphibole gneisses are much less common in the Cherry Creek area than some other pre-Beltian areas, as for example, in the Ruby Mountains." They estimated the total minimum thickness of the Cherry Creek Group in its type area as about 30,000 feet.

Hadley (1969a, 1969b) has mapped the geology of two key 15-minute quadrangles in the area of the producing talc mines of the Gravelly Range and has shown in detail, within that restricted area, the distribution of the dolomitic marble of the type Cherry Creek Group.

Mann (1954, 1960) has described the general geology of that part of the Gravelly Range that is of interest for its talc potential. Most of his attention was devoted to the Paleozoic and Mesozoic Systems; rock types within the Cherry Creek Group were not differentiated.

GEOLOGY OF TALC IN THE GRAVELLY RANGE

There are three known areas of significant talc mineralization in the Gravelly Range: the Yellowstone Mine in sec. 4, T. 9 S., R. 1 W., the Johnny Gulch Prospect in sec. 34, T. 8 S., R. 1 W., and sec. 3, T. 9 S., R. 1 W., and the Tri-State Prospect in sec. 5, T. 8 S., R. 1 W., all in Madison County. Several other occurrences of talc are known in the Gravelly Range, but only these three will be discussed at length here.

Hogberg (1963) generalized that in the Gravelly Range the lens-shaped talc bodies "may be as much as 100 feet wide, 1,000 feet long, 150 feet deep, and are generally concordant with the regional structure". All of the talc that is known in the Gravelly Range occurs within dolomitic marble units and is generally concordant with the metamorphic foliation.

The largest single mass of marble in the Gravelly Range is that one situated between Johnny Gulch and Cherry Creek, which forms an area about 5 miles long and 1½ miles wide, roughly parallels the strike of the strata, and contains all of the currently known commercial talc deposits in the area.

The nature of the formation of talc in the Gravelly Range is similar to that in the Ruby Range, as are the mineralogy and the chemistry of the ores. In addition, the general geology of the two areas is very similar, the starting materials for the talc are everywhere the same, and the structural evolution of the two areas is also similar. For reasons unknown, however, the relationships of the talc ore bodies to their enclosing rocks is markedly different in the two ranges. In the Ruby

Range, for instance, it is not uncommon for an entire wide zone of dolomite between other, non carbonate rock types to have been converted almost completely into talc containing few or no "horses" of foreign rock. Even where the entire "talc-zone" has not been converted to talc, it is common in the Ruby Range to have large thick tabular masses of talc "interbedded" with other rock types within the "talc-zone". This relationship has been nowhere observed in the Gravelly Range, where there is invariably an intimate and small-scale intercalation of talc with dolomite and where there are few bodies of pure talc more than 5 feet thick containing no foreign rock types. The behaviour of the talc in the Gravelly Range is markedly digitate on a small scale; the behaviour of the talc in the Ruby Range is generally tabular and in much larger bodies. Even where the behaviour of talc in the Ruby Range could be described as digitate, it would be more subtly so and on a much larger scale than in the Gravelly Range.

Throughout this area the removal of the talc by either powered shovel or front-end loader is made easier by the profusion of post-talc fracturing and shearing, which is strongly developed and closely spaced as shown in all of the existing workings.

Therefore, if past history is to be a reliable guide, we can generalize that although ore bodies can be mined in the Ruby Range with large mining machinery but without hand sorting, the ore bodies in the Gravelly Range will continue to be mined with similar equipment but the resulting mill feed will necessarily continue to be subjected to hand sorting.

Current investigations by graduate students of the University of Indiana will shed new light upon the intricate problems of the type Cherry Creek sequence, especially with regard to metamorphic events. The major difference between the Cherry Creek sequences of the Ruby Range and those of the Gravelly Range lies in the maximum degree of metamorphism undergone in Precambrian time – upper amphibolite grades having been reached in the areas of talc mineralization in the Ruby Range, whereas in some areas of talc mineralization in the Gravelly Range it may be that only greenschist grades were attained. In the Ruby Range a widespread regional metamorphic event of greenschist grade was experienced after the higher-grade events; therefore, it is possible that the talc in both ranges formed during periods of similar intensity of Precambrian metamorphism (i.e., greenschist grade), whether or not contemporaneously.

TALC MINES AND DEPOSITS IN THE GRAVELLY RANGE

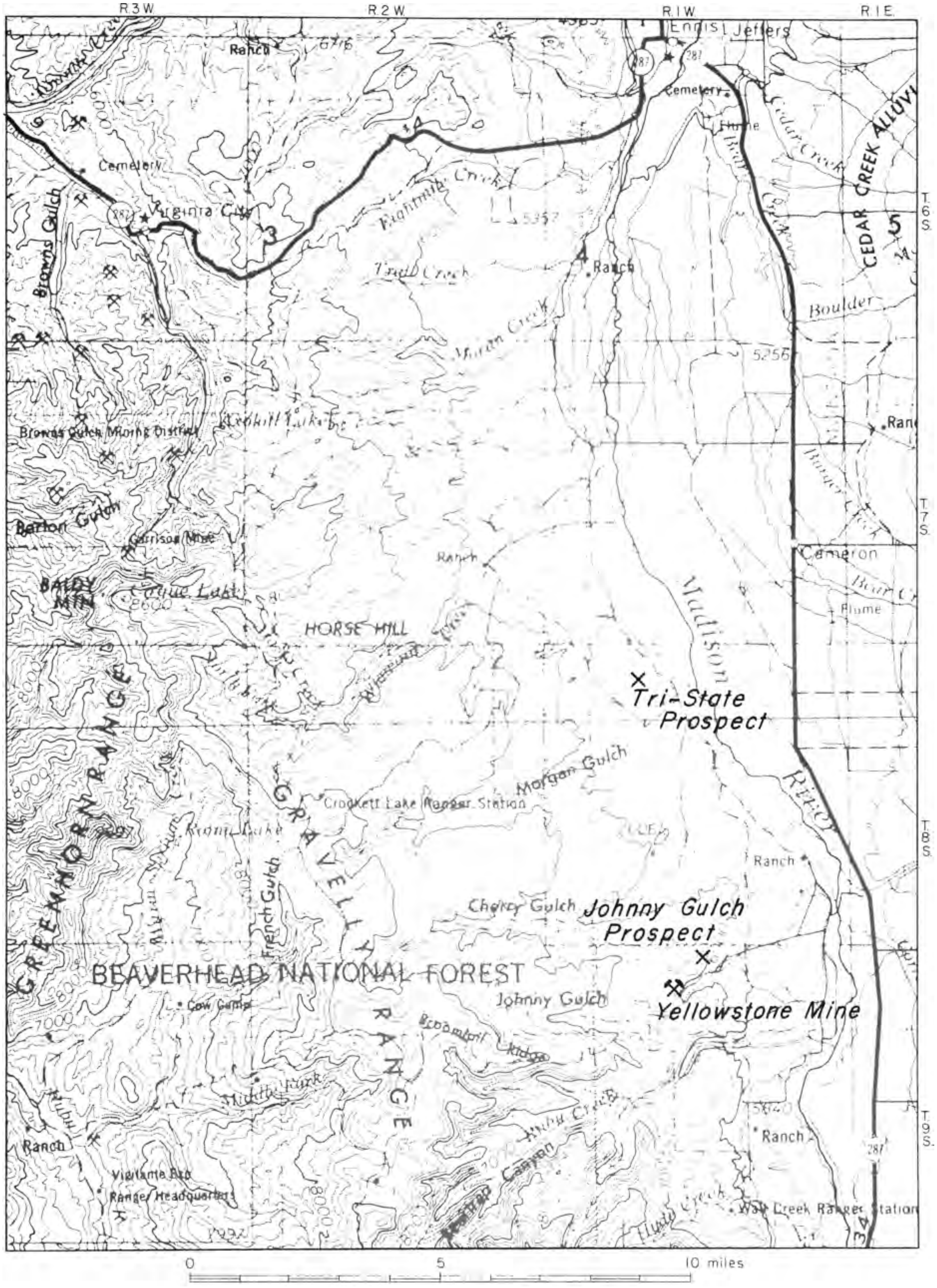
YELLOWSTONE MINE

The Yellowstone Mine, in the S½ sec. 4, T. 9 S., R. 1 W., Madison County (Cameron 15-minute quadrangle) is the primary Montana source of talc ore for Cyprus Industrial Minerals Company and has been so for more than twenty years (Fig. 10-5).

The mineralized area, according to Perry (1948), is at least 2,000 feet long in a northeast direction and about 800 feet wide. Within this area there are several large bodies of talc within the main dolomite mass, but these large talc-bearing bodies enclose abundant dolomite "horses".

The writer was allowed to study the geology of the Yellowstone Mine in the summer of 1974. There are several workings, both underground and open pit, within this large mineralized area. Many of these workings, including all of the underground ones, have been inactive for many years. The main pit, which is also the deepest one, has been developed along an azimuth of N. 20° W. for the most part – a direction that is not exactly parallel to the foliation of the strata but is fairly close to being so. Such a relationship is common throughout the mine area, i.e., a slight directional variance is common between the strike of the dolomite foliation and the longest dimension of the talc ore bodies. The strike of the strata within the main mine area ranges from north to N. 20° E. and dips range from vertical to 50° east. The main pit is now about 2,500 feet long, averages about 200 feet wide, and has been mined to down-dip depths of 150 to 200 feet.

Unlike the producing talc ore bodies of the Ruby Range, talc at the Yellowstone Mine does not form large enough individual bodies to permit the mining of high-purity talc ore by the use of machinery alone; all of the ore now exposed within the area of the Yellowstone Mine must be hand sorted in order to derive suitable mill-feed material. In one area of the Treasure Chest Mine (Ruby Range), the entire dolomite unit ("talc-zone"), about 120 feet wide horizontally, had been converted into commercial talc of the highest grades. In the Yellowstone Mine, thicknesses of more than 5 feet of high-purity talc without included dolomite are uncommon. Talc was noted to be abundant in one local area of the main pit of the Yellowstone Mine, but not a single thickness of more than 1 foot of pure



10-5. –Talc mines and prospects, Gravelly Range, Madison County.

talc was observed. The talc is commonly seen to "make" in a gray fine- to medium-crystalline dolomite, which is generally thin bedded (laminae or foliae commonly less than 6 inches thick). Although most of the talc-dolomite contacts seem to follow primary features, there are indications that many of them may represent fractures or faults of extremely small displacement. It is more common for the contacts of the small bodies of high-purity talc to cross-cut the dolomite foliation at low angles than for them to be concordant, although in the lowermost levels of the main pit such cross-cutting relationships were observed to form at angles of 30° or more. Shear surfaces developed at such angles to the foliation may have locally exerted a control upon the attitude and shape of individual talc bodies. Most of the talc at the Yellowstone Mine is green or light gray (almost the color of the enclosing dolomite), not pale green to white, as is much of the talc in the Ruby Range.

All of the ore at the Yellowstone Mine is taken to sorting facilities where workers remove either the waste from the ore or the ore from the waste, depending upon grade. The high-grade ore is taken to an old enclosed and permanent hand-sorting facility along the north hillslope of Johnny Gulch, where the waste is picked out and the talc is discharged from the end of the conveyor belts into holding bins. The lower-grade ore is taken to a portable hand-sorting facility in one of the upper pits, where the talc is picked out and the waste is discharged off the end of the conveyor belt. This portable facility was placed in operation in 1972 and will result in a much longer life for this mine. The lowest-grade material, not regarded as waste, is taken to large stockpiles north of the mining area. These stockpiles, called "bone piles" by the miners, consist of material that is too low in grade to justify hand sorting at present but which may prove to be susceptible to flotation-beneficiation processes in the future. If such methods of beneficiation ever prove feasible, these "bone piles" would constitute an immense supply of high-purity Montana talc ore. All of the hand sorting or "picking" at the Yellowstone Mine is done upon dry rock, unlike the Pfizer operations, where hand sorting at their Barratts mill is performed upon wet rock.

The hand-sorted ore from the Yellowstone Mine is trucked either to Alder, Montana, for shipment to Cyprus' processing facilities in Belgium or Grand Island, Nebraska, or to their mill at Three Forks, Montana.

During World War II, the Yellowstone Mine area became extremely important because the U.S. was shut off from foreign sources of "block talc" or "lava talc". Underground exploratory work was performed during that war with governmental support (U.S. Bureau of Mines) in an effort to locate a replacement source for such denied material, which had formerly been readily obtainable from Italy. These underground workings proved one talc lens to extend to a depth of about 80 feet and another talc outcrop was traced at that time through a vertical distance of 150 feet. Seemingly the "block talc" (also known as "lava talc" or "carving talc") occurred only in the deeply weathered siderite zone, from the surface down to a depth of no more than 45 feet or so. Ankerite and black manganese dioxide were also abundant within this intensely weathered zone. The "block talc" graded downward into ceramic grades of talc, which in turn were underlain by hard unaltered dolomite.

Hogberg (1963) has described the history of the exploration and development of the Yellowstone Mine. Tri-State Minerals Company leased the property in 1942 and began exploratory work under the direction of Mr. L. F. Teutsch. The Sierra Talc Company of South Pasadena, California, purchased the land from Mr. Lewis Clark, the original discoverer, in January 1949 and then went from underground prospecting to open-pit mining. Hogberg (1963) gave the Yellowstone Mine "approximately 75 years of reserves based upon an annual production rate of about 20,000 tons of cleaned talc". Initial construction on the Three Forks, Montana, mill was completed in 1961 at a cost of about $400,000; the expansion, which was completed in 1974, is reported to have cost about $2,500,000.

JOHNNY GULCH PROSPECT

Those talc occurrences in sec. 34, T. 8 S., R. 1 W., and sec. 3, T. 9 S., R. 1 W., Madison County (Cameron 15-minute quadrangle), which have been intermittently prospected over the years, are here referred to as the Johnny Gulch Prospect. These occurrences lie within the same thick dolomite unit as do those of the Yellowstone Mine less than a mile to the southwest, but unless isoclinal folding has afforded an incredible coincidence they are not in equivalent strata.

Talc has been mined from deep strike trenches and is exposed in shallow bulldozer scrapings over a strike length of about 1,500 feet. The foliation of the dolomite strikes on the average N. 25° E. and dips 75° to 80° northwest. In the area of the main pit in sec. 3, where talc was mined to depths estimated at 30 to 40 feet over a total strike length of 425 feet, talc in place is sporadic over a horizontal width of as much as 275 feet.

The talc forms more or less concordant lenses with digitate outlines and most are less than 6 inches thick. The talc is generally darker than that in the Yellowstone Mine.

In the 1960's the American Chemet Corporation of Chicago, Illinois, mined talc on this property in the SW¼ NW¼ sec. 3.

TRI-STATE PROSPECT

During World War II, the Tri-State Minerals Company prospected by pits and a 25-foot shaft a talc lens 5 feet thick and several tens of feet long in the NE¼ SE¼ sec. 5, T. 8 S., R. 1 W., Madison County (Cameron 15-minute quadrangle). This property "was abandoned because of low grade and lack of quantity" (Perry, 1948).

MINOR OCCURRENCES SOUTH OF YELLOWSTONE MINE

A small talc prospect has been opened in the SE¼ NE¼ sec. 8, T. 9 S., R. 1 W., Madison County (Cameron 15-minute quadrangle) about 1 mile southwest of the Yellowstone Mine. Dark talc is here associated with weathered and altered marble.

Several small nearly vertical talc bodies are known in the NW¼ NW¼ sec. 9, T. 9 S., R. 1 W., Madison County (Cameron 15-minute quadrangle), and the pattern of the dispersion of the talc float indicated to Hogberg (1963) that the aggregate thickness may be 100 feet. This area, unlike the others described in the Gravelly Range, is complicated by a local cover of Tertiary volcanic rocks.

GEOLOGY AND TALC DEPOSITS OF THE GREENHORN RANGE

The Greenhorn Range lies between the Ruby Range on the west and the Gravelly Range on the east. A belt of "Cherry Creek-type rocks" extends from the east-central part of the Ruby Range eastward into the Greenhorn Range in the vicinity of Ruby Dam. Little is known of the overall geology of this range, but several talc occurrences are known within it.

TALC RIDGE MINE

The most notable talc deposit in the Greenhorn Range is the Talc Ridge Mine, along Little Willow Creek on the western flank of the range in the SW¼ NE¼ sec. 30, T. 8 S., R. 3 W., Madison County (Home Park Ranch 7½-minute quadrangle). This deposit was recently leased by American Talc Company of Summit, New Jersey, and has been mined by them during the period 1973-75. The ore is trucked to Alder, Montana, where it is stockpiled on concrete pads for shipment by rail to processing facilities in South Plainfield, New Jersey, and Alpine, Alabama. The writer has not seen this deposit since American Talc Company began recent mining operations; the following description is based upon a brief visit to the property in 1969.

All of the observed talc is contained within dolomitic marble units. The "talc-zone" is not completely converted to talc but contains abundant intercalated carbonate rock. The strata strike N. 45° E. and dip 25° to 40° northwest. Small pits on the property suggest that small-scale high-angle to vertical faulting is widespread and well developed and would severely complicate the conduct of large-scale open-pit mining operations. Left-lateral fault displacements were noted, but their magnitudes could not be determined. Individual veins of high-purity white talc are as much as 20 feet wide. Footwall and hanging-wall rocks are either dolomite, granite gneiss, or mica schist; locally the rock type of the footwall of one talc vein will be similar to that of the hanging wall of an adjacent talc vein and vice versa, suggesting that some of the talc veins may be repeated by isoclinal folding. Although on a large scale the talc is generally concordant with the foliation of the dolomitic marble, the contacts of the talc bodies are locally strongly discordant over relatively small distances.

The American Chemet Corporation of Chicago, Illinois, once held a lease upon this property, at which time the existence of the uppermost talc vein was seemingly unknown.

WILLOW CREEK PROSPECT

The Willow Creek Prospect, in the NW¼ NE¼ sec. 31, T. 8 S., R. 3 W., Madison County (Home Park Ranch 7½-minute quadrangle) is covered by the Willow Creek #1 and #2 mining claims. Exposures in a small trench on this property indicate that the strata strike N. 40° E. and dip about 30° northwest. No talc thicknesses in excess of 10 feet were observed, and despite the presence on the property of a small stockpile of talc in 1969, no appreciable lateral extension of the talc had then been proved. The geology is extremely similar to that of the nearby Talc Ridge Mine, which lies less than 1 mile north of this prospect. It is extremely unlikely that this deposit could be an extension of the one at the Talc Ridge Mine, but it may represent a structural repetition of the same strata by isoclinal folding.

OTHER DEPOSITS

Perry (1948) reported the presence of a talc deposit "southwest of Virginia City on Idaho Creek" along the western flank of the Greenhorn Range. No locality information is given, and the writer has not visited this reported occurrence. Although Perry described the talc as "good" in hand specimens, he further stated that "as a whole the deposit is said to be small and the average material impure".

Many questions concerning the geology of the Precambrian strata in the Greenhorn Range, particularly the relationships of its "Cherry Creek-type rocks" and its bearing on the origin of talc in Montana, may be answered by the ongoing investigations of Dr. Richard B. Berg of the Montana Bureau of Mines and Geology, who is currently mapping and studying the relationships of the dolomitic marble and associated pre-Beltian rocks within the Ruby Dam and adjacent 7½-minute quadrangles.

GEOLOGY AND TALC DEPOSITS OF THE TOBACCO ROOT MOUNTAINS

The Tobacco Root Mountains lie north of the Ruby, Greenhorn, and Gravelly Ranges and contain the northernmost significant exposures of pre-Beltian rocks in this area of southwestern Montana.

Tansley, Schafer, and Hart (1933) have described a sequence of metasedimentary rocks in the southern and southwestern parts of the Tobacco Root Mountains, which they refer to as the "Cherry Creek Series". The lithologic types that they recognized in this series are quartzite, limestone, schist, and gneiss, whose sedimentary origin is unquestionable, and they noted the high garnet content in many of its members. The major difference that they brought out in comparing the Tobacco Root sequence to that of the type section at Cherry Creek along the eastern flank of the Gravelly Range is the great abundance of garnet rock in the Tobacco Root region, a rock that is rare near Cherry Creek. They divided the "Cherry Creek Series" into three divisions, of which the limestone occurs in the medial division. The thicknesses of the limestone units range from 1,500 feet, where they have been thickened by intense folding, to complete "pinch-outs" where stretched out on the limbs of folds. In certain areas, units that were once calcareous have been replaced by abundant garnet and hornblende and lesser amounts of tremolite, actinolite, epidote, and quartz, suggesting widespread contact metamorphism. This relationship is further complicated by the local development of a more intense metamorphism imposed upon these rocks in proximity to the Tobacco Root Batholith, of Laramide age. There is the strong possibility that limestone members have been repeated in overturned tight isoclinal folds of the type that is well known in the Ruby Range to the south.

Reid (1957, 1959, 1963) has studied and mapped large exposures of the "Pony" and "Cherry Creek" metamorphic rocks over large areas in the northern Tobacco Root Mountains. Despite the detailed lithologic descriptions in these texts, no differentiation of individual lithologic types within these two major metamorphic rock groups was made in his mapping. Within his map area in the north end of the Tobacco Root Mountains (Reid, 1957), the only marble found is calcitic rather than dolomitic.

