

INDUSTRIAL MINERALS IN MONTANA

Richard B. Berg¹ and Christopher H. Gammons²

¹*Montana Bureau of Mines and Geology, Butte, Montana*

²*Department of Geological Engineering, Montana Technological University, Butte, Montana*

*With a Special Contribution on Talc and Chlorite Deposits by:
John F. Childs, Childs Geoscience, Inc., Bozeman, Montana*

INTRODUCTION

In the discussion of mineral deposits, mineral commodities are generally divided into three groups: mineral fuels, metals, and industrial minerals (sometimes also called nonmetallics).

Mineral fuels include oil and gas, coal, and uranium minerals, and **metals** are those minerals mined for specific metals. The rest are **industrial minerals**, which are often divided into specialty minerals and mineral commodities such as fertilizer minerals (phosphate and potash) and construction materials. Specialty minerals, such as talc, ground calcium carbonate, diatomite, certain clays, and wollastonite, have physical properties that qualify them for certain markets. Other minerals or rocks such as salt, soda ash, boron, and sulfur fall into the specialty minerals category because of their importance in chemical/manufacturing processes. Gemstones, obviously, are valued for their unique beauty and rarity.

Transportation costs are a major factor in marketing industrial minerals. Construction materials are usually sold only locally because of low value and large tonnage. Specialty minerals typically command a higher price than the commodity industrial minerals, so are less restricted by transportation costs.

The following summary of industrial minerals in Montana is devoted to the geologic occurrence of previously or currently mined industrial minerals, as well as those with potential for future development. Several industrial mineral commodities mined in Montana within the past 50 years are no longer produced because of foreign competition, health concerns, or associated mining and transportation costs. Examples include fluorspar, vermiculite, phosphate, silica, and barite. Typically, new mining ventures in industrial minerals are driven by new markets, in some cases developed by the producers themselves.

Figure 1 shows some Montana geologic features and formations that are mentioned in the text. It must be noted that this chapter was written during late 2017 and includes information and references as of that date.

AGGREGATE

Sand and gravel deposits are generally extensive throughout the State, but because of differing source rocks and proximity to use areas, the deposits may have unpredictable value beyond local use. Those deposits derived mainly from quartzite of the Belt Supergroup are suitable for concrete aggregate. In northeastern Montana, north of the Missouri River, well-sorted gravel deposits above any modern floodplain and outwash deposits from continental glaciers provide aggregate resources. Western Montana has ample gravel deposits suitable for aggregate for the foreseeable future. High-quality gravel deposits in eastern Montana are more limited; however, scoria formed by the fusing of shale beds that overlie burned coal beds finds local application in surfacing roads.

Because of the general abundance of sand and gravel deposits in Montana, crushed stone is a minor source of aggregate, with the exception of specialized uses such as railroad ballast where a higher degree of durability is required. Fine-grained diorite is quarried a short distance east of Butte for this use. Other igneous rocks, such as shonkinite and basalt, as well as sandstone and metasedimentary rock of the Belt Supergroup, are intermittently quarried and stockpiled for construction markets (Garrett Smith, written commun., 2017). Transportation costs will ultimately limit how widely aggregate from any source can be successfully marketed.