Gillmeister (1971) described a coarse, dominantly calcitic marble, which has restricted occurrence along the southwestern part of the Tobacco Root Mountains. The thickness of this marble unit ranges from 0 to 1,000 feet. He has named this unit the "Occidental Marble" after the Occidental Mine on the ridge between the North and South Forks of Indian Creek.

Burger (1967) has described the bedrock geology of the Sheridan District along the western flank of the Tobacco Root Mountains. He described both marble and calc-silicate rocks, the latter being relatively uncommon. Thicknesses of marble units range from 100 to 800 feet and average 300 feet.

Hess (1967) noted the presence of both calcitic and dolomitic marble in the central and southern Tobacco Root Mountains and further contributed toward an eventually better understanding of local Precambrian geology by pleading against the dogmatic usage of such stratigraphic terms as "Cherry Creek" and "Pony" when one is unable to prove stratigraphic equivalence from place to place. He suggested that a "single, long-lasting metamorphism took place in the Tobacco Root Mountains between 1550 and 1700 million years ago", accompanied by the development of isoclinal folding along northeast-trending axes and the intrusion of ultramafic and mafic rocks. This is a similar history to that described in the central and southern parts of the Ruby Range by Garihan (1973) and Okuma (1971), respectively.

Cordua (1973) cited evidence which suggests that the marble in the southern part of the Tobacco Root Mountains was impure siliceous dolomite prior to metamorphism. He further described the continuity of at least one of the marble layers for more than 30 miles along strike and described it as uniformly dolomitic.

Perry (1948) described a small talc occurrence in marble of "Cherry Creek-type rocks" along Granite Creek about 2 miles north of Virginia City, Montana. Small stringers of high-grade talc are present within a marble unit 65 feet thick, but commercial talc cannot be extracted from this deposit under current conditions.

Levandowski (1956) described thicknesses of marble units in the Sheridan-Alder area along the southwestern flank of the Tobacco Root Mountains as ranging from only a few feet to as much as 1,700 feet. He described two talc deposits as having maximum known widths of 25 feet and lengths of 55 feet. Both of these talc bodies have been developed within marble and are spatially associated with garnet schist and granite gneiss.

Although the Tobacco Root Mountains have dolomitic marble similar to that found in the Ruby Range to the south, and the conditions of regional metamorphism and granitic intrusive activity are similar in both areas, relatively few talc occurrences are known in the Tobacco Root Mountains. It is not yet clear whether this discrepancy might be due to lack of attention and prospecting or to actual paucity of talc there. The range has been studied for several decades by graduate students of the University of Indiana, which maintains a summer field camp near Whitehall, at the northeastern corner of the range. These investigations, both past and ongoing, will contribute to a better understanding of the detailed geology of the Tobacco Root Mountains and may well help to result in the discovery of new talc deposits – but only time will tell.

OTHER ASSOCIATED MINERAL DEPOSITS

Several other mineral commodities are closely associated spatially or stratigraphically with Montana talc deposits, the most important being graphite, sillimanite, iron formation, kyanite, and manganese.

GRAPHITE

High-grade crystalline graphite has been mined from deposits in the Axes Canyon area of the Ruby Range southeast of Dillon (Perry, 1948; Ford, 1954). The graphite occurs in veins and veinlets in gneiss and pegmatite as well as being disseminated in smaller masses and flakes in those same host rocks. Ford (1954) suggested that the deposition of graphite occurred after the emplacement of the pegmatite and after the period of regional metamorphism. Despite their close spatial association, the graphite was obviously deposited long after the dolomitic marble in the "Cherry Creek-type rocks" was recrystallized.

SILLIMANITE

Sillimanite deposits in the central and southern parts of the Ruby Range have been described by Heinrich (1950). The most common types of occurrence and the ones having the greatest economic potential are biotite-sillimanite schist and biotite-garnet-sillimanite gneiss. The sillimanite also occurs in pegmatite and locally as a massive rock, the latter type commonly being found as residual cobbles and boulders. There seems to be some relationship between the abundance of pegmatite and the abundance of the sillimanite; furthermore, sillimanite "pods" are commonly developed along pegmatite contacts. The most promising deposit, situated on the Art Christensen Ranch near the Sweetwater Road east of Dillon, is a silvery biotite-muscovite schist, which contains differing amounts of sillimanite. Locally, there is also the possibility of placer sillimanite deposits. All of the sillimanite occurrences are in rocks that are closely associated, both spatially and stratigraphically, with the dolomitic marble that contains all of the known commercial talc deposits.

IRON FORMATION

A unit of banded "iron formation" (magnetite schist) as much as 1,000 feet wide and 2 miles long is present to the west of and across the Carter Creek Fault from the Regal (Keystone) talc mine in the southwestern part of the Ruby Range. Mapping by James and Wier (1972) shows the complexity of this small local area. Similar bands of "iron-formation" are present in the type area of the Cherry Creek Group along the base of the eastern flank of the Gravelly Range south of Ennis. In both of these mountain ranges, the iron is closely associated both spatially and stratigraphically with the dolomitic marble that contains all of the known commercial talc bodies.

KYANITE

Kyanite gneiss and schist and kyanite pegmatite and veins have been described by Heinrich and Rabbitt (1960) in the type area of the Cherry Creek Group along the base of the eastern flank of the Gravelly Range south of Ennis, but only the layers of kyanite gneiss and schist seem to have any potential economic significance. Although these kyanite occurrences are not far from the talc deposits to the south in Johnny Gulch, it must be noted that their metamorphic grade is considerably higher than that of the Johnny Gulch area, and it is possible that structural events have placed these two areas in much closer juxtaposition than they were originally.

MANGANESE

Manganese oxide minerals have been widely developed in the pre-Beltian marble of the Ruby Range and the Gravelly Range. Such mineralization, as described by Heinrich (1960) in the southwesternmost part of the Ruby Range, "is generally low-grade but highly variable". This impregnation and subsequent alteration has been locally so intense that the marble may be converted to a crumbly, porous, and commonly incoherent rock. The manganese minerals have formed in the same marble that contains all of the known commercial talc bodies, but even though both the manganese and the talc must have formed in Precambrian time, the possibility of any genetic relationship is unknown.

PROSPECTING HINTS

In most mining districts, whether they produce metals or industrial minerals, the original discoveries are made by prospectors and miners; geologists come along later and refine the details. This is certainly true of the Montana talc-mining district, for the writer is aware of only a single talc occurrence that has been discovered by a geologist. This situation will obviously change in time to come as future talc deposits are sought on the fringes of the now-known "elephant country" and as more sophisticated techniques are developed to find buried deposits, but for the time being, the Montana talc prospector must be given full and well-deserved credit for his most significant contributions to the development of the Montana talc industry.

Guidelines for talc prospecting may be presented here based on present knowledge, but the main problem with applying them dogmatically is that it is still not certain whether they are truly diagnostic for areas of talc mineralization *only*, or whether they might include features that could be present or even abundant in barren areas as well. Their diagnostic reliability, by and large, must await more thorough geological studies in larger areas away from known areas of mineralization.

The only certain criterion known at this time is that *all* of Montana's known commercial talc ore bodies occur within dolomitic marble of the pre-Beltian sequence of "Cherry Creek-type rocks". Therefore, there seems little to be gained by searching for talc in other lithologic units or formations.

From his work in the southern part of the Ruby Range, Okuma (1971) has formulated guidelines for prospecting for talc, and these are quoted verbatim:

"a) All the commercial talc deposits are intimately associated with the marble units. Dolomitic marbles seem to be a prerequisite for the formation of high quality talc in the Ruby Range.

b) The talc generally occurs in areas of structural weakness, such areas being marked by faulting, brecciation, silicification and, in many cases, recrystallization.

c) The talc deposits are related to the presence of intrusive rocks, probably of granitic or other composition, from which they obtained their supply of hydrothermal solutions. To some degree the nearness to Dillon Granite Gneiss especially of the olive-gray variety may be a useful guideline for prospecting.

d) Areas of retrograde metamorphism may be of special significance in talc prospecting."

Garihan (1973) has likewise developed similar guidelines, derived from his work in the central part of the Ruby Range, and these are also quoted verbatim:

"1) Look in areas of structural complexity in the vicinity of known mines, both along the trend of the marble host and in adjacent coarse dolomites; the deposits tend to occur in groups spatially. Isolated occurrences are unusual. All the marbles should be walked out, with an eye out for float chips on the ground or stringers of talc in outcrop. This is considerably easier than mapping all lithologies.

2) Look in areas where non-carbonate rocks have been chloritized and talcified. This is certainly the case in the vicinity of the Treasure mines, where the Dillon Gneiss has been chloritized extensively. Elsewhere, however, rocks such as the Dillon Gneiss are not altered near known talc deposits, so that this is at best a secondary criterion.

3) Bulldoze and drill prospects to evaluate the talc body in the third dimension.

4) Rely on prospector's scratchings; they usually mean something!"

To these valuable guidelines the writer will add here some from his own experience. Occurrences of bedrock talc should not be ignored simply because they are relatively thin. In the first place, one might be looking at the edge or the top of what might continue downward or laterally into a much larger body. In the second place, it must be remembered that the form or shape of Montana talc bodies may be markedly digitate and that only an extremely thin apophysis of a large ore body may have been exposed by erosion at the time one comes across it. Talc ore bodies characteristically swell and pinch, thinning on the limbs of folds and thickening on the crests and in the troughs of folds. This plasticity, plus the natural lenticular habit, renders this caution against cavalier treatment of such occurrences advisable here.

The time-honored technique of tracing float chips of talc uphill to their source will continue to be useful, but this method of course can aid in locating only those talc bodies that have already been breached by erosion. With practice one may develop the ability to discern the presence of talc float chips as small as ¼" or so from the standing position; when one has thus determined that talc is indeed present and then gets down on hands and knees, the distribution of float chips smaller than a matchhead may be readily traced.

The aid of digging and burrowing animals, evidence free for the taking, should be utilized wherever possible. Badgers digging their burrows commonly throw out talc fragments in areas where such would not otherwise be exposed on the surface, so never pass by a badger hole in pre-Beltian dolomite country without inspecting its spoils pile! Ants will commonly build their abodes of the coarsest rock chips available, and the writer has seen many such anthills composed of an abnormally high percentage of talc chips; therefore, anthills in pre-Beltian dolomite country should also be inspected, even though (unlike badger and gopher holes) such debris would represent only surficial material.

In areas of talc mineralization still undisturbed by mining, the writer has observed that one of more of the following associated features will be present:

a) Dolomitic marble is exceptionally coarse grained.

b) Dolomitic marble is exceptionally closely foliated, individual foliae being commonly 1 inch thick or less.

c) Silicification is common, not as veins but as irregular masses, adjacent to and near the talc.

d) Large calcite rhombs, 1 inch or more on a side, are locally developed.

e) Pervasive "soaking" of dolomitic marble by iron oxides or manganese oxides.

POSSIBLE FUTURE TRENDS IN THE MONTANA TALC INDUSTRY

It is likely, in the writer's opinion, that solid, thick, homogeneous talc ore bodies without included waste rock (e.g., Treasure Chest Mine) will not continue to be the source of such ores in Montana for a much longer period of time. More and more, I think that talc ores will be procured from deposits such as the Yellowstone Mine, which are characterized by the digitate interfingering of talc with included waste rock on a relatively small scale. This will require sorting, of course, either by manual labor or possibly by some mechanical or photoelectrical means yet to be perfected, but the grade of talc fed into the mill in the future should not suffer as compared with today's mill feed.

This will be most advantageous from a conservation standpoint, for it is an unfortunate but nevertheless true fact that many thousand tons of high-grade talc ore has been thrown onto the dumps of Montana talc mines because operators did not want to bear the expense of setting up sorting methods. This reluctance to establish such installations may have been due to budgetary reasons or to competition for investment dollars with other divisions within large companies – whatever the reason, it has been and still is a dolefully wasteful procedure and should be stopped! Whether or not a sorting method can be installed at any given time is not as important as the fact that many operators have been reluctant to even go to the added expense of separately stockpiling such "middling" fractions for later sorting or other up-grading processes. A case in point may be found in Stone Creek in the Ruby Range, where many thousand tons of high-grade talc lie irretrievably lost because they are now hopelessly mixed with abundant waste rock in those large dumps. It becomes increasingly more difficult to locate new sources of Montana talc ore; such waste should not be allowed to continue!

Of the two talc-grinding mills in Montana at the present time, one is served by only two mines and the other obtains virtually all of its feed from only one mine. Future milling operations in the Montana talc industry may not be so fortunate; it seems likely to the writer that such operations will instead be served by numerous mines. This may not only become necessary, but it may also become desirable if it affords the opportunity for carefully performed and intelligently directed blending of ores from numerous sources.

Underground operations have been pursued at the Yellowstone Mine in the Gravelly Range and at the Smith-Dillon Mine in the Ruby Range, but all present operations are open pit. The reluctance of present operators to adopt underground mining methods in the face of open-pit competition is fully understandable, but it should be understood by them and by others contemplating new entries into the Montana talc industry that the profit margin in such operations can probably withstand the increased costs of underground mining, particularly when such advantages as year-round operation, increased selectivity in extraction, and other factors inherent in underground mining are considered. Therefore, it may well be that future exploration for Montana talc deposits will not be confined to areas where only open pitting is feasible – as has generally been the case in the past.

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VERMICULITE IN THE UNITED STATES

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ABSTRACT

Vermiculite deposits occur in twenty of the fifty states, but ore has been produced from only six states, and in the last quarter century only from Montana and South Carolina. The mineral, a mica, is a supergene alteration product of micas, pyroxenes, amphiboles, olivine, and serpentine. It is much like biotite, its most common parent, but with magnesium occupying most of the sites held in biotite by potassium and with a double layer of water molecules in the interlayer spaces. When heated rapidly above 870°C (1,600°F), vermiculite expands in volume 8 to 15 times: commercial expansion is done usually at about 1,100°C (2,000°F).

Most vermiculite deposits are associated with ultramafic rocks, predominantly those of Precambrian age, cut by silicic, alkalic, and carbonatitic rocks. The largest deposits, such as Libby, Montana, form in large ultramafic intrusive bodies cut by syenite, carbonatite, or both. Deposits in small to large dunite, pyroxenite, or peridotite intrusive bodies, cut by pegmatite, syenite, or granite, differ in size but most are small. They are characteristic of the Blue Ridge region of the southeastern United States. The most common occurrence is in layered ultramafic schist that has been cut by pegmatite, less commonly with pyroxenite or peridotite. This type characterizes the second largest productive district in the United States (in the Piedmont of South Carolina) and most of the deposits in Colorado, Wyoming, and Texas.

Nearly half of all the vermiculite used is as aggregate in construction, about a third as insulation, and nearly a fifth in agriculture. Miscellaneous uses are numerous; some of the interesting applications are as a dust suppressant in underground mining and as a filter for radon daughter products in uranium mining.

Vermiculite production increased almost uniformly from about 285,000 tons in 1970 to 365,000 tons in 1973, but declined to about 340,000 tons in 1974. The total value has increased steadily from about $6.5 million in 1970 to about $10 million in 1974, and the average price has increased even more steeply. About two-thirds of the entire United States production comes from the deposit at Libby, the other one-third from the deposits of the Enoree district, South Carolina. A promising deposit, as yet unopened, is known in the Piedmont of central Virginia.

Although the theme of the Eleventh Forum on the Geology of the Industrial Minerals is resources in the northwestern United States, the entire country has to be the setting in which the vermiculite resources are appraised. Most of the vermiculite in the Northwest occurs in Montana; it is now produced only from the deposit at Libby, and the only other production has been from one small deposit in Skagit County, Washington, which yielded some ore in 1947 and 1948. In the "being developed" category, the Gilliam prospect near Pony, Montana, has had occasional interest over the last quarter century; the other known occurrences of even very moderate interest include two additional deposits in Montana: the Gird Creek, near Hamilton, and the Rocky Boy, in the Bearpaw Mountains on the Rocky Boy Indian Reservation.

Vermiculite deposits, however, are widely distributed (Bush, 1972)—they occur in twenty of the fifty states. They are lacking in the center of the country, except in Texas (Fig. 11-1) where there are significant deposits in the Llano region of the central highlands. The only western state where vermiculite cannot be pinpointed is Idaho; vermiculite has been reported but no location given. Geologically, Idaho has suitable terrane where vermiculite could occur. In the East, vermiculite occurs in most of the Appalachian states, and mineralogical occurrences are known in New England. As a matter of fact, vermiculite was first recognized, described, and named from an occurrence near Worcester, Massachusetts (Webb, 1824).

The purpose of this paper is to provide a broad survey of the types, distribution, and resources of vermiculite throughout the country, as a background against which the largest known deposit in the world, the Libby deposit, can be evaluated. A brief description of the Libby deposit is given below, drawn from the geologic literature.

In the approximately 60 years since the first mining of vermiculite, significant production has come from only six states, Montana, South Carolina, North Carolina, Colorado, Wyoming, and Texas (Fig. 11-2), and the Libby deposit has produced about twice as much vermiculite as the rest of the country. Since 1950, production has ranged from 200,000 to about 350,000 tons a year (Fig. 11-3), virtually all from Montana and South Carolina,

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*U.S. Geological Survey, Denver, Colorado.

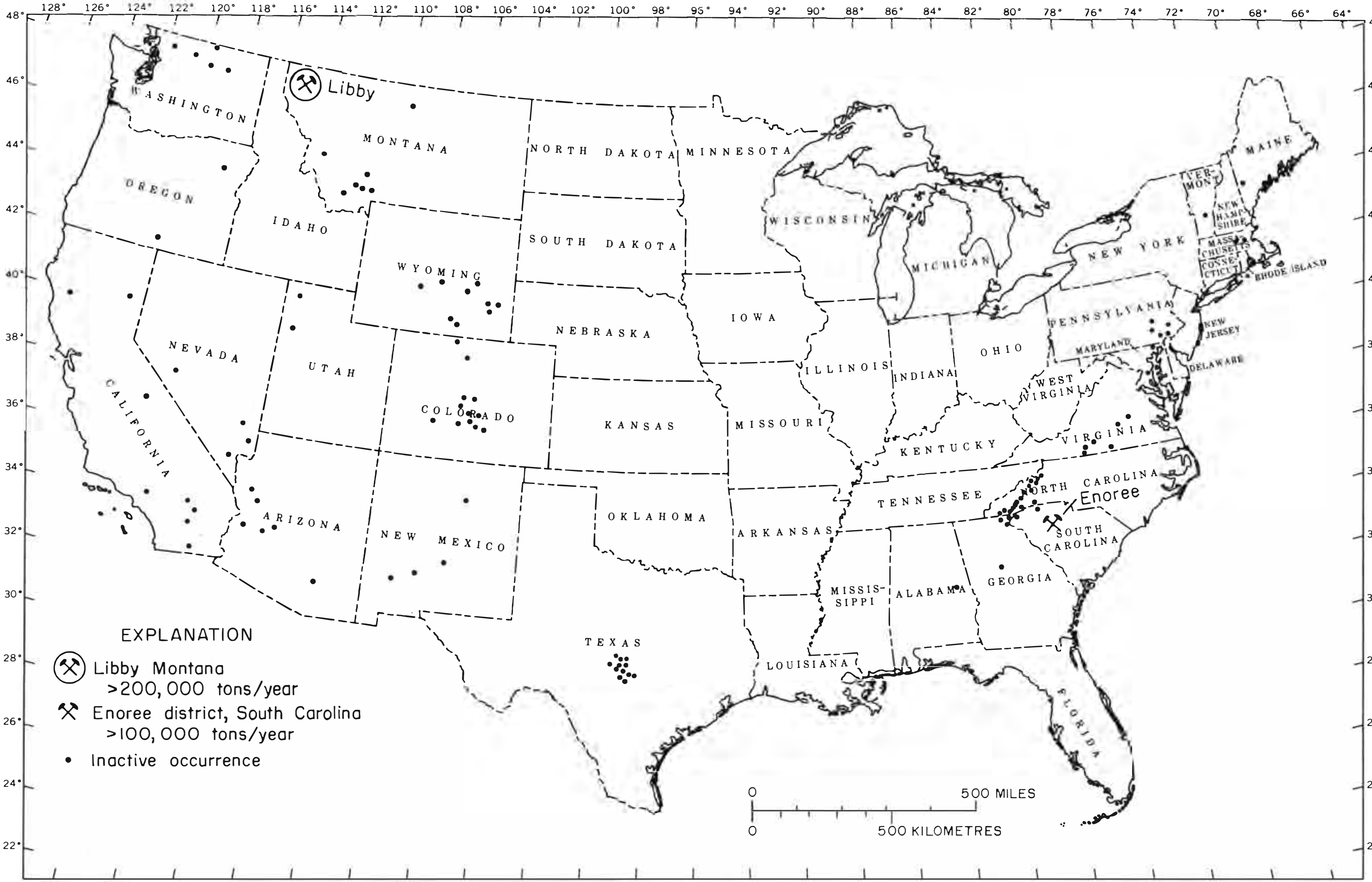

Figure 11-1. —Distribution of vermiculite in the contiguous United States, showing both producing and inactive deposits.

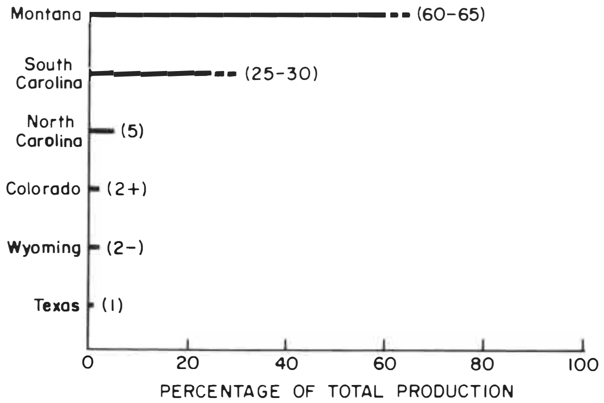

Figure 11-2.–Production of crude vermiculite in the United States, 1915-1975.

in an approximate 2:1 ratio. In 1974 the total value of the crude ore produced was about $10 million, and the approximate value of the finished product was about $31 million.

Vermiculite is a micaceous mineral that expands when heated (Fig. 11-4); the expansion is accordionlike, perpendicular to the cleavage. In the laboratory the expansion can be as much as 30 times the original thickness; in the plant, about 20 times is the maximum, and 8 to 15 times is the common range. Expansion requires rapid heating above 1,600°F (870°C), and commercial expansion is usually done at about 1,800-2,000°F (1,000-1,100°C). After expansion the bulk density ranges from 5 to 10 pounds per cubic foot, so that expanded vermiculite is ideal for use as an ultralightweight aggregate. Vermiculite does not react with weak inorganic acids and bases or with organic solvents; it has a high cation-exchange capacity, is fairly refractory, and has low thermal, electrical, and acoustical conductivity. These properties make it suitable for an impressive number of uses, among them lightweight concrete and plaster (roof decks, curtain walls, acoustical and fire-retardant plasters, and spray insulation for steel beams). So much vermiculite goes into the construction industry that the curves for production and value of vermiculite closely reflect the variations in the level of new construction (Fig. 11-3). Vermiculite is widely used for loose-fill insulation in hollow masonry walls, in double-walled cyrogenic tanks, and in insulating hot ingots and covers for molten-metal ladles. In the loose form it is also used for packing, especially for corrosive or reactive materials. Finely ground vermiculite is used as an extender, filler, or pigment in paint, enamel, rubber, plastic, inks, and lubricants. In agriculture it is used as a carrier for pesticides and fertilizers, as an absorbent in dry additives, as a soil conditioner, and a component in chicken, swine, dog, and stock feeds. There are also several unusual uses. It may not be common knowledge that in commercial baking of bread, vermiculite saturated with water is put into the first row of bread pans to enter the oven, to absorb the "flash heat" that used to scorch and burn those first loaves. The water is not reclaimable, but the vermiculite is! In 1973 about half the vermiculite produced was used in aggregates, one-third in insulation, nearly a fifth in agriculture, and 5 percent for other purposes.

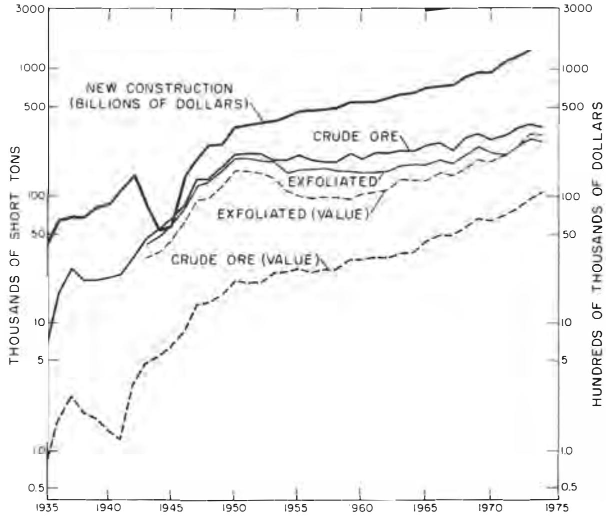

Figure 11-3.–United States production of vermiculite, 1935-1974.

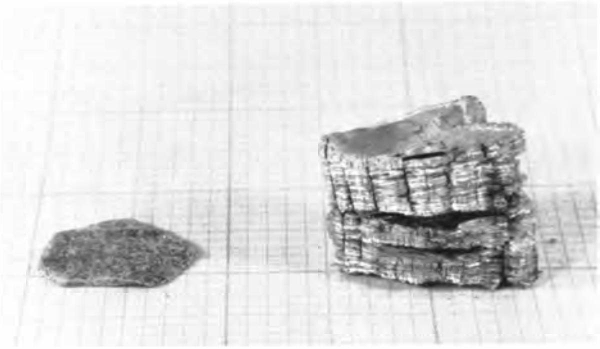

Figure 11-4.–Vermiculite flakes, before exfoliation (left) and after, showing about 20-fold expansion; flake at left is 5/8 inch in length.

We need to know a little bit about the crystal structure of vermiculite (Fig. 11-5) to understand its geologic habit and distribution and the possible variations in grade of the mineral itself. The mineral, like a mica, is a hydrated sheet silicate containing variable amounts of magnesium, iron, aluminum, and water. On the molecular level, the basic unit is composed of two tetrahedral silicate sheets that face each other and that are joined by an octahedral sheet containing the aluminum and iron.

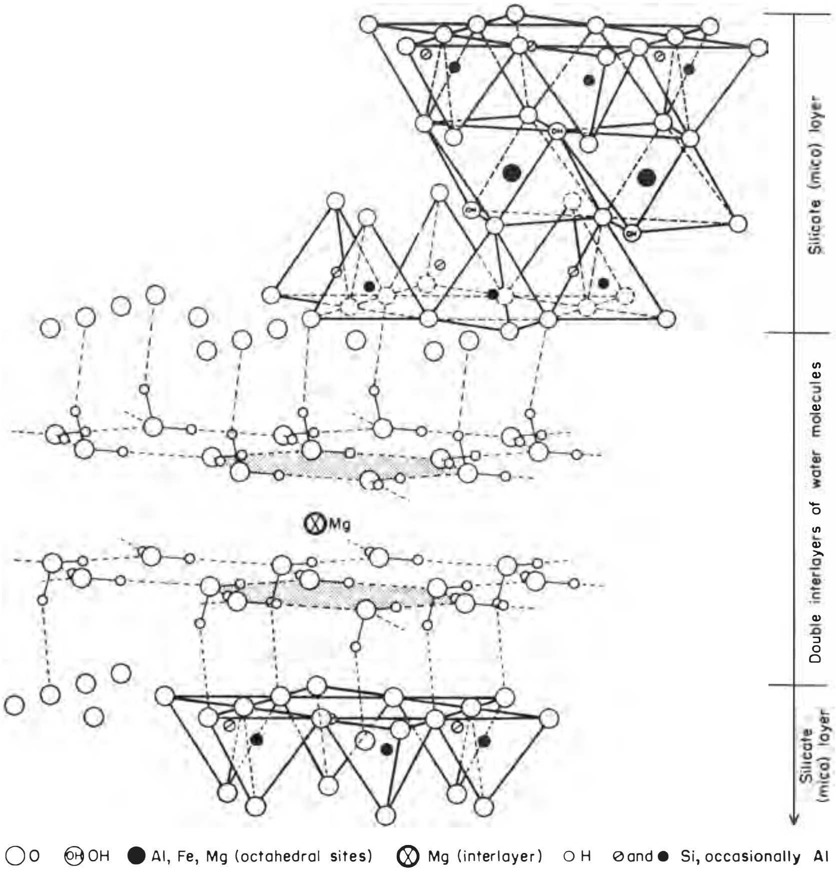

Figure 11-5.–Diagrammatic sketch of the structure of fully hydrated vermiculite, showing silicate (mica) layers with double interlayers of water molecules surrounding interlayer magnesium cations (one interlayer site shaded). Modified from Hendricks and Jefferson (1938) and Grim (1965).

This configuration is also the basic structural unit of a single biotite layer. Mica flakes are built up by a repetitive stack of these layers and, under the scanning electron microscope (Fig. 11-6), even at a magnification of only 4,600 times, the regularity of the stacking of the flakes is impressive. Each unit layer has regularly arranged "holes" on its upper and lower surfaces that overlap corresponding sites on adjoining layers. In biotite, potassium atoms occupy these sites, and their electronic charges help to hold the layers together. In vermiculite, only some of the sites are occupied, and these generally by magnesium, but a double layer of water molecules also is present in these interlayer regions. It is this water that flashes into steam and causes the expansion of the vermiculite (Fig. 11-7), here seen at a magnification of 660 times. The bulging and separation of layers is very evident (and is most striking in the third dimension), as are the curved septae that give expanded vermiculite its compartmented porosity. On the molecular level, vermiculite and mica commonly are interlayered, in either regular or random sequences.

Almost all vermiculite deposits are associated with mafic and ultramafic rocks, either igneous or metamorphic, that have been intruded by silicic, commonly alkalic, igneous rocks and, in some deposits, by carbonatite. The deposits can be broadly grouped in three different categories, but there are strong points of similarity among all the classes: Type-1 deposits have been formed within large ultramafic intrusive masses–such as pyroxenite plutons, some of which are zoned–that are cut by syenite or alkalic granite and by carbonatitic rocks and pegmatite (examples are deposits at Libby, Montana, and Loolekop, Phalaborwa, Republic of South Africa); Type-2 deposits are associated with small to large ultramafic intrusive bodies, such as dunite and unzoned pyroxenite and peridotite, that are cut by pegmatite and syenitic or granitic intrusive rocks (examples are deposits in the Blue Ridge region of the southeastern United States, especially the North Carolina deposits); the Type-3 deposits formed from ultramafic metamorphic rocks (especially amphibole schist) that may have originally

Figure 11-6.–Scanning electron microscope stereophotograph of raw vermiculite. Edge view, X 4,600.

been igneous rocks, some of which are cut by, or in contact with, pyroxenite or peridotite and cut by pegmatite (examples are deposits in the Enoree district, South Carolina, and most of the deposits in Colorado, Wyoming, and Texas). With the major exception of the deposit at Libby, most of the vermiculite deposits in the world seem to be in rocks of Precambrian age.

In all these types of deposits, the vermiculite is an alteration product of the mafic minerals; it has not been found as a primary rock constituent. Emplacement of the intrusive rocks caused metasomatism or hydrothermal alteration of the older rocks, in effect adding potassium, silica, and water. Depending on the composition of mafic host rocks, a variety of minerals were formed: biotite,

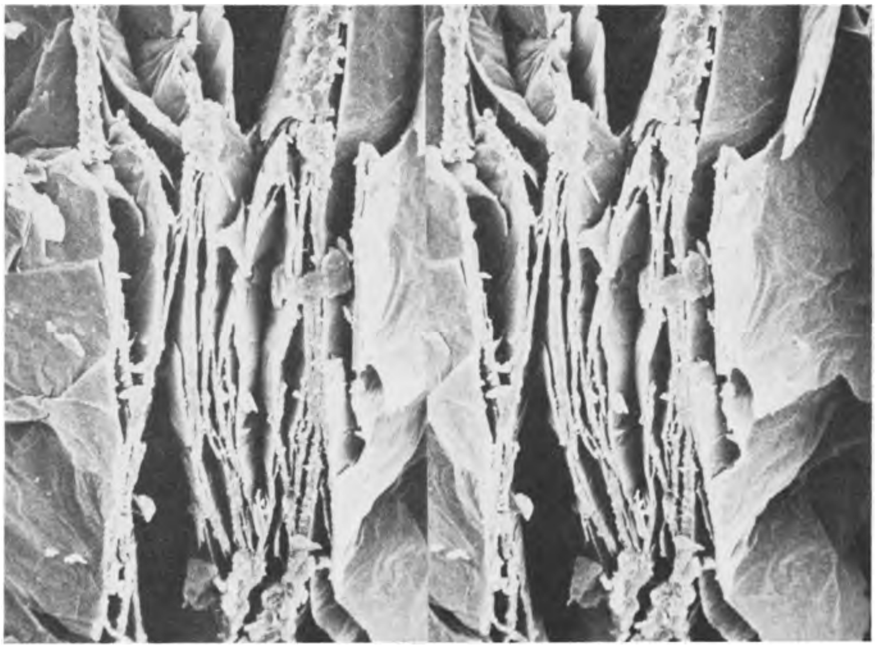

Figure 11-7.–Scanning electron microscope stereophotograph of exfoliated vermiculite. Edge view, X 660.

phlogopite, diopside, tremolite, augite, hornblende, olivine, chlorite, and serpentine. Vermiculite has formed by alteration from each of the listed minerals, and the geologic literature has many descriptions of such occurrences. The alteration may have included an intermediate biotite or chlorite stage, for X-ray diffraction studies of the vermiculite show interlayering with both biotite and chlorite, even though megascopic and microscopic examination may show no biotite or chlorite elsewhere in the rock. Biotite is the common parent mineral, and the similarity of the biotite and vermiculite crystal structures permits an intimate interlayering on a molecular scale in the

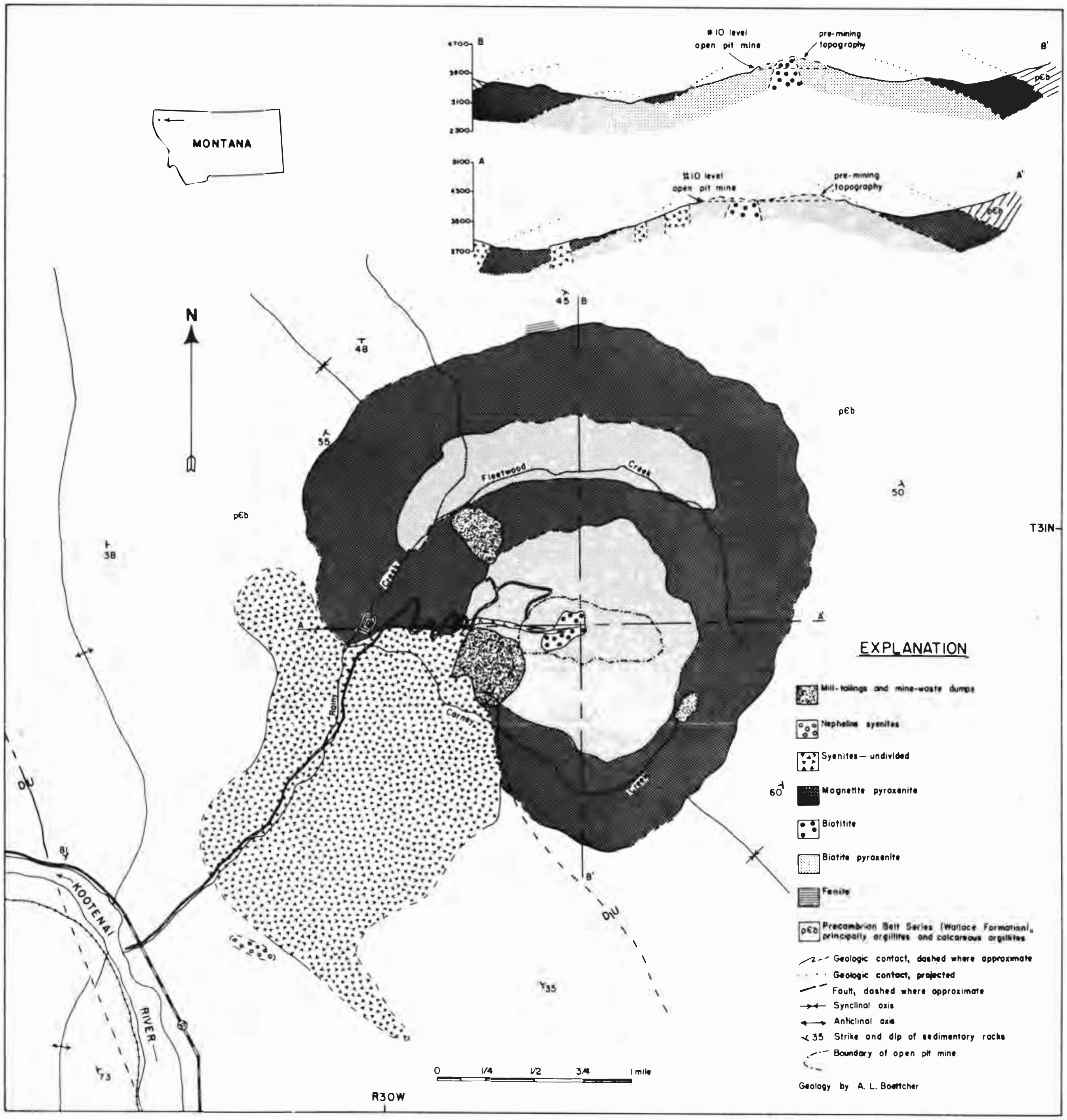

Figure 11-8.–Geologic map and sections of the Rainy Creek Complex near Libby, Montana (reprinted from Boettcher, 1967, with permission from University of Chicago Press).

series that ideally extends either regularly or irregularly from pure biotite through 1:1 biotite-vermiculite to pure vermiculite. Commercially the entire crystal is called vermiculite, but mineralogically it may be only part vermiculite—and therefore there can be a large range in the expansibility of vermiculite flakes from the same deposit.

Although most early investigators thought that vermiculite was formed as a mineral of the hydrothermal suite, most now believe that the vermiculite results from supergene alteration alone, a combination of the effects of weathering processes and the circulation of meteoric water. Both chemical and mineralogical studies increasingly support this concept, as experiments show that vermiculite can be formed from biotite in the laboratory at ambient temperatures (Groves, 1939; Bassett, 1959; Carter, Harward, and Young, 1963) and that vermiculite is unstable above 350°C and partly unstable down to 150°C (Romo and Roy, 1954; Roy and Romo, 1957; Boettcher, 1966). Most importantly, field relations indicate that vermiculite at the outcrop changes downward to biotite or another of the mafic minerals. I know of no contradictory field evidence.

The acceptance of a supergene rather than a hydrothermal concept for the origin of vermiculite obviously and markedly affects the estimation of reserves in the known deposits and of resources everywhere. If we are dealing only with the thickness of the zone of circulating meteoric water, we are dealing with ore bodies generally tens of feet thick and only exceptionally a few hundreds of feet thick.

The Libby deposit (a Type-1 deposit) is very large—an example of the "hundreds of feet thick" category. Figure 11-8 is a simplified geologic map of the Libby deposit and the Rainy Creek mine, as Boettcher (1967) mapped it in 1964. The pluton is a zoned pyroxenite mass having a core of biotite (biotitite) in a central biotite pyroxenite. There is a shell (like a ring dike) of magnetite pyroxenite that has been intruded into the zone of weakness at the contact of the biotite pyroxenite with the country rock, the Precambrian sedimentary rocks of the Belt Supergroup. At the time of Boettcher's work, the pluton was dated radiometrically as middle Cretaceous, but more recent work has identified it as older—it is now thought to be Early to Middle Jurassic (Fenton and Faure, 1970). A younger mass of syenite cuts both the magnetite and the biotite pyroxenite, and alkalic syenite dikes cut the biotite core. Fenitized Belt Supergroup rocks and a small nepheline syenite mass nearby suggest the presence of a carbonatitic mass at depth. Biotite in the biotite pyroxenite is altered to vermiculite (Fig. 11-9), and to a smaller extent it is altered in the magnetite pyroxenite; the biotite of the dense core is virtually unaltered (Fig. 11-10). Vermiculite is reported to have been penetrated to a depth of about 1,000 feet (Kujawa, R. J., oral comm., 1975). As the deposit underlies a ridge that has as much as 1,200 feet of relief, it is very possible that the vermiculite from the bottom of the 1,000-foot hole was still

Figure 11-9.—Vermiculite and biotite in the biotite-pyroxenite pluton, Rainy Creek mine, Libby, Montana. Largest crystal is biotite; about three-fourths of rest of face is vermiculite. (Knife is 3¾ in. long.)

Figure 11-10.–Giant crystal of unaltered biotite (about 5 feet long) from biotitite core, Rainy Creek mine, Libby, Montana.

in the zone of circulating ground water, the zone of surficial alteration. Figure 11-11 shows the pit as it was in August 1966 and gives an idea of the size of the deposit–indicated by diesel shovels and ore trucks on the bench in the middle ground. Vermiculite production since mining began about 1925 totals several million tons.

Vermiculite in the dunite-type (Type-2) deposits of the Blue Ridge province (Murdock and Hunter, 1946) occurs in veins and lenses along the commonly serpentinized contact of dunite and pyroxenite bodies with the metamorphic country rocks and with crosscutting pegmatite and along fractures within the bodies (Fig. 11-12). Generally the largest deposits are at the contacts, but the highest vermiculite concentrations are along the internal fractures. Where the country rock also is mafic (hornblende gneiss or biotite schist), the vermiculite may occur on both sides of the contact. In these deposits, vermiculite typically occurs in lenses that are as much as 5 feet thick and 60 feet long. A few lenses are 20 feet thick and more than 100 feet long. The typical deposit contains a few hundred to a few thousand tons of ore. Most of these deposits were worked by narrow trenches or were mined underground; since mining ceased 20 years ago or more the workings have been thickly overgrown or have caved.