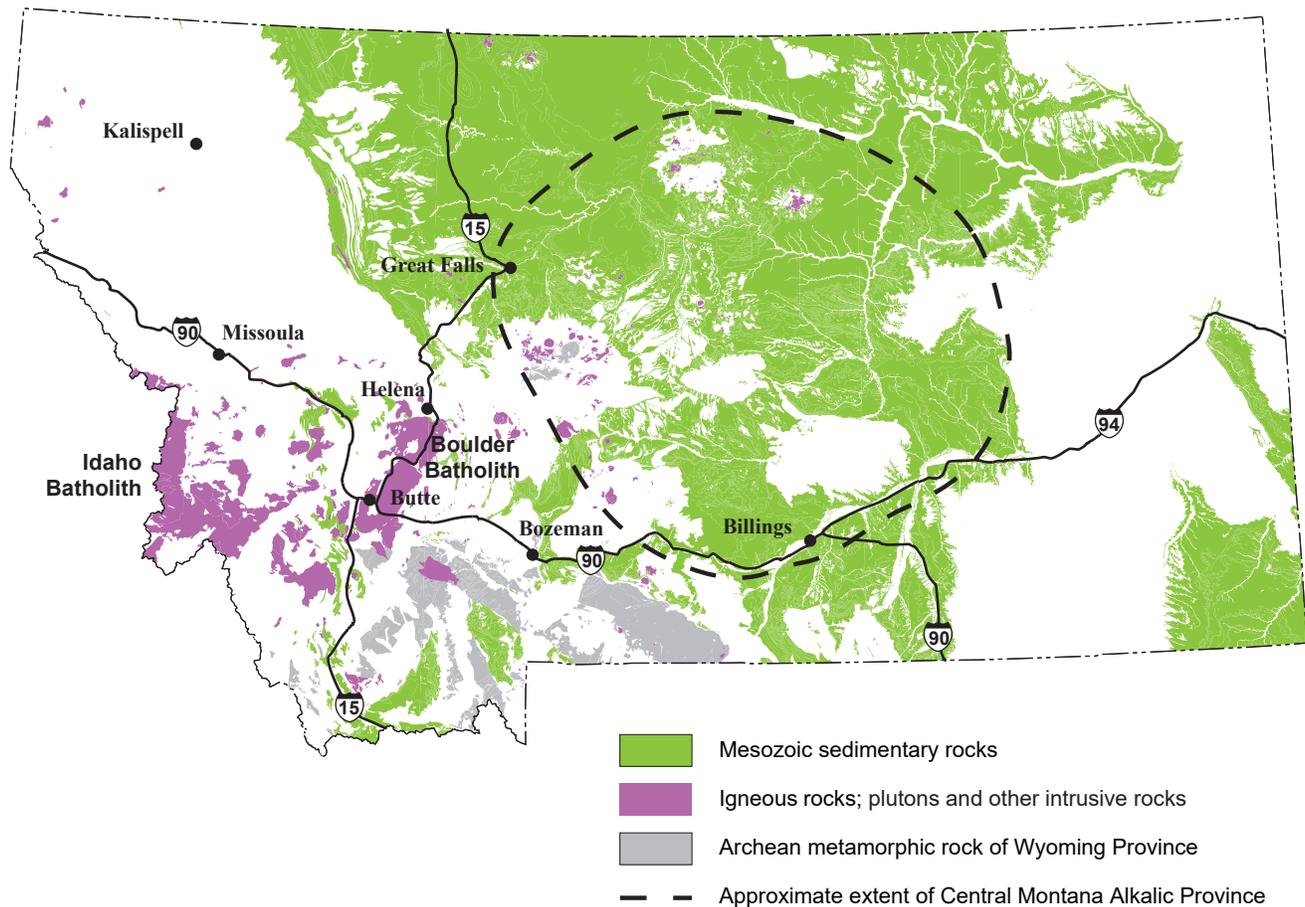


Figure 1. Simplified geologic map showing geologic features mentioned in text. Modified from Vuke, 2015.

BARITE

More than 80 percent of Montana barite deposits, and all of those that have been mined, occur as veins in metasedimentary rocks of the Proterozoic Belt Supergroup, mainly in the Missoula Group. The mineralogy of these veins consists of coarse-grained white barite with quartz and fragments of country rock as impurities. Occurrences range from veinlets only a few centimeters thick to a vein in the Elk Creek–Coloma district 35 mi east of Missoula that reportedly ranges up to 27 ft thick (fig. 2). Berg (1988) suggested that metasedimentary beds of the Belt Supergroup were the source of barium. Mudge and others (1974) stated that these beds contain 3,000 to 5,000 ppm Ba as stringers and veinlets. It seems likely that remobilization of Ba from these sources was responsible for the formation of mineable, vein-barite deposits. Most Montana barite was used as a weighting agent in drilling mud, where, because of its purity, only drying, pulverizing, and bagging were necessary.