Considerable variety exists among the deposits in the layered metamorphic rocks (Type-3). Some of the amphibole and biotite schists may have been sedimentary rocks, others, intrusive or extrusive rocks, but all deposits are characterized by granitic or syenitic crosscutting pegmatite. The deposits in the second most important group

Figure 11-11.–Part of Rainy Creek vermiculite mine near Libby, Montana (August 1966). Note shovel and trucks on bench in middle ground.

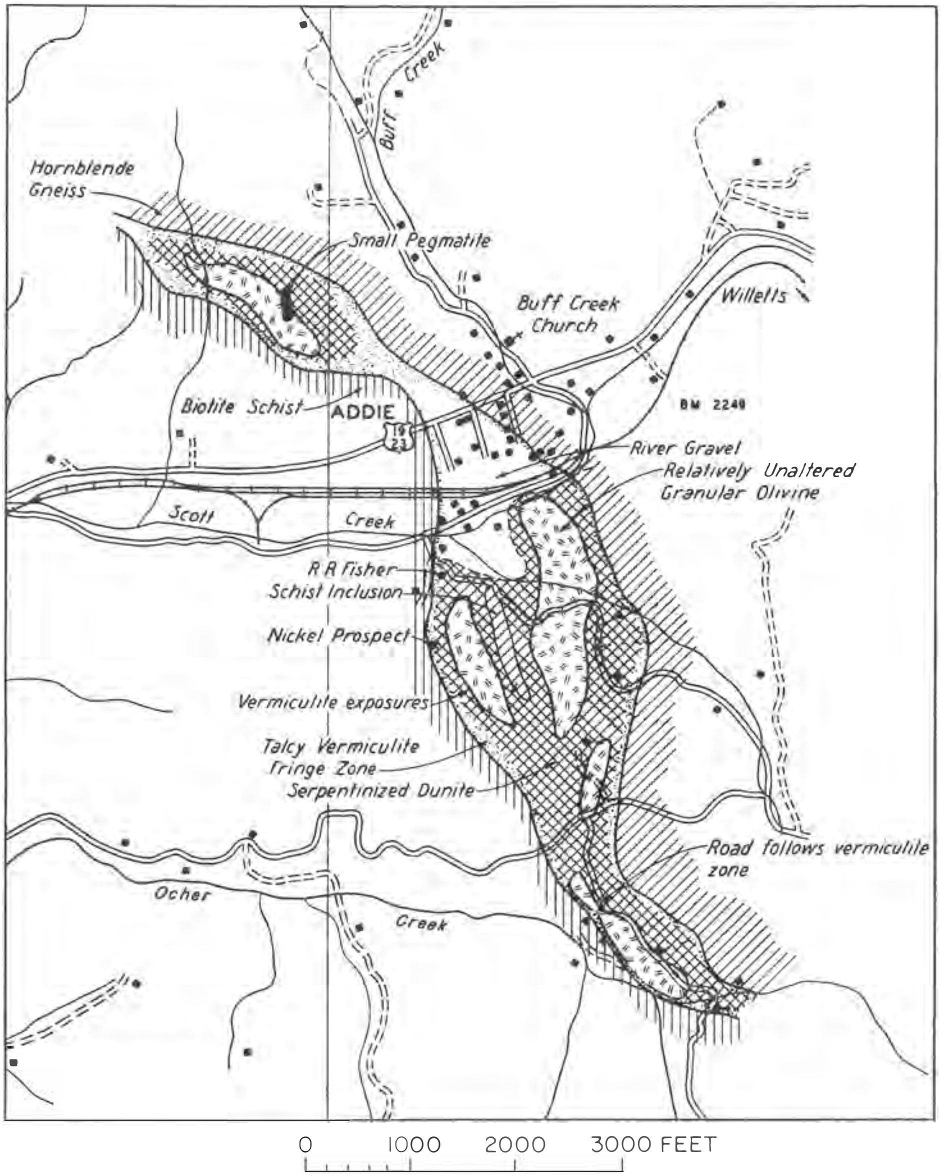

Figure 11-12.—Geologic map of the Addie dunite body, Jackson County, North Carolina, showing development of vermiculite along contacts and fractures (slightly modified from Murdock and Hunter, 1946).

in the United States, in the Enoree district of South Carolina, are of this type; in this district many deposits have contained 20,000 to 50,000 tons of ore, and some as much as 100,000 tons. In the Enoree district, weathering is so intense that rock types are difficult to identify and the contact relations are very obscure. The vermiculite may have developed by deep weathering of biotite from lenses of pyroxenite in contact with biotite gneiss and schist. The pyroxenite bodies may have been metamorphosed nearly completely to amphibole schist (which has been mapped in the Enoree area by McClure. 1963), for only remnants of pyroxenite have been found in the deposits. "Core-like" biotite masses are present in several South Carolina deposits (Fig. 11-13), and in a few places vermiculite is found partly underlying them. All the deposits are cut by stringers of pegmatite, and small masses of "granite" have been reported. Hunter (1950) described vermiculite lenses 450 feet long and 150 feet wide, with a depth to unaltered biotite of about 80 feet, but most of the deposits have length-width ratios of 5:1 or greater—consistent with favorable zones in layered rock.

The most numerous deposits, but those containing the smallest amounts of vermiculite, are also in layered

Figure 11-13.–Dark, unaltered biotite core about 10 feet thick, partly underlain by vermiculite, at the Waldrep No. 1 mine, near Enoree, South Carolina.

metamorphic rocks (Type-3). Characteristically, the deposits are in biotite schist, amphibole schist, or mica-amphibole schist and are cut by pegmatite. The deposits are only a few feet thick, although they may be several hundred feet long, and the depth of weathering is no more than a few tens of feet. Ore content ranges from a few hundred tons to several thousand tons. Most of the deposits in Colorado, Wyoming, and Texas are of this type.

What is the size of the vermiculite resources of the United States and what is the outlook for new discoveries? In 1972 I estimated that we would need about 19 million tons of crude vermiculite for use through the year 2000, based on a 5 percent growth rate, and that there was then about that amount in sight (Bush, 1972). Since then, there has been much interest in a Type-3 deposit in the Green Springs area of western Louisa County, Virginia, a deposit that has not been developed as of 1975. The deposit may be similar to those of South Carolina; if so, resources may be on the order of many thousands and perhaps hundreds of thousands of tons. New deposits are almost sure to be found in known districts (hypothetical resources), most likely deposits of the Enoree type in the Inner Piedmont region of South Carolina and perhaps in similar environments in Georgia, North Carolina, and Virginia (speculative resources). Deposits of the size of the "Libby" ore body are unlikely in the known districts, but it seems unlikely that there is only one such deposit in the United States. The association of ultramafic plutons with syenite, alkalic rocks, and carbonatite is too common to be a coincidence; this association is known from several deposits in the United States (Rocky Boy, Montana; Gem Park-McClure Mountain and Powderhorn, Colorado), in the U.S.S.R., and in several places in Africa south of the Sahara Desert. Several generalized clues to places where these rocks may be found together are (1) the rocks are most common in Precambrian terranes, (2) they may be related to Precambrian structural trends, (3) they may exhibit significant magnetic anomalies, and (4) they may be characterized by ring-dike structures. Although a second "Libby" ore body has not yet been found in the United States, the chances that one will be found seem good.

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GEM MATERIALS OF BRITISH COLUMBIA

Wilbert R. Danner*

ABSTRACT

Gem materials have become an increasingly important mineral resource of British Columbia. The province is the major producer of the nephrite variety of jade in North America and probably in the world. Nephrite is obtained both from float and in situ deposits. Production of high-quality material is sufficient to satisfy demand. Rhodonite of good quality is produced at several localities on a small scale. Rhodonite from Salt Spring Island is world famous for its fine-grained texture, variation in pink color, and associated brown manganese minerals. "Dallasite", an attractive volcanic "breccia" containing prehnite, pumpellyite, quartz, and other minerals, is found in the Triassic volcanic rocks of Vancouver Island and is an important and distinctive gem material used across Canada. Probably the most valuable ornamental material is the Indian-carved argillite from the Queen Charlotte Islands. Most of the argillite "carvings" sold today are of synthetic materials. Quartz varieties such as agate, thunder eggs, petrified wood, jasper, amethyst, and opal are abundant locally but are rarely of high quality. Fire opal has been found in small amount. Pegmatite gem materials are rare. Olivine of facet quality occurs but is difficult to extract from bedrock. "Picture rock" and "snowflake porphyries" are becoming increasingly popular. Gold-nugget jewelry has become more common but very expensive since the increase in the price of gold. A deposit of sodalite occurs in a National Park and is therefore inaccessible. Much of the province remains unexplored for gem materials.

INTRODUCTION

Since the Second World War the search for and cutting and polishing of gem materials has become an important professional and amateur activity in British Columbia. The most important and unusual materials are nephrite (jade), rhodonite, and dallasite, but many other minerals and rocks such as jasper, agate, argillite, picture rock, and "flowerstone" are used.

Much of the interest has centered around the nephrite variety of jade, first picked up as float boulders and cobbles from bars and river beds. Now, in addition to the alluvial sources, it is obtained from bedrock deposits. The early Indian inhabitants of British Columbia as far back as 1,500 B.C. used nephrite for adze blades and other tools (C. E. Borden, personal communication). A nephrite adze was worth one to three slaves. The first geologic report of the jade was in 1887 by George Dawson, who picked it up as float in a river bed in the southwestern part of Yukon Territory. Chinese gold hunters and laborers working on the Canadian Pacific Railway in the 1800's in British Columbia collected it and shipped it to China but it received little notice otherwise. Only after North American interest was aroused in the Wyoming nephrite in the 1940's did people take a second look at British Columbia nephrite and also nephrite in California and Alaska.

Two minerals are commonly referred to as jade. Jadeite, a pyroxene mineral, $NaAlSi_2O_6$, is the most expensive and rarest jade mineral and is sometimes referred to as "Imperial Jade". In gem quality material it is obtained almost entirely from stream-worn boulders in Burma and does not occur in China as is commonly believed. To date it has not been identified in British Columbia as a gem material although other minerals resembling it in appearance have been cut and polished and sold as jadeite. Nephrite, an amphibole mineral in the tremolite-actinolite series, $(MgFe)_5(Si_4O_{11})_2(OH)_2$, is the more common variety of jade, and although a rare material, it is found in many parts of the world and most abundantly around the Pacific rim. It is the variety of jade found in British Columbia. Jadeite is slightly harder than nephrite but nephrite is tougher. The toughness is due to its being made up of microscopic hair-like fibres in twisted and interwoven bundles. Jadeite occurs in many colors (gray, bluish, purple, orange, white, green, etc.), but most nephrite is green with some black (which may be due to weathering) and possibly some white varieties. Much nephrite contains tiny black spots of magnetite as impurities; a few of these in some specimens may give the nephrite a more attractive appearance. Black grains of chromite have been noted in California nephrite, and black grains of graphite are found in Siberian nephrite from the Lake Baikal area. Some of the British Columbia nephrite contains uvarovite (chrome-bearing garnet) as bright-green spots. It is

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especially abundant in jade from the Cassiar area. Chrome spinel is also found. Iron is thought to give the green color to nephrite. Nephrite of a bluish color seems to contain abundant chlorite.

British Columbia nephrite is found associated with alpine-type serpentine ultramafic bodies. Leaming (1974) listed three types of occurrences:

1. Contact between serpentine and country rock.

2. Tectonic inclusions of country rock with serpentinite.

3. As veins of nephrite within or close to serpentinite.

The environment of formation is believed to be high pressure and low temperature. The nephrite is formed by metasomatic alteration of serpentine with addition of calcium, silica, and possibly iron, by intrusion of gabbro and dioritic rocks (Evans, 1966), or by reaction between chemically dissimilar rocks in a shearing environment (Leaming, 1974). Associated minerals are diopside, hydrogrossular, vesuvianite, talc, chlorite, prehnite, and actinolite-tremolite. The Wyoming deposits are not associated with serpentine but are believed to have been formed by metasomatic alteration of amphibolite xenoliths during emplacement of a quartz diorite dike. The Siberian deposits are also metasomatic but contain no indication of shearing. The Wyoming deposits are of Precambrian age. Those in British Columbia are thought to range in age from Permian to late Triassic or Jurassic. Typical bedrock deposits of nephrite are lenticular bodies as much as 10 feet long and 6 feet wide, weighing 20 tons or more. Many in situ bodies and large alluvial boulders have white weathered crusts or rinds around them, which make them look like ordinary rocks, so they easily escape notice by people prospecting for jade and expecting to see a smooth rock of bright-green color. The usual jade boulder must be cored or sawed to determine its value. Jade miners cut the jade boulders into 1,000- to 2,000-pound blocks with wire saws and then into smaller blocks with diamond saws.

From 1957 to 1970 approximately 596,395 pounds of nephrite jade was produced commercially in British Columbia and it had a value of $531,670. In 1970, production was 262,602 pounds. Production in recent years has been variable. Most of the jade is stated now to be exported to Germany, Japan, Taiwan, Hong Kong, China, and the United States. Good quality nephrite for local lapidary use is becoming scarcer. It is widely used for ring settings, charms, and polished carvings. A large carving of a bear, exhibited in a Vancouver department store in 1973, was priced at $75,000. A seagull carving with an 18-inch wingspread sold for $20,000 at a show in Calgary, Alberta.

Varieties of nephrite containing gray diopside or other gray to white minerals is often sold as "intestinal jade", and some of the material does contain inclusions that strongly resemble intestines (Fig. 12-1). Rarely nephrite occurs in botryoidal form. This variety is polished for baroque jewelry. It is very expensive and is known from only a few localities in California and Washington and in British Columbia from the Bridge River area.

RHODONITE

Rhodonite ($MnSiO_3$) is pink manganese silicate. It ranks next to nephrite in commercial importance in British Columbia. It has a hardness of 5.5 to 6.5 and is commonly massive but may occur in good crystals. The color ranges from pale pink to deep raspberry red. Massive gem-quality rhodonite in small amounts is widespread around the world, but the most important deposits are in the Ural region of Russia, in Australia, and on Salt Spring Island, British Columbia. Noted areas where good crystals occur are Broken Hill, Australia, with galena, and Franklin Furnace, New Jersey (variety fowlerite with as much as 10 percent ZnO). Common minerals associated with rhodonite are quartz, jasper, garnet, and other manganese silicates and oxides. Rhodonite deposits are commonly coated on weathered surfaces with black manganese oxides, and the penetration of the oxides into cracks and joints gives a "spiderweb" effect when the material is cut and polished. The manganese oxide may range from thin coatings to masses several feet thick if there has been deep and extensive weathering. The black oxides are regarded as an ore of manganese, but the tough, chemically resistant silicate is not.

Many rhodonite deposits in British Columbia are associated with sequences of bedded radiolarian chert and in some deposits with volcanic rocks. The origin of rhodonite is not well understood, and various authors have attributed it to (a) replacement of sediments by manganese-bearing solutions, (b) metamorphism of manganese-bearing sediments, (c) ascending thermal solutions of igneous origin. Deposits in British Columbia seem to be formed as a result of metamorphism of manganese-bearing sediments. Parts of the deposit on

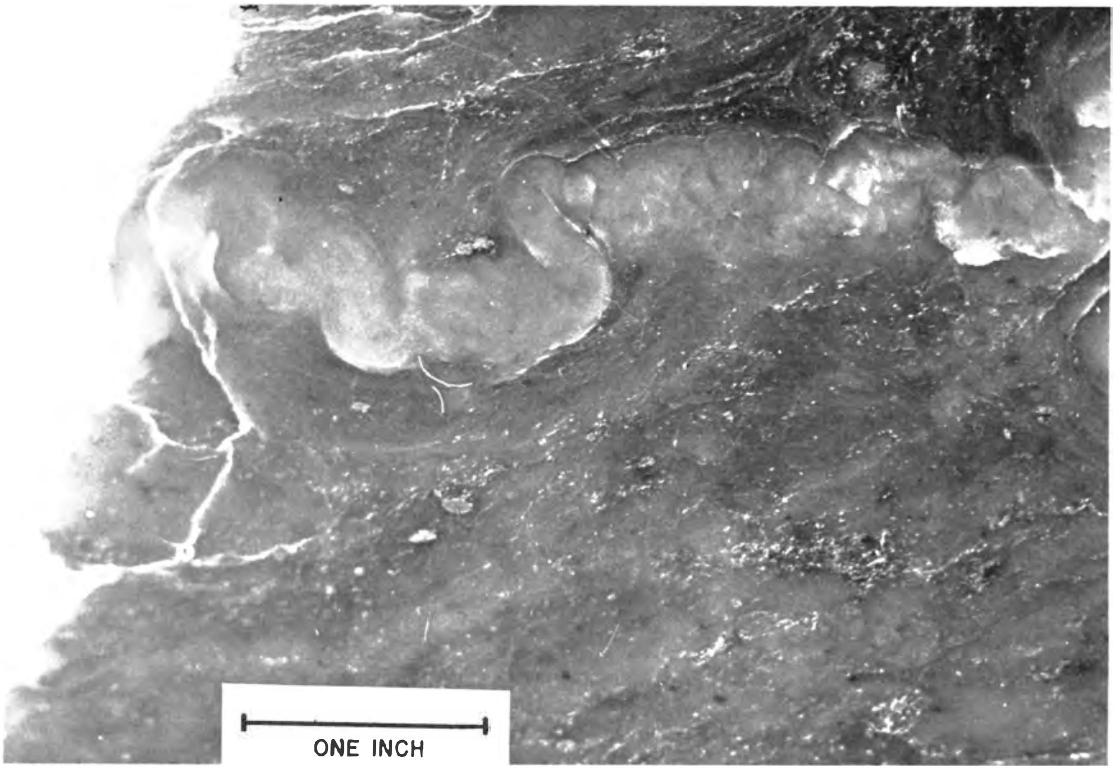

Figure 12-1.—Polished surface of nephrite from Lillooet, British Columbia, showing "intestinal structure".

Figure 12-2.—Massive lens of rhodonite interbedded in metachert. Salt Spring Island quarry of Fred Hollings. View looking north, May 1972.

Salt Spring Island near Vancouver seemingly have been made more coarsely crystalline by intrusions of gabbro porphyry sills.

In British Columbia rhodonite of excellent gem quality has been found in late Paleozoic rocks of the Sicker Group on Salt Spring Island and in the Cowichan Valley region on Vancouver Island. The two deposits are of similar quality and may be of the same geologic unit but this is not yet proved by geological studies. The Salt Spring Island deposit is quarried commercially on a small scale and is owned and operated by Mr. Fred Hollings of Fulford Harbor. The material is sold in chunks of various sizes by the pound or in sawed blocks and slabs. Most of the production is sold in rock shops for amateur use. Prices vary according to quality and are as high as $25 per pound. Polished ring-size cabochons sell in Vancouver for $3 to $5 per stone. Large chunks free of black manganese oxide veinlets may be obtained, and the irregular bands of pink to bright red rhodonite along with various shades of brown manganese silicates, garnet (spessartine), and quartz make attractive specimens for polished slabs, paperweights, or book ends (frontispiece). The rare "liver brown" manganese silicate neotocite is common in translucent to transparent veins. Specular hematite borders parts of the manganese lenses. The rhodonite occurs in lenticular bodies (Fig. 12-2), which pinch and swell rapidly along strike and seem to be restricted to a sequence of metachert layers.

The Cowichan Valley deposits have had little commercial production and have been collected mainly by amateurs as home cutting and polishing material. These deposits are difficult of access but the quality is reportedly as good as that of Salt Spring Island deposits. The most important location is known as "Hill 60".

Rhodonite is widespread in Triassic and possibly Paleozoic rocks in the Keremeos-Oliver area of south-central British Columbia. The material seems to be more oxidized than the rhodonite of Salt Spring Island and is a duller pink color. Most of the supply is picked up as float.

Several rhodonite localities are known in late Paleozoic rocks of the Cache Creek Group in northern British Columbia in the vicinity of Fort St. James and Williams Lake. In this area most of the rhodonite has been obtained as float boulders in streams. Rhodonite reported to be from this area seen for sale in rock shops has fewer shades of pink than rhodonite from Salt Spring Island, and many specimens are seen to have partly replaced gray chert. The color and quality are good and it is an attractive stone.

Float rhodonite boulders have been found in streams near Barriere, Little Fort, and Clearwater along the North Thompson River in central British Columbia. The specimens seen by the writer are not of as good quality as Salt Spring Island material, but many have a pleasing banded or bedded appearance and are associated with chert and jasper.

DALLASITE

Probably the third most important gem material in British Columbia is dallasite. The name is given to a volcanic breccia of Triassic age found most abundantly on Vancouver Island. The name is derived from Dallas Road in Victoria where specimens of this attractive material were first found as cobbles and boulders on the beach below the road. It is believed that dallasite originates as a breccia formed between lava "pillows" in submarine lava flows. The skin of the lava pillow ruptures and mixes with tuffaceous volcanic debris. This is then altered by replacement of part of the matrix by chlorite, epidote, pumpellyite, tremolite, chalcedony, quartz, prehnite, calcite, and zeolites. An attractive rock results, composed of greenish rectangular or irregular fragments and slivers of altered volcanic rock in a white to dark-green matrix. Dark-green to black radiating needle-like crystal masses border some fragments, and many of the fragments themselves have light-colored altered borders. Not all pillow breccias produce this material and it is not certain whether it is confined to Triassic lavas of the Karmutsen Formation, but it is found abundantly in areas where the Karmutsen lavas occur. Dallasite is reported to be relatively common along the east side of Vancouver Island as beach and river float around Parksville, Horne Lake, and Buttle Lake, and on Quadra Island. The writer has found it in large pebbles on beaches on the west coast of Vancouver Island, and the specimen illustrated (Fig. 12-3) was picked up on the beach at Point Roberts, Washington, where it must have been derived from glacial outwash gravel and till, partly of Vancouver Island origin. Dallasite is widely used for cabochons, ring settings, broaches, bolo ties, bookends, and paperweights, and the writer has noticed it for sale in jewelry stores across Canada. It would not be thought attractive by everyone. It is probably the only gem material named after a road, but the road was named after Alexander Grant Dallas, Hudson's Bay Company representative in Victoria from 1857 to 1861 and later Governor of Rupert's Land. The writer has seen material similar to dallasite on beaches north of San Francisco derived from the Franciscan Formation pillow lavas.

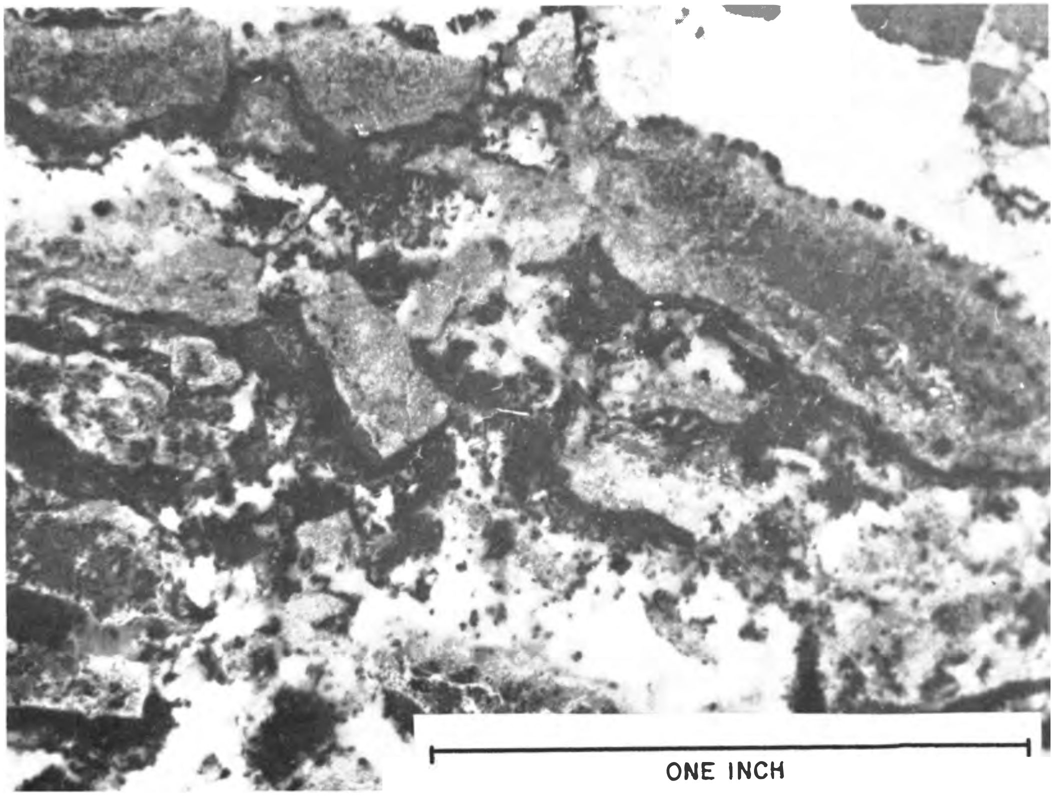

Figure 12-3.—Dallasite. Polished surface. Volcanic breccia formed between pillows in pillow lava sequence. Beach float specimen from Point Roberts, Washington.

FLOWERSTONES

Along with cobbles of dallasite, gem hunters also look for porphyritic-textured volcanic rocks with pleasing crystal patterns. The beaches of Vancouver Island contain the best of these. They are usually divided into two groups: gabbro porphyries and feldspar-quartz porphyries. The gabbro porphyries are prevalent on Vancouver Island beaches. The most attractive are glomeroporphyritic in texture and are referred to as "flowerstones" (Fig. 12-4). Others are given such names as "Snowflake porphyry", "Chinese-writing stone", or "mouse-track porphyry". Sills of glomeroporphyritic gabbro are found in the Karmutsen lavas on Vancouver Island and in the Sicker Group rocks (Paleozoic) on Salt Spring Island. The sills are thought to be of Triassic age.

The feldspar-quartz porphyries, many of which are monzonite or dacite in composition, have a light-gray matrix containing well-shaped white crystals of feldspar, many of which are zoned (Fig. 12-5). They are found on Vancouver Island and Vancouver area beaches and also up the Fraser and Chilliwack Valleys on the mainland. The source of at least some of these porphyries is a phase of the Chilliwack Batholith in the Cascade Mountains. An attractive pink feldspar porphyry occurs as boulders, cobbles, and pebbles in the Springbrook Formation (Cenozoic) near Olalla in south-central British Columbia. The pink feldspar crystals are aligned and zoned, and some have white interiors. Many of the crystals are twinned.

ARGILLITE

Another rock that may be regarded as a gem material is the famous argillite of the Queen Charlotte Islands. It is not widely used today but carvings of it done many years ago are very valuable. After 1785, when ships entered the waters of the Queen Charlotte Islands to barter with the Indians for sea otter pelts and to hunt whales, the Indians noticed that the sailors were doing scrimshaw (carving) in their spare time. Soon Haida men went to sea on the whalers, and they took up the carving using yellow and red cedar, whale teeth, walrus tusks, and grizzly bear teeth. About 1820 they started to use "argillite" quarried from sedimentary rocks of the Queen Charlotte Group (Upper Cretaceous) found on the mountainside up Slatechuck Creek on Graham Island about 8

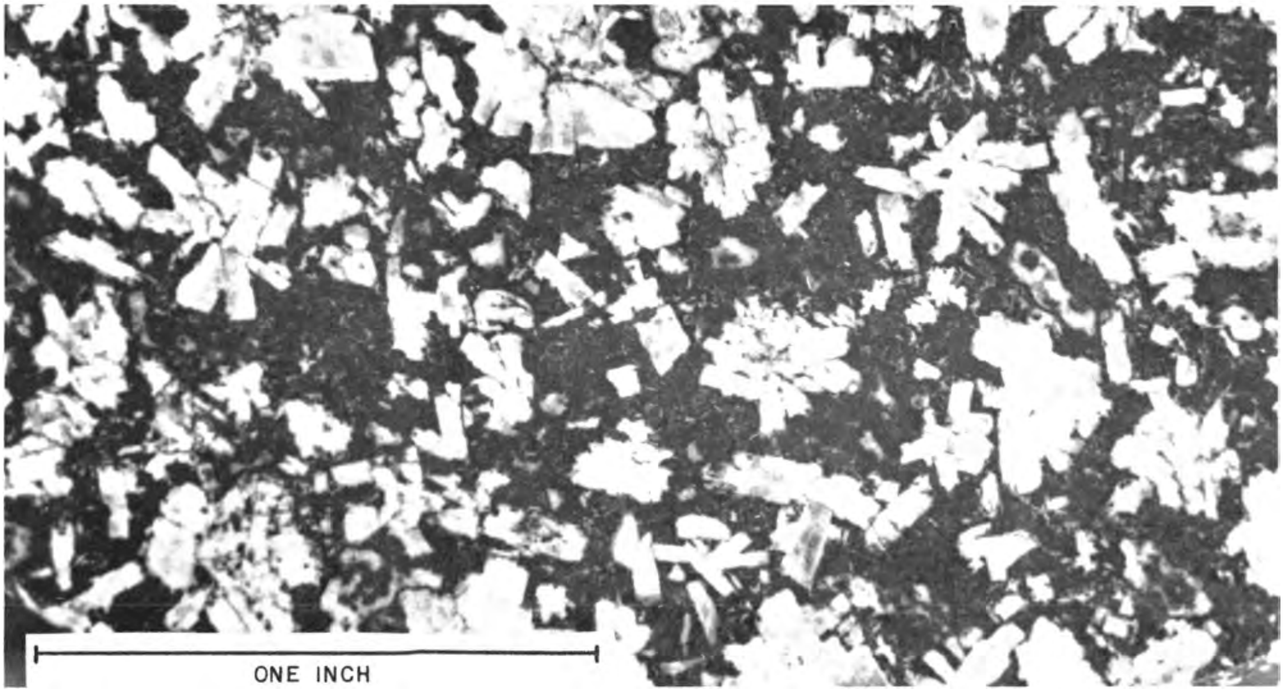

Figure 12-4.–"Flowerstone". Glomeroporphyritic texture of feldspar crystals in gabbro. Karmutsen Intrusives, Vancouver Island.

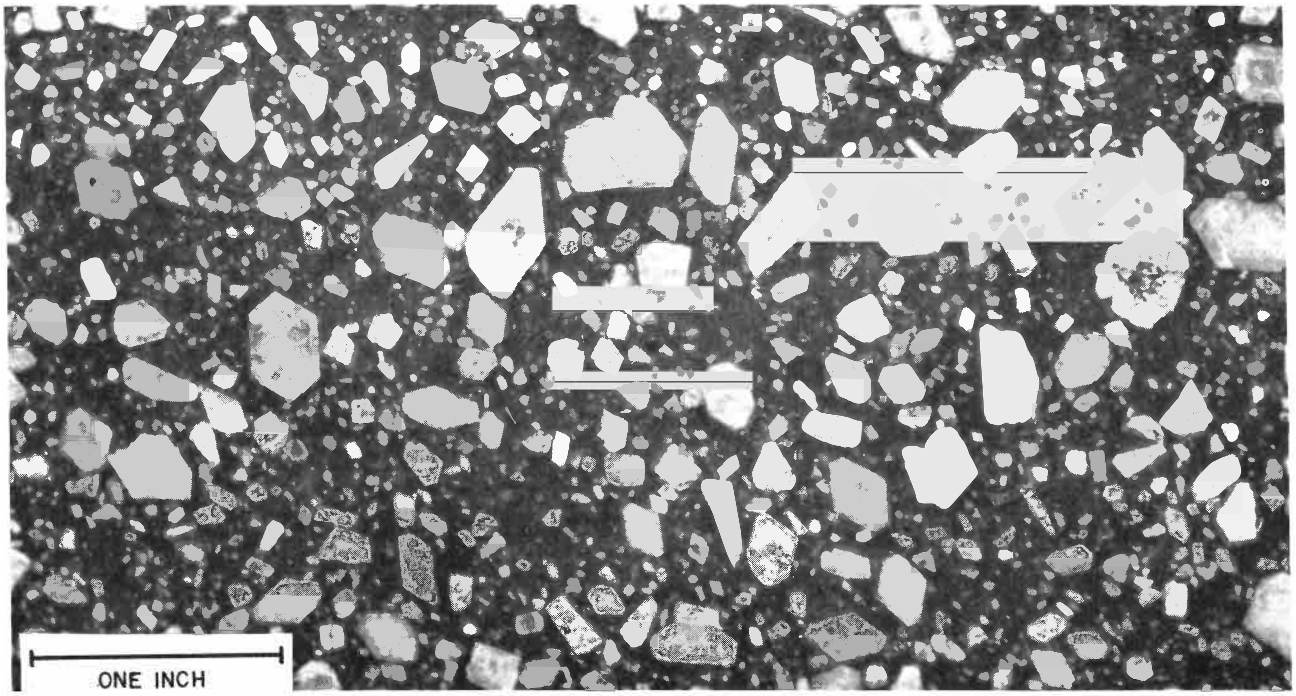

Figure 12-5.–Feldspar-quartz porphyry. Float specimen from Chilliwack Valley, Skagit Ranges, southwestern British Columbia.

miles from Skidegate. One report states that the deposit was discovered by white prospectors looking for copper and coal. The deposit was examined by G. M. Dawson in 1878, who noticed that the carvings were being produced "merely to fulfill the demand for such things as curiosities by the whites". Pipes, flutes, plates, boxes, dishes, etc., were purchased by sailors and taken back to New England. Art authorities did not regard the material as art but merely souvenirs manufactured for the "tourist trade". The pipes were not smoked, the dishes were not used, the boxes were not filled; however, some of the flutes were played. Many of the carved objects in black argillite were inlaid with bits of mother of pearl from the abalone shell, and mussels, ivory, and bone; sometimes pigments such as red iron oxide were rubbed into grooves in the carvings to emphasize the linear features of certain designs. Over the years several important collections of these carvings were assembled and fortunately today preserve this remarkable art. The stone is weak and after a time parts of the original design, especially protuberances, break off and are lost.

These art objects soon caught on and by 1850 were known throughout the world. The peak of the carving occurred between 1840 and 1880. After 1880 the quality diminished, and small totem poles (*Kexen* and *Xat*) were made by the hundreds. Tribal legends, actual happenings, and events in tribal history were depicted on the carvings. In recent years the carving of argillite has almost died out but today stores in Vancouver and Victoria carry small carvings, pins, and pendants of argillite. The argillite totem poles were always the most popular shape, and replicas of them made by casting are for sale today in almost every souvenir store and counter in British Columbia. The material used and the exact method by which it is done are kept secret. In 1949 the price of true argillite totem poles was about $1.50 an inch for a six-inch pole, which might take two or three days to carve. Today the price is $12 to $25 per inch. Older argillite objects are priceless.

The stone is sometimes called haidite, sometimes "black jadeite", and is locally called slate. The Indian name is Kwawhlhal. Only Indians may quarry the stone. It is relatively soft when first quarried. When dry it is very brittle and splits easily. The Haidas kept it in moist cloths or buried it to keep it moist until they wanted to carve it. When carved, some specimens are coated with glue, then sandpapered, with vaseline smeared on the sandpaper. Next graphite powder is put on and rubbed thoroughly. This brings out the beautiful jet black sheen of the surface. In the old days soot and oil mixed with shoe polish was used. The surface was smoothed with dogfish skin and rubbed with halibut oil.

Sutherland-Brown (1968), while working on his monumental "Geology of the Queen Charlotte Islands", made a study of the argillite and described it as follows:

> The slate or argillite used for carving by the Haidas is a fairly unique rock composed of silt-sized fragments of kaolinite and less montmorillonite in a macerated very fine carbonaceous clay matrix that forms some 40 to 75 percent of the rock. There is no detrital quartz, and any detrital feldspar appears to be altered to kaolinite. In addition, crudely barrel-shaped grains of kaolinite with a different texture appear to be porphyroblasts that have grown out of the fine matrix. The rock has a well-developed foliation but is compact unless sharply hit. ....There is a considerable tonnage of rock on the claim, although not all of good quality (that is, some contains detrital minerals). A similar rock without the low-grade metamorphism induced by folding and metamorphism by the adjacent eruption of the Masset Formation would be unlikely to have the same subtle characteristics that make the rocks desireable for carving.

Black to dark-gray argillite of similar properties is carved in central Japan and it may be that some argillite carvings in British Columbia could have a Japanese origin.

OTHER GEM MATERIALS

Several varieties of quartz gemstones have been found in British Columbia. Larger clear quartz crystals have been collected in the rugged alpine country east of Harrison Lake and from a deposit in the Skagit Ranges near Mt. Cheam east of Vancouver. Small "herkimer diamond" type quartz crystals have been found in a fault zone up Liumption Creek in the Chilliwack Valley area of southwestern British Columbia. Amethyst has been collected from the area between Kamloops and Monte Creek but is reported to fade upon continuous exposure to strong sunlight. Agates are found in several areas. A few blue-gray and white banded varieties of large size occur in the Monte Creek area east of Kamloops (Fig. 12-6), and veins and amygdale fillings of orange agate occur in the Chilliwack volcanic rocks of the Tamihy Creek area. Attractive agates are found near Shaw Springs and in the Cenozoic lavas of the Queen Charlotte Islands and central interior of British Columbia (Fig. 12-7).

Thunder egg types of agates occur in the Chilcotin region east of the Coast Mountains, but the specimens seen by the writer are not equal in quality to most of the thunder eggs found in Oregon.

Red jasper is widespread and much is found associated with rhodonite. Interesting spherulitic patterns are found in the Chilliwack volcanic rocks (Permian). These seem to form in interpillow spaces by precipitation. Hematite is commonly associated with the spherulitic jasper.

Petrified wood occurs in several areas, notably between Kamloops and Monte Creek, and opalized plant material and wood, some of which may be polished with good results, are found at Vermillion Bluffs near Princeton. Fire opal in small amounts has been collected in a few places but none of the deposits has yielded more than a few stones.

The hard non-quartz gem materials are as yet little known in British Columbia, and most are found in the metamorphic belt of the eastern interior west of the Rocky Mountain trench. Beryl, tourmaline, garnet, and kyanite have been reported. Gem-quality sodalite occurs in place in Yoho National Park, but the park is closed to collecting, so one must look for float specimens in streams draining the park area. A few peridots of excellent quality have been obtained from Lightning Peak east of Vernon but the olivine is in solid lava and difficult to extract without extensive fracturing.

Gypsum of the variety alabaster occurs near Falkland in southern British Columbia, and has been carved. Attractive appearing limestone is widespread. Limestone containing large crinoid columnals is found in the Chilliwack Valley, and some has been cut into bookends. Red algal pisolites found in the Nicola Limestone (Triassic) are also attractive when polished (Fig. 12-8). Travertine and travertine onyx occur in a few places. A beautiful brown banded onyx travertine was found when Highway No. 1 was built, 6 miles east of Golden at the crossing of the Kicking Horse River (Fig. 12-9). Much of it is stalactitic.

Obsidian has been found in the Mt. Edziza area, in the Mt. Garibaldi area, and in the mountains north of Anaheim Lake.

Dumortierite is abundant in the Island Copper mine at Rupert Inlet on northern Vancouver Island but little of it is of gem quality.

Amber and mineral resins occur in several coal deposits, notably near Quesnel and Princeton and at Hat Creek.

When the Hope landslide occurred east of Vancouver in the winter of 1965 a large quantity of weathered light-colored volcanic rock was exposed in the slide debris. This was found to show nice "scenes" when cut into slabs (Fig. 12-10). The slide area is now closed to collecting, however.

Gold nugget jewelry has always been a popular tourist item in British Columbia. Heirloom pieces show up from time to time in antique shops and pawnshops but the prices have become very high in recent years (Fig. 12-11). Many rock shops are producing modern gold nugget jewelry, and the combination of gold nuggets and British Columbia jade is very attractive. One must be wary of gold nuggets and gold-in-quartz specimens offered for sale, as many fakes are on the market; some gold-in-quartz specimens are found to be quartz with gold leaf painted onto the surface and down into cracks and crevices. Some gold prospectors in the province have melted gold dust to form nuggets to obtain higher prices, and this practice has been going on for many years.

The question often arises whether diamonds have been found in British Columbia. Camsell (1913) reported tiny diamonds in the peridotite of the Olivine Mountain area of the Tulameen Valley in southern British Columbia. The diamonds were described as being in chromite embedded in serpentinized peridotite. None were visible with a hand lens; they could be seen only in thin section. The largest size was reported to be the size of a pinhead and all the diamonds were opaque. It was also stated that when the diamonds were released from the chromite they disintegrated. No diamonds have been found in the extensive gold and platinum placers of the Tulameen Valley, and no similar type of diamond occurrence is known in the rest of the world. Thus it is doubtful that this material was really diamond. Only one verified diamond has been found in Canada and it was found in glacial drift in Ontario.

At least one incident of diamond salting is known to have taken place in British Columbia, where real diamonds were placed where they would be conveniently found (R. M. Thompson, personal communication). The fact that all known diamond-producing kimberlite pipes are located in Precambrian shields leads one to suggest that the highly deformed island arc sequences that make up most of British Columbia will be unlikely places to find diamonds. Alluvial diamonds, however, may be transported long distances, and alluvial diamonds have

Figure 12-6.—Banded gray, blue, and white agate from Cenozoic lavas near Monte Creek, southern British Columbia.