CLAYS

Bentonite

Major clay resources in Montana including brick clay and bentonite occur in Mesozoic sedimentary rocks (fig. 1). There are two major sources of bentonite in Montana: Tertiary formations exposed in the intermontane basins of southwestern Montana and marine Cretaceous formations exposed in central and eastern Montana (Berg, 1969). The Tertiary sediments contain bentonite suitable for lining irrigation ditches and similar uses, but are generally of the Ca-rich, low-swelling variety and contain too much non-colloidal material for most applications. Ca-bentonite was mined in a small pit just north of I-90 between Butte and Anaconda and used to line cyanide heap-leach pads at the nearby Beal Mountain gold mine to the west.

Knechtel and Patterson (1956, p. 48) identified numerous Cretaceous bentonite beds in the Belle Fourche, Mowry Shale, and Newcastle Formations in the Montana part of the Hardin district southeast of Billings. They tentatively estimated bentonite resour-

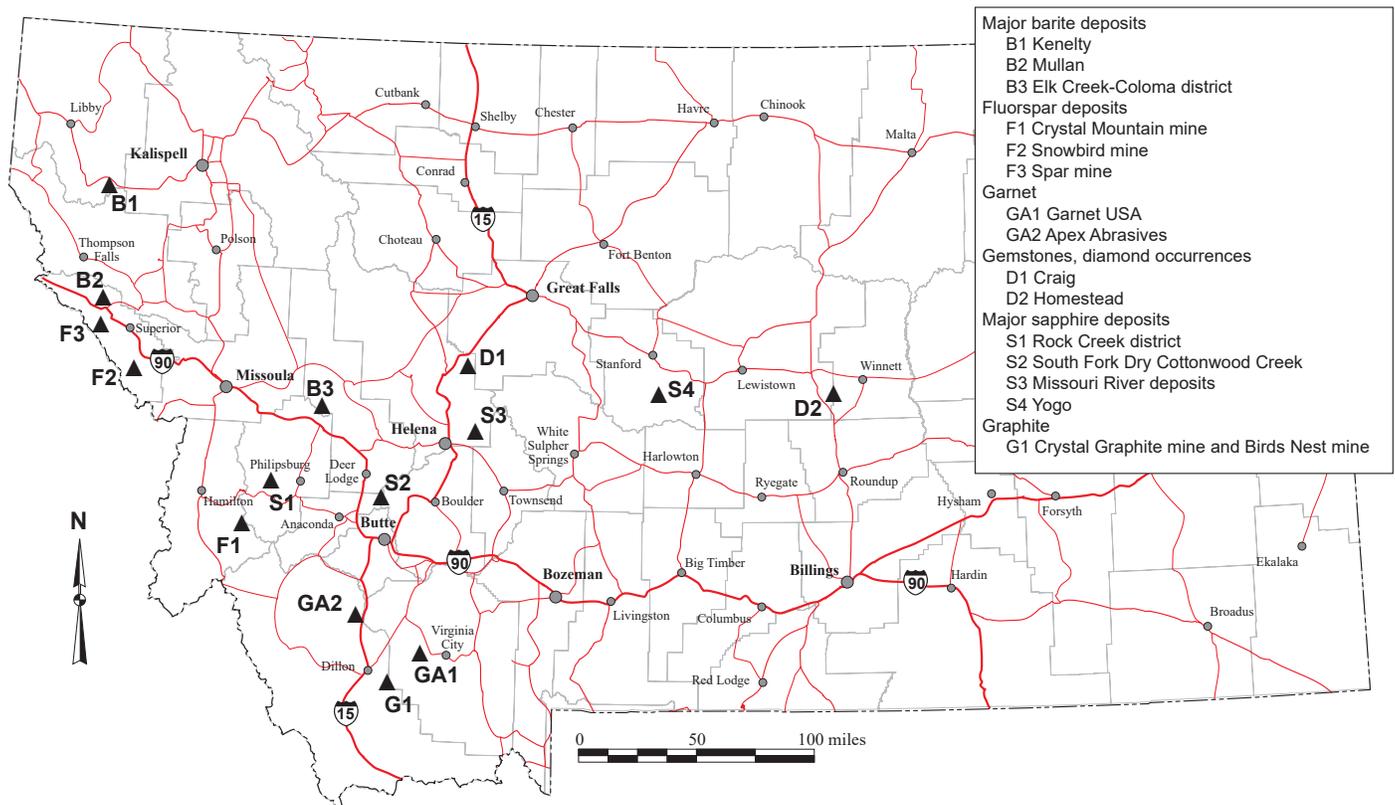


Figure 2. Barite, fluorspar, garnet, gemstone, and graphite deposits and occurrences.

es in this area of 108 million tons, with the majority occurring as low-swelling and low-viscosity bentonite in the Belle Fourche Formation. In Rosebud County, northwest of Forsyth, two bentonite beds 3 to 4 ft thick in the lower part of the Bearpaw Shale were mined for a brief period in the 1970s (Berg, 1970). These appear to be the same two beds that crop out in Blaine, Phillips, and Valley Counties in northern Montana, where they were also mined during the 1970s. The very productive Clay Spur Bed of the Mowry Shale in the Black Hills bentonite district extends into southeastern Montana, where it has been extensively mined since the mid 1930s (Knechtel and Patterson, 1962, p. 971). More recently, the younger F and G bentonite beds in this same formation have also been mined in the northern Black Hills district in southeastern Montana (Richard Brown, written commun., 2017).

Extensive mining continues on at least five bentonite beds in the Frontier, Mowry, and Thermopolis Formations in the north end of the Big Horn Basin southeast of Warren, Montana. Bentonite beds in the Belle Fourche and Mowry Formations are exposed north of Warren, close to Wyoming and southwest of Billings. Wolfbauer (1977) presented a tabulation of exchangeable cations in bentonite from Montana and

Wyoming and correlated these values with physical properties. Frahme (1978) provided locality information for these samples.

Expandable Shale

Some marine Cretaceous shales expand when heated in a kiln to make a lightweight aggregate. The Blackleaf Formation was a source of expandable shale in the Great Falls area (Sahinen, 1957), and other clay deposits in Montana were mined for this market.

Brick Clay

Around 100 years ago, most cities in Montana had a brick plant using local clay, and also had a brewery. The breweries have come back, but not the brick plants. Clay was mined from beds in the Morrison Formation (Jurassic) and overlying Kootenai Formation (Cretaceous) for manufacture of brick and other structural clay products. Kaolinite clay was mined from beds near the base of the Kootenai Formation near Great Falls. The Montana Bureau of Mines and Geology analyzed more than 700 samples of clay and shale from Montana, describing their ceramic properties, mineralogy, bulk chemical composition, and suitability for lightweight aggregate (Berg, 2011).

Kaolinite

The largest known kaolinite deposit in Montana is the Whiteware deposit situated 8 mi northwest of Lewistown in the South Moccasin Mountains. This deposit of the dickite polytype formed by hydrothermal alteration of shale and sandstone of Cretaceous or Pennsylvanian age next to Tertiary intrusives (Dougan, 1947). In addition, kaolinitic sandstone in the Cretaceous Whitemud Formation of southern Saskatchewan has been investigated as a potential source of kaolinite (Pruett and Murray, 1991). The Whitemud Formation is equivalent to the Colgate Member of the Fox Hills Formation in northern Montana.

DECORATIVE STONE

In common with many states, the stone industry of Montana has changed dramatically from an industry dominated by granite quarries in the Butte and Helena areas that produced dimension stone, to a fragmented industry that produces a variety of decorative stones. Metasedimentary beds in the Proterozoic Belt Supergroup yield thinly bedded material for facing and thicker bedded material used in fireplaces and walls. Boulders from alluvial deposits, often from abandoned placers, also have a market and are referred to as river rock in the industry. Some Cretaceous sandstone in central Montana with well-spaced joints that produce roughly rectangular blocks is used in facing. Collecting granite boulders and unusual boulders weathered from quartzite beds in the Belt Supergroup to be used in landscaping has become a cottage industry in the past several decades, to the extent that it has demanded the attention of federal land management agencies. Travertine was formerly quarried from deposits in the Gardiner area north of Yellowstone National Park and also to a lesser extent from other Montana deposits (Berg, 1974).