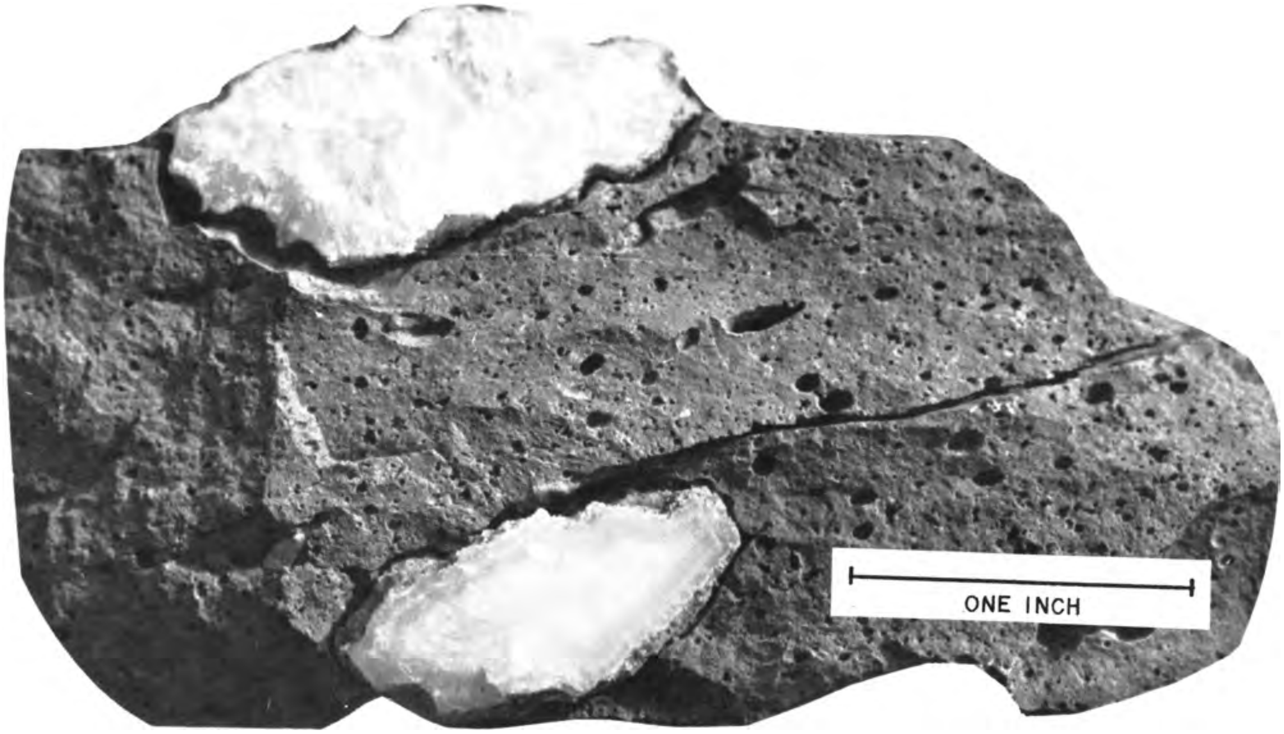

Figure 12-7.—Agates in amygdales of Miocene basalt from Harper Ranch east of Kamloops, British Columbia.

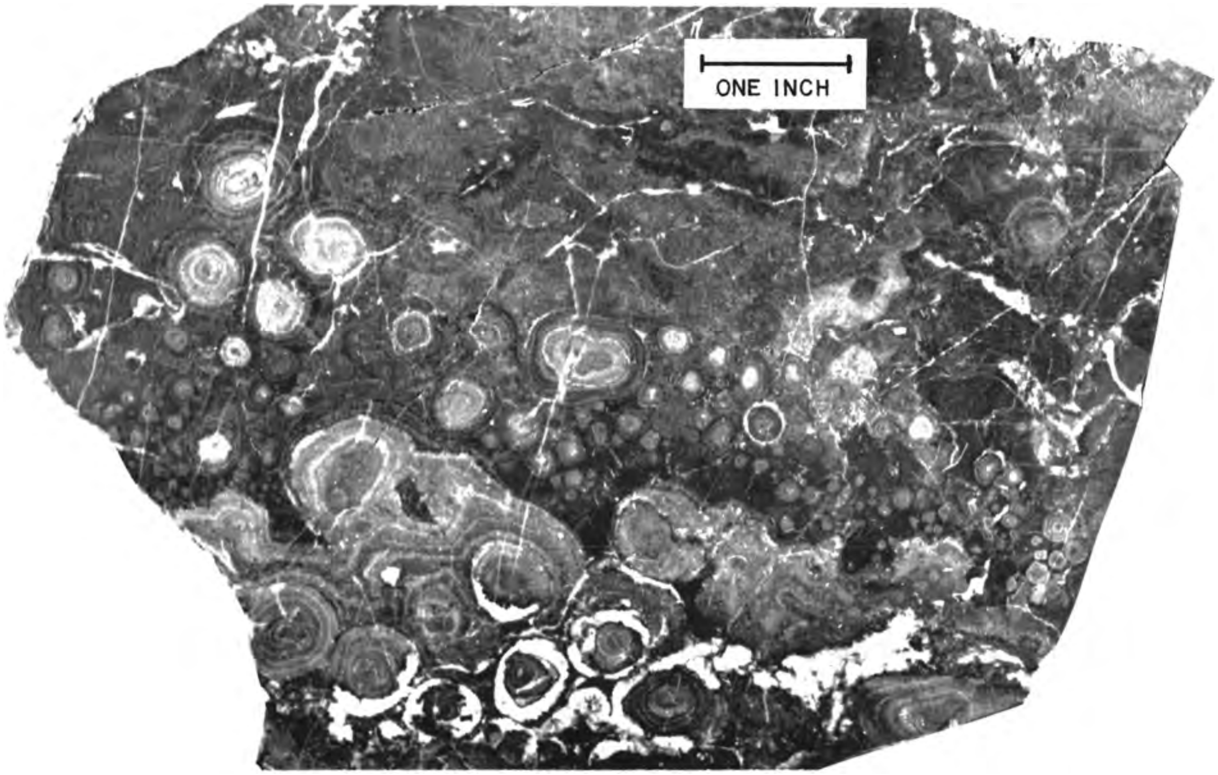

Figure 12-8.–Red algal pisolites in Nicola Limestone (Triassic) north of Princeton, British Columbia.

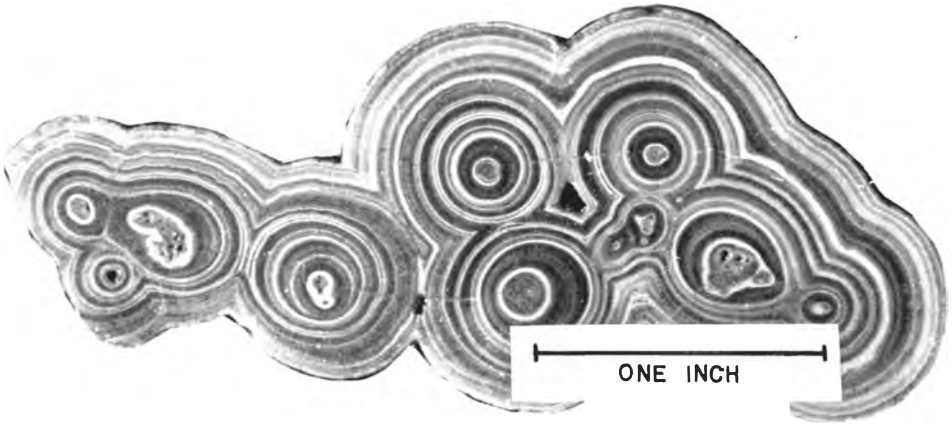

Figure 12-9.–Polished surface of stalactitic travertine onyx, Kicking Horse River near Golden, British Columbia.

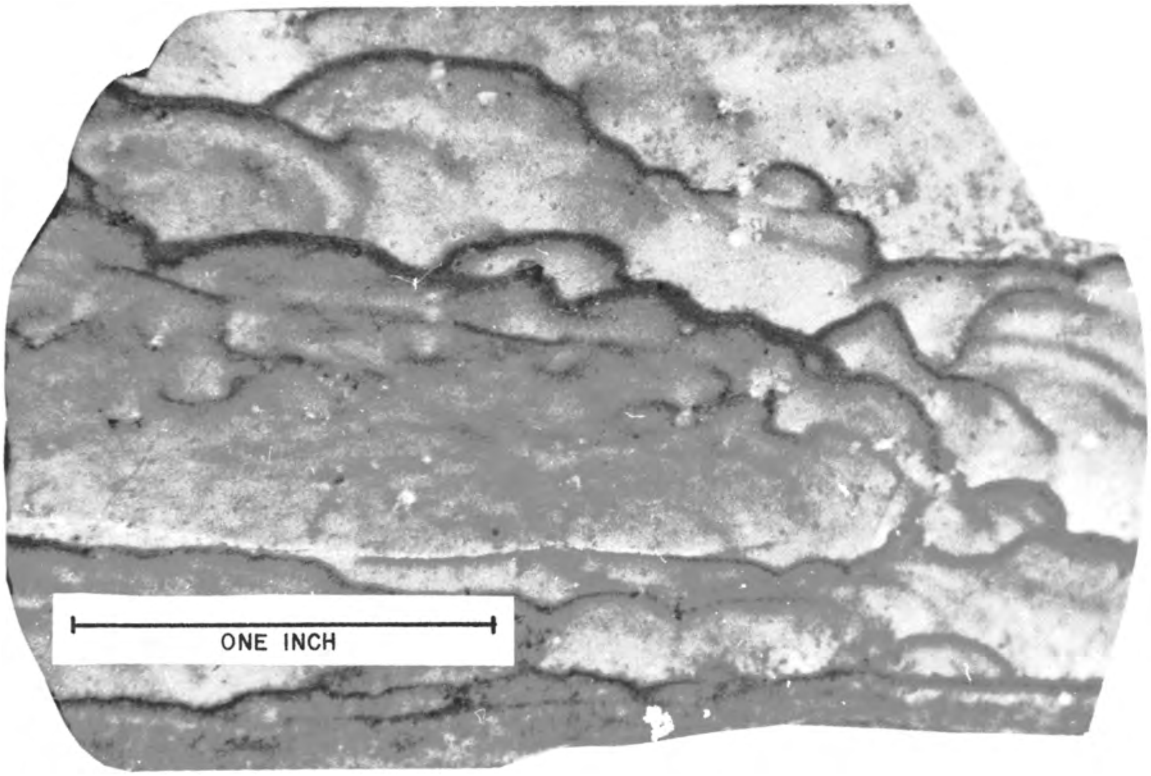

Figure 12-10.—"Picture rock". Polished surface of weathered volcanic rock, Hope slide area, southwestern British Columbia.

Figure 12-11.—British Columbia gold nugget jewelry: A. Gold assay button, B. Watch chain, C. Watch fob, D. Pendant, E. Tie pins, F. Flat nugget, G. Initial pin made of small nuggets.

been found in California in gold placers. One must not be too dogmatic in coming to conclusions about the possible occurrences of gemstones nor for that matter about anything in geology.

As more people have more leisure time and penetrate the more inaccessible areas of this large province, more gem materials will be found and the industry will continue to grow.

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APPENDIX

Jade producers of British Columbia, 1974 (latest list available from British Columbia Department of Mines and Petroleum Resources):

Cassiar Lapidary, Cassiar
Ben Seywerd, Seywerd Creek, Dease Lake
Continental Jade Ltd., Mount Ogden
Comaplex Resources International Ltd., Marshall Creek
New World Jade Ltd., 1696 West First Avenue, Vancouver
Delphi Resources Ltd. and Nephro-Jade Canada Ltd. 4458 West Tenth Avenue, Vancouver
Frobex Limited, 902, 8 King Street East, Toronto, Ontario.

LIMESTONE RESOURCES OF SOUTHWESTERN BRITISH COLUMBIA

Wilbert R. Danner

ABSTRACT

Limestone in economic quantity and quality is found on Vancouver Island, Texada Island, Chilliwack, Clinton-Cache Creek, and Kamloops areas in southwestern British Columbia. The deposits are of Pennsylvanian, Permian, and Triassic ages and seem to represent banks formed on island arcs and possibly an oceanic ridge. Pennsylvanian deposits that formed in the island-arc environment have more argillaceous facies than those of other ages. Triassic deposits are locally sandy. Geologic age correlates fairly well with quality. Secondary geologic pollution by volcanic dikes and sills, pluton intrusions, dolomitization, and chertification is prevalent in many of the areas. The major use of limestone is for cement manufacture. Small deposits of Holocene fresh-water marl and calcareous tufa have been exploited from time to time for agricultural purposes. Economic development is dependent upon nearness to population centers, accessibility, and water transportation. Thus Texada Island deposits are the most important and supply limestone also to the northwestern United States. Development of inland deposits for local use is now taking place.

INTRODUCTION

Limestone resources are becoming of increasing importance in southwestern British Columbia. The major uses are for the production of portland cement and lime. Chemical purity, size of the deposit, and location near population centers and transportation facilities are the criteria for development. Location on tide water is important for local transportation and for export. Descriptions of individual deposits have been published by the Canadian Federal Government (Goudge, 1945) and by the British Columbia Department of Mines and Petroleum Resources (Mathews, 1947; Mathews and McCammon, 1957). From time to time descriptions of individual deposits are published in the annual volumes of "Geology, Exploration and Mining in British Columbia" and "Geological Fieldwork" published by the British Columbia Department of Mines and Petroleum Resources. This paper will concentrate on some of the regional geological aspects that have a bearing on the quality and occurrence of the limestone resources.

GEOLOGIC AGE AND ORIGIN OF THE LIMESTONE BODIES

The largest limestone bodies in southwestern British Columbia are of Pennsylvanian, Permian, and Late Triassic ages. They occur in four distinctive geologic provinces (plate tectonic units), each of which has its own geologic history (Fig. 13-1). To the west is the Vancouver Island-Sicker-Karmutsen province; east of it on the mainland is the Cascade Mountain-Chilliwack province. To the north and east is the Cache Creek-Tethyan province, and east of it is the Kamloops-Harper Ranch province. The last is believed to be an offset part of the Cascade Mountain-Chilliwack province. The distinctive differences between these areas in their stratigraphy, structure, and faunas indicate that they were separate tectonic units, which originated in the Pacific Ocean as island arcs or ridges. The Vancouver Island-Sicker-Karmutsen province, on account of its Australian-Timor fauna (Fritz, 1932; Crockford, 1957) and from Triassic paleomagnetic evidence (Irving and Yole, 1972), seems to have originated in the southern hemisphere. In Jurassic time it became a part of North America. The Cache Creek-Tethyan province may represent a part of the Permian Tethyan equatorial belt. After the Permian it drifted northeastward to also join North America in Jurassic time. It extends for a great distance along the western part of North America from California to Alaska, and its Permian limestone strata contain the very distinctive fauna of large Tethyan fusulines not found elsewhere in North America. The Cascade Mountain-Chilliwack and Kamloops-Harper Ranch provinces contain a "foreign" fauna and seem to have developed in a less tropical climate than the Tethyan belt. The Kamloops-Harper Ranch province Paleozoic rocks are overlain by a widespread Upper Triassic sequence (Nicola Group) containing coral reefs and reef faunas similar to those of the present-day South Pacific. Tozer (1970) suggested on faunal grounds that the warm-water Triassic limestone strata of the western Cordillera were originally deposited south of the latitude of contemporaneous rocks in the eastern Cordillera. All of these provinces moved eastward and northward with the spreading of the Pacific Ocean plate and collided with North America during Jurassic time as North America drifted northwestward after the

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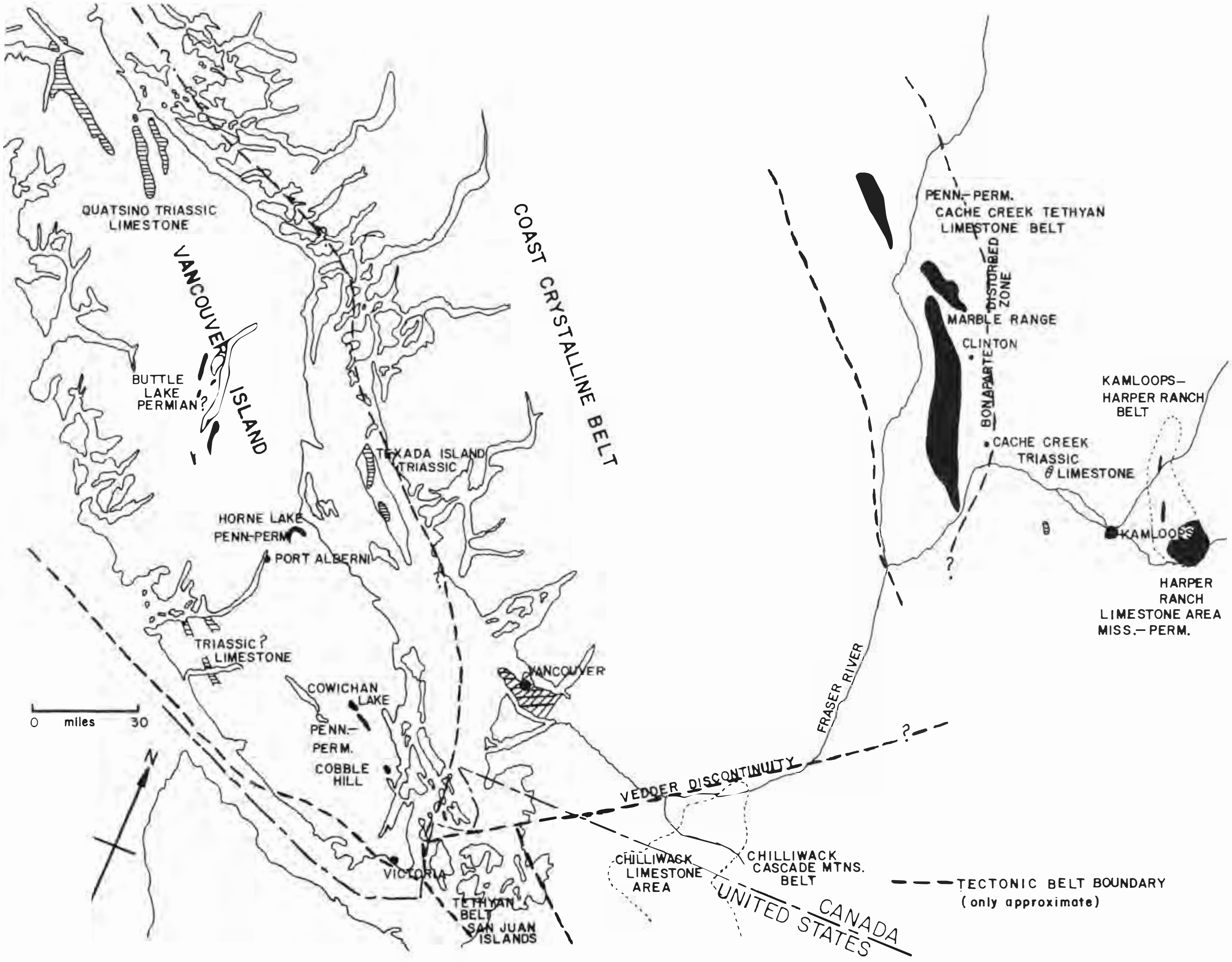

Figure 13-1. –Limestone areas in southwestern British Columbia.

opening of the Atlantic Ocean. The western Cordillera of North America is an example of a unique type of plate tectonics not so far noted elsewhere in the world. It is composed of at least four long narrow tectonic and stratigraphic packages, which have collided and crumpled against the North American craton (Fig. 13-2). After their consolidation with North America, continued northward plate motions ripped asunder parts of the ancient belts and the younger tectonic-stratigraphic sequences deposited on and against them. The process is still going on along the San Andreas fault in California and along faults in Alaska. In recent years more and more geologists have referred to the western Cordillera as the "exotic belt", and over the years many geologists working in the area have been puzzled by the evidence of what was to be later called plate tectonics, as they were unable to explain what they saw on the basis of a "complete continent" North American geological history.

Many years ago I jokingly told an audience that I thought western British Columbia "was made in Japan". Today I would say probably not Japan but perhaps we are made up of parts of Borneo or the Philippines and Timor and other places in the Pacific. The plate tectonic story of the western Cordillera is an exciting one and is perhaps best deciphered by study of its limestone units. It behoves all "plate tectonic" geologists to give more time and energy to studying these rocks, which are so important for deciphering geologic history as well as being the most important of all rock materials for industrial use.

It is important to realize that none of the limestone-bearing areas of southwestern British Columbia were part of North America before at least mid-Mesozoic time. Their geologic history and stratigraphy have no relationship to North American continental geology before that time. Their limestone deposits were formed in the Pacific Ocean far from North America. After they became part of continental North America, marine environments in the western part of the continent were smaller, and rapidly filling successor basins dominated the tectonic picture. Limestone formation did not have much of a chance with the rapid influx of clastic debris. No economic limestone deposits were formed in British Columbia after mid-Mesozoic time. A few small limestone deposits of Cretaceous and Cenozoic ages were formed along the Pacific Coast in the United States and in California and probably also in western Washington. Mesozoic limestone strata that formed out in the Pacific were brought up against the continent in subduction zones and melanges.

VANCOUVER ISLAND-SICKER-KARMUTSEN LIMESTONE

The westernmost plate tectonic province includes Vancouver Island, Texada Island, and smaller islands in Georgia Strait between Vancouver Island and the mainland. The major limestone units are the Sicker Group (Pennsylvanian-Permian) and the Quatsino Limestone, Sutton Limestone, and Marble Bay Formation of Late Triassic age. Sicker Group limestone crops out in the central part of Vancouver Island, and the largest outcrop areas are Buttle Lake (Fig. 13-3), Horne Lake (Fig. 13-4), and Cowichan Lake. Smaller areas of Sicker limestone extend to the north and south of these three main areas. The inland location of these deposits tends to make them expensive to develop. The limestone bodies are generally lenticular and range from a few square feet in area to several square miles. Small limestone bodies on northern Vancouver Island and on north Ballenas Island contain middle Pennsylvanian fossils. Pennsylvanian fossils are also known from the Cowichan Lake and Horne Lake areas, but how much of these larger limestone masses is Pennsylvanian and how much is Permian is as yet unknown (Yole, 1963; Muller, Northcote, and Carlisle, 1974; Sada and Danner, 1974). Sicker Group limestone is composed in large part of crinoid columnals and plates. Brachiopods and bryozoans are abundant in some outcrops, but corals and fusulines are rare. The fauna indicates a relatively cool water environment. Secondary chert nodules (Fig. 13-5, 13-6) and silicification of fossils are common, and chert is a major impurity in many parts of the Sicker limestone. The beds have been intruded by sills and dikes of the younger Karmutsen volcanic rocks (Triassic), but large parts of the limestone seem to be free of such intrusions. Limestone in the Sicker is high-calcium grade and generally contains less than 1 percent magnesium. Exploitation of the limestone has been virtually confined to southern Vancouver Island, where British Columbia Cement Company is operating a major quarry at Cobble Hill for cement raw materials for their plant at Bamberton. Production in 1974 was 763,694 tons.

TRIASSIC LIMESTONE

The most important limestone deposits, economically, in southwestern British Columbia are those of the Marble Bay Formation (Triassic) on the northern part of Texada Island in the Strait of Georgia. The limestone

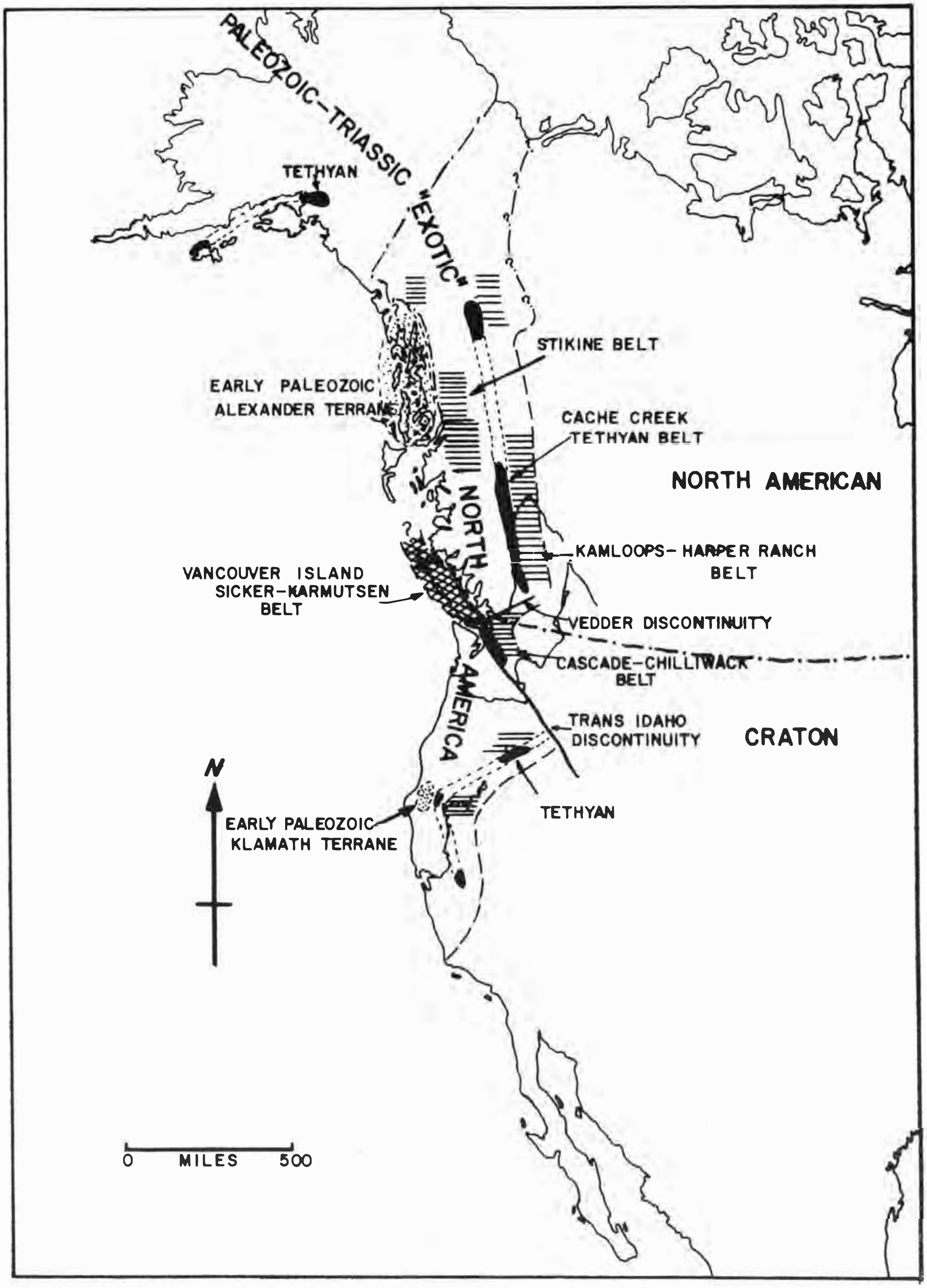

Figure 13-2. –Paleozoic-Triassic tectonic belts, "exotic" western North America.

Figure 13-3. –Permian? limestone of the Sicker Group exposed on ridge south of Mt. McBride, west of Buttle Lake, Strathcona Provincial Park. Overlain by Karmutsen volcanic rocks (Triassic). View looking west, August 1972.

Figure 13-4. –Pennsylvanian-Permian limestone intruded by Triassic gabbro sills on Mt. Mark, north side of Horne Lake. View looking north, September 1957.

Figure 13-5. –Secondary chert nodules formed along bedding and along jointing, Sicker Group limestone on ridge west of Buttle Lake, Vancouver Island.

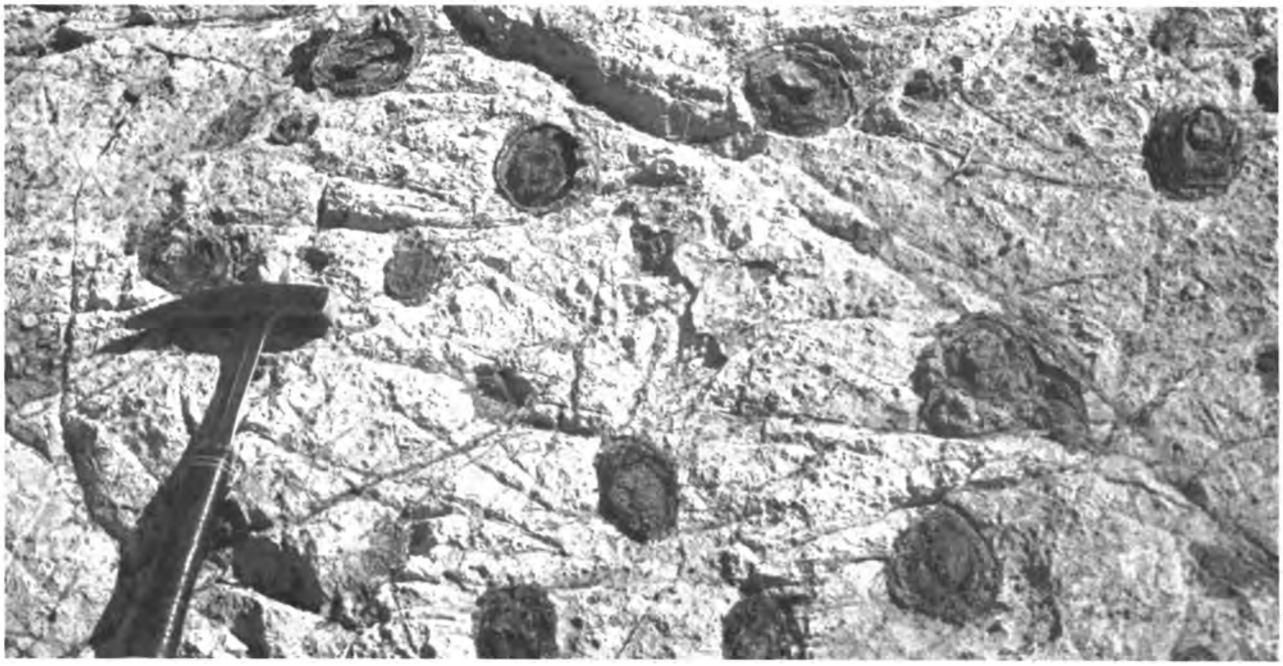

Figure 13-6. –Secondary chert nodules replacing algal? or sponge? structures, Sicker Group limestone on ridge west of Buttle Lake, Vancouver Island.

ranges in composition from high-calcium to dolomitic and is exposed in the central part of a northerly plunging syncline in a belt about 8 miles long and as much as 2 miles wide (Fig. 13-7). The limestone is as much as 2,500 feet thick, and parts of it are intruded by dikes and sills of Triassic volcanic rocks and by stocks of quartz diorite and gabbro. Contact metasomatism along the borders of the plutons has produced skarn zones of garnet, wollastonite, serpentine, and sulphides such as pyrite, chalcopyrite, and bornite. Magnetite occurs in large enough bodies to constitute an ore deposit. One occurrence of native gold has been found in sheared limestone. Faulting and local fold structures complicate the limestone in different quarries, and layers containing excessive magnesium are present. Most of the limestone is dense (micritic), but in a few places it contains fragments of pelecypods, gastropods, and crinoid plates. Corals and ammonites are very rare. Identifiable fossils are scarce, and early descriptions of the geology of Texada Island placed the limestone beds in the Paleozoic. The color ranges from blue gray and light gray to black.

The location of these limestone deposits near or on tidewater has made them the most economic on the Pacific Coast south of the Alaska Panhandle, and limestone from Texada Island is exported in considerable quantity to Seattle and the Portland area. In 1973 the Port of Seattle imported 2.1 million tons of Canadian limestone, which exceeded the tonnage of any other foreign product.

A second area of limestone is found along the west coast of Texada Island in a belt 4 miles long and as much as 1 mile wide; the thickness attains 1,000 feet. The exploitation of this belt is expected to increase in the future.

Companies operating on Texada Island in 1974 were:

Imperial Limestone Company Limited, Seattle, Washington

Ideal Cement Company (Rock Products Division), Vancouver

Canada Cement Lafarge Ltd. (Pacific Region), Vancouver

Domtar Chemicals Limited (Lime Division), Vancouver

Black fetid and argillaceous limestone of Triassic age occurs at Open Bay on Quadra Island. The thickness may reach 500 feet. A kiln existed at this deposit at one time, but seemingly the operation continued for only a brief period.

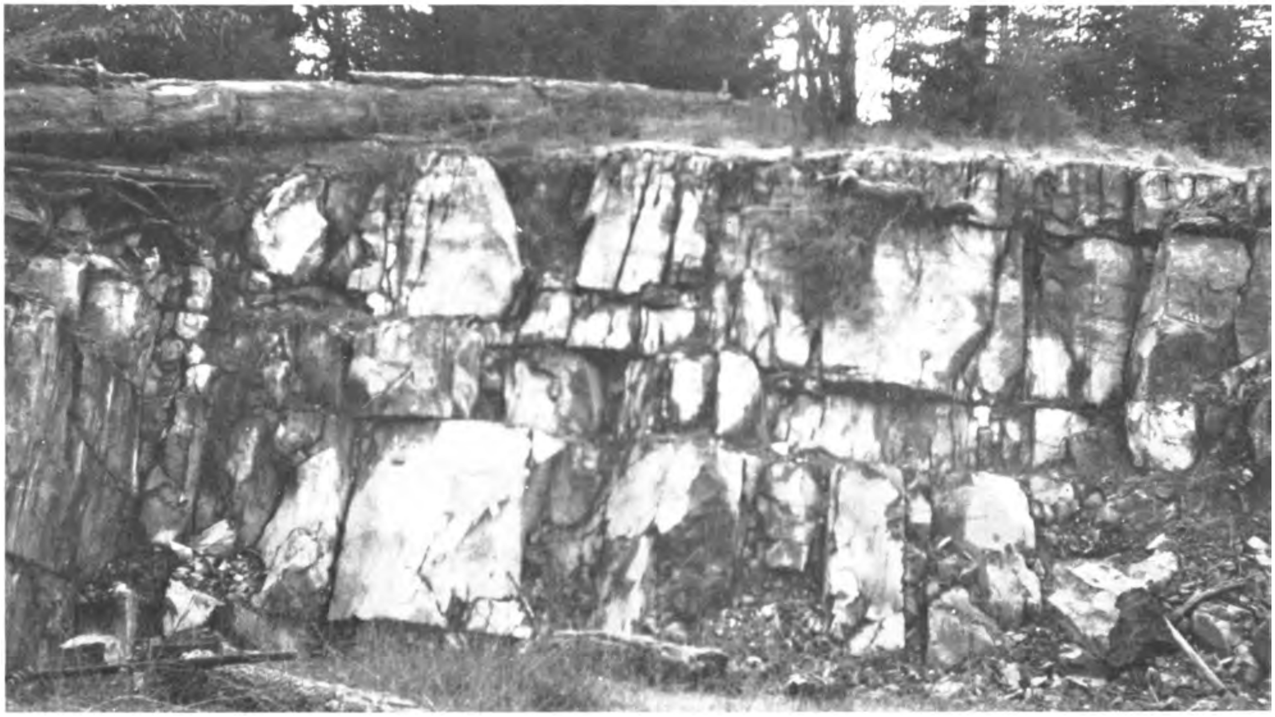

Figure 13-7. –Limestone of Marble Bay Formation (Upper Triassic), Texada Island.

Several small bodies of limestone crop out north and west of Victoria on southern Vancouver Island. Many of these have been quarried for various purposes from time to time but none are large enough to be of economic value today except for decorative stone or for use in rock gardens. They have been referred to generally as "Sutton" limestone and classed as being of Triassic age but their true age is unknown. They are extensively recrystallized. Several large bodies of crystalline limestone are found along the west coast of the southern part of Vancouver Island but very little is known about them. Most are probably of Triassic age. Their location near tidewater offers some economic potential for the future.

The main Sutton limestone crops out on the south shore of Cowichan Lake, where it is richly fossiliferous with reef corals and pelecypods and has a strong bituminous odor when freshly broken. Fyles (1955) found fossil tree trunks, probably of driftwood origin, in the limestone. The maximum thickness is about 500 feet.

Large areas of Upper Triassic limestone of the Quatsino Formation occur on northern and central Vancouver Island. One belt of this limestone has been traced for nearly 75 miles (McCammon, 1968). The limestone is light gray to black and contains sparse fossil remains – crinoid plates and spines and plates of sea urchins, pelecypod and gastropod shells, rare brachiopods, corals, and ammonites. Oolites and pellets occur with the fossils (Fig. 13-8). Much of the limestone is dense and may be an algal precipitate caused by upwelling of cool waters into shallow warm banks. Secondary chert is common, and the limestone is intruded in places by volcanic dikes. Parts are dolomitized. Around intruded diorite plutons, skarn zones and iron and copper mineralization have been found. Because of their location in areas of sparse population remote from industrial areas, only small quarries have been established, and these produce bulk or crushed limestone. Outcrops on tidewater may in the future be of economic value when deposits on Texada Island have become exhausted.

CHILLIWACK AREA

The Chilliwack Valley lies approximately 60 miles east of the city of Vancouver. On the mountains on both sides of the valley are large bodies of Lower Pennsylvanian and Lower Permian limestone of the Chilliwack Group.

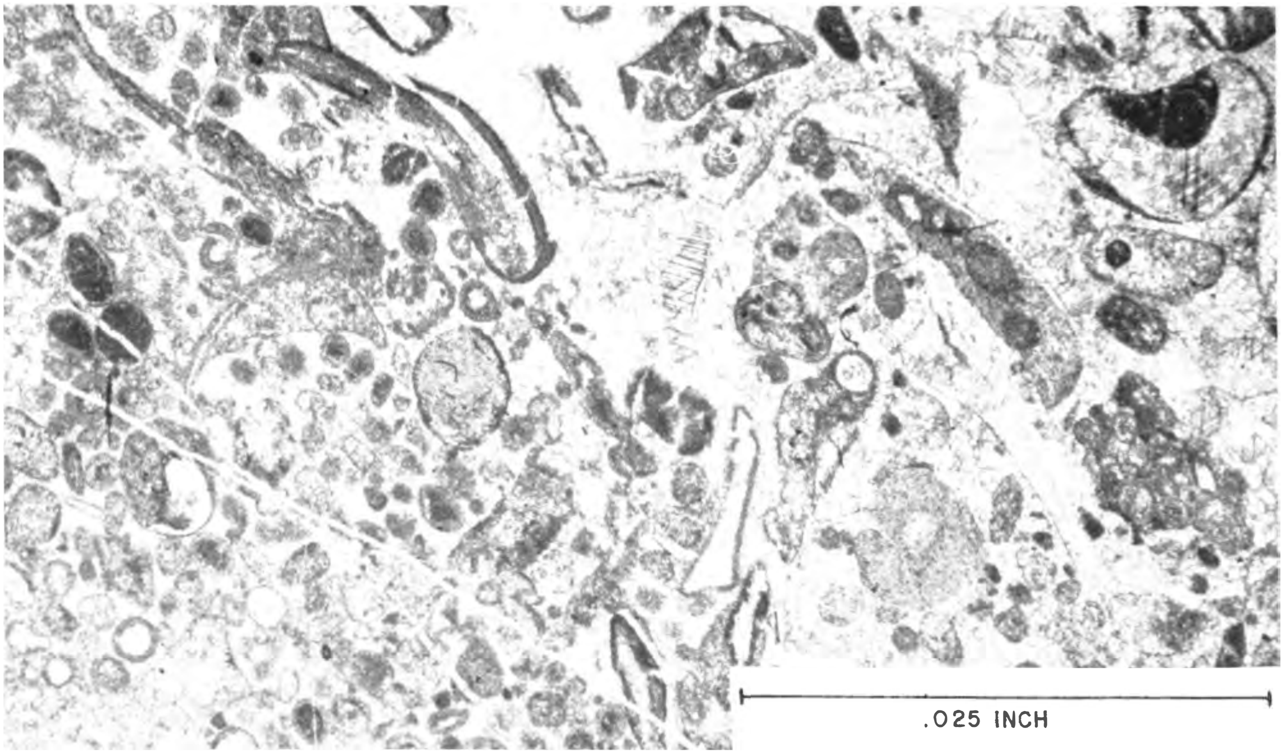

Figure 13-8. –Photomicrograph of thin section of Quatsino Limestone (Upper Triassic), Gordon River, Vancouver Island, Molluscan debris, oolites, and pellets.

Many of these limestone beds are folded and faulted and some are internally folded (Fig. 13-9). They extend north down the steep mountainsides to the floor of the Fraser Valley, and a few small quarries have been established in this area near Popkum and Agassiz. One limestone body is found on the north side of the Fraser Valley southeast of Harrison Lake. To the south of Chilliwack limestone extends across the border with the United States into Washington State, where it has been quarried extensively in many places at low altitudes. The United States deposits have been quarried for use in paper mills and for the cement plant in Bellingham. An increasing market is developing for crushed limestone for roads and paths and for roofing granules. On the American side of the border, limestone beds of Devonian age appear and these, along with limestone of early Pennsylvanian age, may be traced southward in scattered outcrops for a considerable distance to the Skagit River and on into the Cascade Mountains. It is possible that some of these limestone strata may be as old as Ordovician or Silurian (Danner, 1966).

Detailed studies of the Chilliwack Permian limestone strata have shown them to be time transgressive, being younger on the Canadian side of the border and older on the American side. Chilliwack limestone becomes more crystalline eastward, and large areas are dolomitized. Secondary chert is common. Many of the limestone strata are well bedded and argillaceous. The cement plants on the American side use the more argillaceous Lower Pennsylvanian limestone as their source of supply, in part because the beds are of greater thickness and volume. The Pennsylvanian limestone is characterized in many places by very large crinoid columnals (Fig. 13-10) and where not recrystallized it also contains small fusulines and other foraminifera and microfossils. The crinoid columnals are an important stratigraphic marker. The Permian limestone contains abundant large fusulines, rare large horn corals, and bryozoa. Many of the fusulines are silicified. A large part of the Devonian limestone is composed of reefs and reef breccias containing corals and stromatoporoids. Chemically the Devonian limestone, where not silicified or dolomitized, is the purest limestone in the sequence. Limestone of the Chilliwack Group just south of the border shows relatively high concentrations of vanadium (Danner, 1966). Small lenses of limestone are found interbedded with volcanic rocks of Permian and Devonian age in the

Figure 13-9. –Internally folded limestone of Chilliwack Group (Permian) at mouth of Slesse Creek, Chilliwack Valley.

Figure 13-10. –Large crinoid columnals in Lower Pennsylvanian limestone of Chilliwack Group, Cascade Mountains.

Chilliwack Group and are important marker beds in prospecting for ore deposits in the area. One limestone unit in the Liumption Creek area of British Columbia contains abundant clastic quartz grains as an impurity. Its geologic age is unknown but it is probably Paleozoic.

The largest limestone bodies in the Chilliwack area seem to be at higher altitudes and along ridge crests, but several bodies of large size are found in the valley bottom of the Chilliwack River. Small areas of karst topography and a few small caves are found both on the ridge crests and in the valley. As settlement increases up the Fraser Valley and into the Chilliwack Valley these limestone deposits may become of increasing economic importance and could become the basis for local industry.

CACHE CREEK AREA

West of the village of Cache Creek in the southwestern interior of British Columbia is a large area of Upper Permian limestone. It makes up a range of mountains called the Marble Range, which is about 50 miles long. The limestone is called the Marble Canyon Formation and is part of the Cache Creek Group, which forms the long narrow Tethyan belt through the interior of British Columbia. The sequence is characterized by bedded radiolarian chert, basic pillow lava flows, and large masses of pure limestone. The limestone is in part time transgressive, consisting of Middle Pennsylvanian and Lower Permian limestone in the northern part of the Marble Range and the lowlands farther north and of Upper Permian limestone in the main range and the area farther south in Marble Canyon (Fig. 13-11). Small limestone lenses are common interbedded with the chert and volcanic rocks below the main Upper Permian limestone mass in the south, and these lenses contain Middle and Lower Permian fossils. Large Tethyan fusulines are most abundant (Fig. 13-12). Associated with them are other foraminifers and numerous dasycladacean algae. Some of the limestone contains structures similar to stromatolites. Most of the limestone strata are massive and poorly bedded. Much of the rock is recrystallized, but secondary chert and dolomitization are relatively minor. The association of this large volume of high-calcium shallow-water limestone with a thick sequence of radiolarian chert containing limestone interbedded with the chert implies that some radiolarian chert may be of shallow-water origin. The lack of thick clastic sequences in the Cache Creek Group suggests that it was deposited far from the continent and perhaps was a Pacific oceanic ridge. During the Permian the Pacific Ocean was probably twice as wide as today, and this Permian Tethyan belt may have stretched across the ocean near the equator.

A small quarry has been opened in the Marble Range southwest of Clinton on the Kelly Lake Road but it was idle when examined in 1974. A large quarry

Figure 13-11. –Marble Canyon, Marble Range, northwest of Cache Creek. Permian limestone containing Tethyan fusulines.

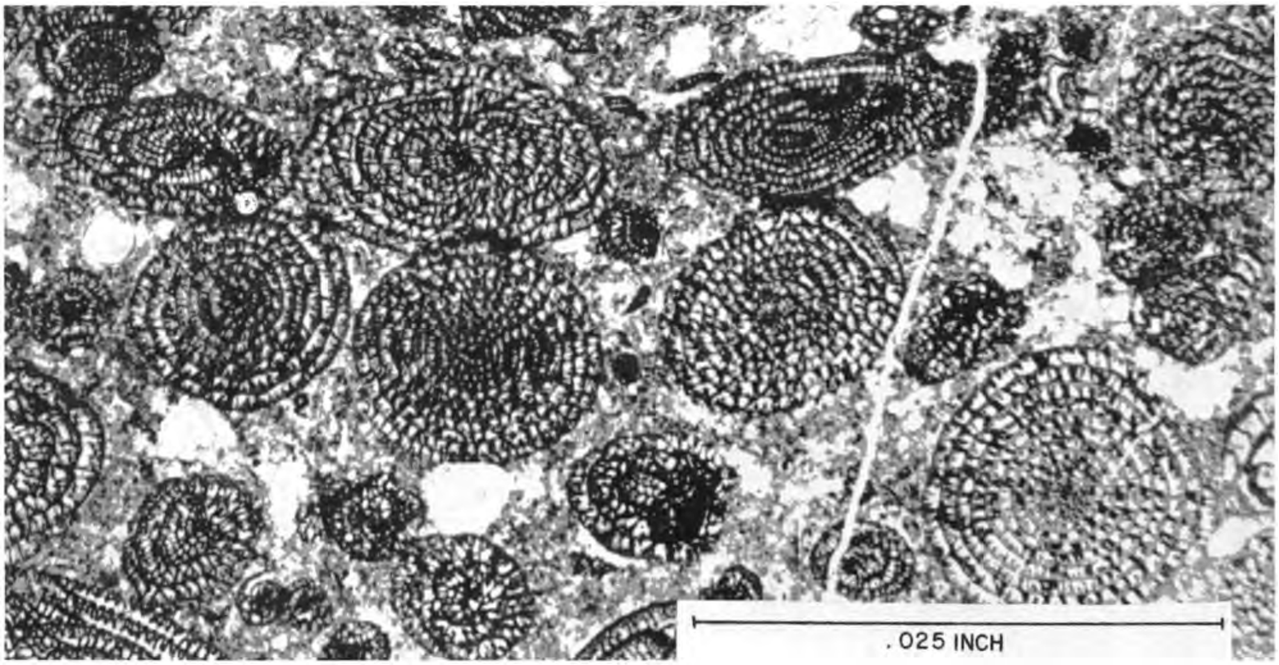

Figure 13-12. –Photomicrograph of thin section of Upper Permian fusuline limestone from Marble Range near Clinton. Tethyan fusuline genus *Yabeina*. Marble Canyon Formation.

has recently been opened in Marble Canyon by Steel Brothers Canada Limited on the Pavilion Indian Reserve. The processing plant was erected and the quarry opened in 1974, and it produced 1,500 tons of crushed limestone per day and 300 tons of quick lime per day in 1975. The limestone averages 98 percent $CaCO_3$ and contains 0.5 to 1.5 percent silica. The development of the Hat Creek Cenozoic coal field just south of the Canyon may bring more industry into the area.

Part of Marble Canyon with its high spectacular limestone cliffs is included within a Provincial Park to preserve part of this limestone terrane and some of the areas of unique vegetation developed on it as well as an area around some of the limestone springs and calcareous tufa deposits.

Some strange structures (Fig. 13-13) are developed in limestone bodies interbedded with chert and volcanic rocks southwest of Cache Creek. They consist of large radiating "blades" of limestone bounded by fractures. One possibility is that they were large crystals of aragonite formed by low-temperature high-pressure regional metamorphism in the prehnite zone. If they were once aragonite, they have now reverted to calcite. Similar structures have been seen in Paleozoic limestone on Orcas Island, Washington, and along Boulder Creek in the Chilliwack area of Washington. In all examples the structures are developed near major faults or zones of disturbance. The limestone bodies north and south of Cache Creek are in an intensely sheared and deformed area (Bonaparte Disturbed Zone), which may be close to the eastern tectonic border of the Tethyan Belt. Numerous bodies of serpentine are present along this zone.

HARPER RANCH

About 50 miles east of Cache Creek in the Kamloops area is a large region of limestone outcrops on the north side of the South Thompson River. The largest limestone area is at the east end of the Harper Ranch. Here Lower Pennsylvanian limestone is overlain with apparent conformity by Lower Permian limestone. The Pennsylvanian limestone is in part well bedded and argillaceous. The Permian limestone is more massive and of better quality. Large crinoid columnals similar to those of the Chilliwack area are common in the Pennsylvanian limestone and serve as a good stratigraphic marker. Along with them are beds of large brachiopod

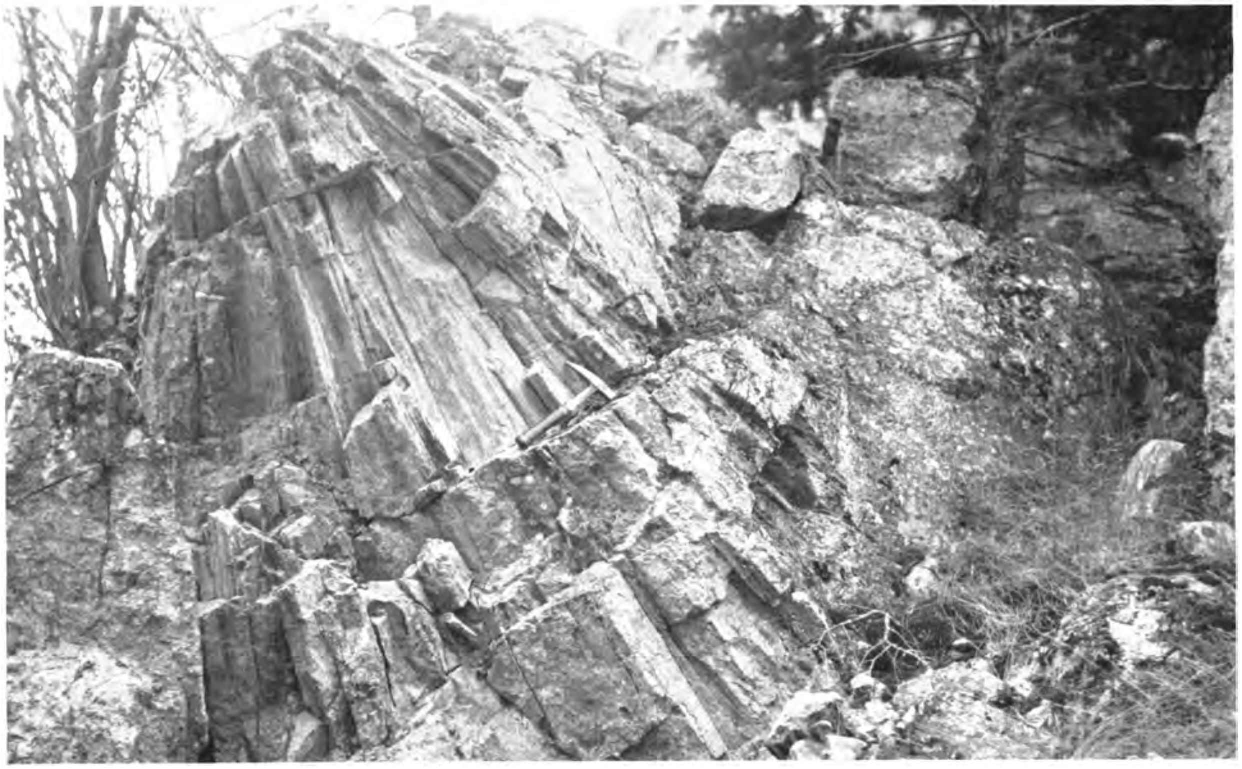

Figure 13-13. –Radiating structure in limestone of Cache Creek Group southwest of Cache Creek.

shells. Small fusulines and other foraminifera are abundant. The Permian limestone contains large fusulines. A few small reefoid bodies are found in the Pennsylvanian. The sequence is overlain unconformably by Triassic sedimentary and volcanic rocks and locally by Tertiary volcanic rocks. Parts of the basal Triassic sequence are composed of pink clastic limestone and light-gray limestones containing numerous chert grains.

Northwest of the Harper Ranch in the Dome Hills is a large ridge of limestone more than a mile in length containing fossils of latest Mississippian age. It contains minor amounts of secondary chert and silicified brachiopods and corals. Smaller limestone lenses to the west seem to be exotic blocks enclosed in a Triassic clastic sequence. One of these limestone blocks is upside down and contains the early Permian-early Pennsylvanian disconformity running through it.

The limestone in one small outcrop near the ridge crest east of Mount Harper contains middle Permian fusulines and is the youngest Paleozoic limestone in the area.

The large area of Pennsylvanian-Permian limestone at the east end of the Harper Ranch is now being quarried to supply a cement plant (Fig. 13-14) of Canada Cement Lafarge along the South Thompson River below the limestone outcrop. The quarry has so far been developed only on the Permian limestone. This plant, built in 1970, uses the dry process and has a capacity of 210,000 tons. Further development of limestone resources in this area is possible, though the largest bodies lie at higher altitudes. Large limestone cliffs and knobs form attractive scenery in the vicinity of Paul Lake to the north and should remain undisturbed. The limestone ridge in the Dome Hills could be developed, but the limestone would have to be transported southward because of more gentle slopes and nearness to market. Part of this limestone is on Indian Reserve lands.

TRIASSIC LIMESTONE

Small areas of Upper Triassic limestone are found in the Nicola Formation in the Kamloops area and west and also to the north and south. Most of these bodies are small and of only minor if any economic importance. Many of them are composed of reef corals and spongiomorphs and probably represent fringing reefs around the Triassic island-arc volcanoes (Fig. 13-15). Some bodies of Triassic lime-

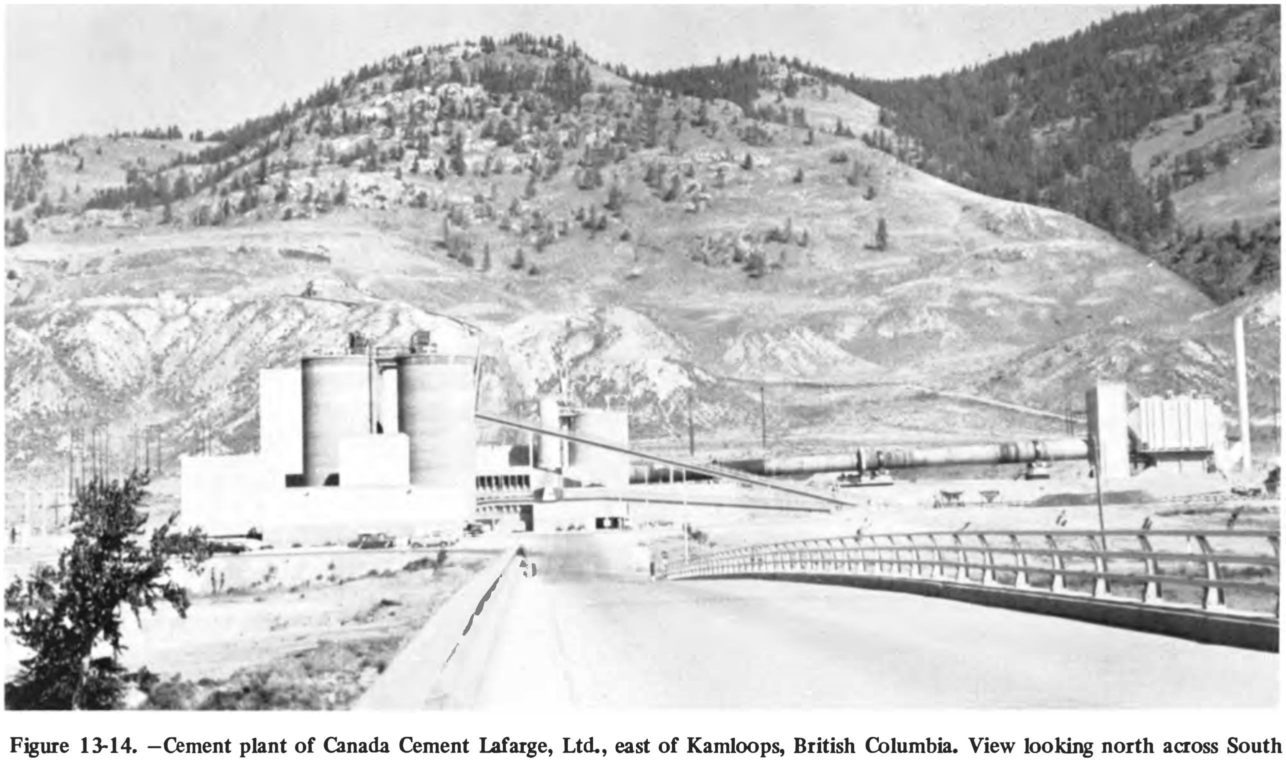

Figure 13-14. —Cement plant of Canada Cement Lafarge, Ltd., east of Kamloops, British Columbia. View looking north across South Thompson River, August 1974. Hillside above plant composed of Lower Permian limestone of Harper Ranch sequence.

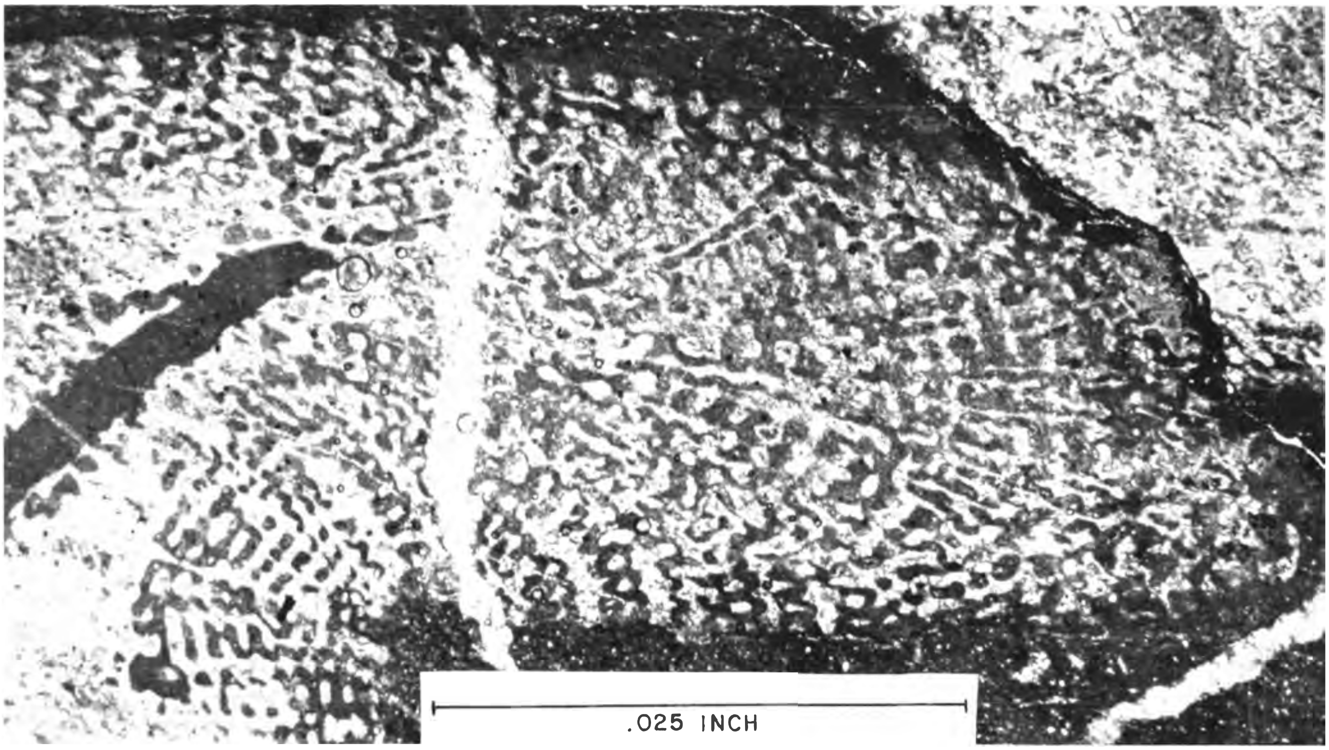

Figure 13-15. –Photomicrograph of thin section of spongiomorph limestone, Nicola Group (Upper Triassic).

Figure 13-16. –British Columbia Railroad cut through Clinton tufa deposit 3 miles west of Clinton, August 1974.

stone contain layers of pelecypod shells and remains of brachiopods, crinoids, and sea urchins. Bodies of micritic texture, which seem to be of deeper water origin, may have formed in basins between islands. Much of the Nicola Group limestone contains chert granules and pebbles.

TUFA AND MARL DEPOSITS

A deposit of calcareous tufa is located at the base of the Marble Range west of Clinton in the Tethyan belt. The British Columbia Railroad cuts through the deposit (Fig. 13-16), which is along the highway from Clinton to Kelly Lake. The deposit was operated for agricultural lime from 1947 to 1953, but there has been no quarrying in recent years, although considerable tonnage remains. The tufa is white, compact, and porous. Well-preserved layers of fossil leaf molds are found in some parts of the deposit. It would be of value for use in rock gardens and as decorative stone.

At least two small tufa deposits have been quarried in the vicinity of Rosedale on the south side of the Fraser River east of Chilliwack. The tufa has precipitated from springs coming out of the Chilliwack Group. The product from these quarries was used for agricultural purposes and for feed supplement. The operations proved to be uneconomic, and both deposits are now idle. In recent years some stone has been removed for rock gardens.

Cheam Lake, 9 miles east of Chilliwack in the Fraser Valley, has long been quarried as a source of marl. The lake level has been lowered and parts of the lake have been drained. The deposit is reported to be 4 to 12 feet thick and consists of light-gray clay-like material containing small gastropod and pelecypod shells. The quantity available is unknown. The marl is removed by dragline and spread on an asphalt drainage pad and air dried for one year. It is used for fertilizer in the Fraser Valley and across the border in Washington State. In 1974 the production was 18,412 tons and shipments totaled 14,889 tons.

The source of the marl is probably the calcium-rich streams draining the Chilliwack Group rocks to the south and flowing into Cheam Lake.

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