FLUORSPAR

The geology and economic potential of fluorspar deposits of Montana was summarized by Ross (1950), Sahinen (1962), and Geach (1963). These works indicate concentrations of fluorspar (the mineral fluorite, CaF_2) are mainly restricted to three igneous provinces: (1) the Idaho Batholith; (2) the Boulder Batholith; and (3) igneous rocks of the Central Montana Alkalic Province (CMAP, fig. 1). Of these, the Idaho Batholith is host to the most significant deposits. Between 1952 and 1986, metallurgical-grade fluorspar was mined at a modest scale from the Crystal Mountain deposit in the

Sapphire Mountains, Ravalli County (fig. 2). This deposit consists of tabular masses of fluorite associated with granite pegmatites and small bodies of melagabro distributed about a larger pluton of granodiorite that cuts metamorphosed Belt sediments (Taber, 1952; Foord and others, 1993). The deposit is host to several rare minerals, including thortveitite $[(\text{Sc}, \text{Y})_2\text{Si}_2\text{O}_7]$, fergusonite (YNbO_4), thorite, and the rare earth minerals allanite-(Ce), and xenotime (Foord and others, 1993). A small amount of scandium was recovered in the 1990s by reprocessing of mill tailings from Crystal Mountain (Hedrick, 2001). Other occurrences of fluorite in the area include the Snowbird and Spar deposits in Mineral County (fig. 2). The Snowbird deposit is also notably enriched in rare earth elements found in parisite and xenotime. Originally thought to be a carbonatite, more recent work has shown that the Snowbird deposit is hydrothermal in origin (Samson and others, 2004). According to Geach (1963) and earlier workers, Boulder Batholith and CMAP deposits have low potential for a mineable fluorspar resource.

GARNET

Many of the Archean metamorphic rocks of southwestern Montana are rich in garnet, and garnet has intermittently been produced (fig. 1; and Van Gosen and others, 1998b). More recently, Garnet USA has opened a large-scale, bedrock garnet mine in the foothills south of the town of Alder. Garnet-rich rock types include "dark ore," which is a garnet-rich hornblende amphibolite, and "light ore," which is a garnet-bearing quartzite. No gem-quality garnets exist at the mine: the garnets are typically opaque and/or riddled with inclusions of quartz and other minerals.

In southwest Montana near Glen, tailings from a tungsten mill that processed skarn tungsten ore were reprocessed for andradite garnet by Apex Abrasives (fig. 2). Their product was sold for water-jet cutting. Although andradite garnet is of slightly lower density than almandine, this skarn garnet performed well in the market (Gene Nelson, oral commun., 2018).

GEMSTONES

Diamond

The only diamond found in place in Montana is a very small (0.14 x 0.16 x 0.32 mm) diamond recovered by caustic fusion from a 98.8 lb sample from the Homestead kimberlite (fig. 2, and Ellsworth, 2000). The Homestead kimberlite is in the Grass Range dia-

tre field 25 mi east of Lewistown, situated within the Archean Wyoming Craton. In 1990, a 14-carat diamond was found by a woman walking along a gravel road near Craig between Helena and Great Falls (fig. 2, and Zeitner, 1991). Gravel believed to have been used in surfacing this road was examined, but no other diamonds were found. Although there are other accounts of diamonds being found in Montana, none of these reports has been substantiated. A lamproite plug along Bear Gulch west of Drummond was explored for diamonds without success (Irving and Hearn, 2003).

It is interesting to note recent discoveries of Cretaceous diamond-bearing kimberlite in the Fort à la Corne area of central Saskatchewan (Lehnert-Thiel and others, 1992; Berryman and others, 2004). Unlike most kimberlites that are pipe-shaped, most of the Fort à la Corne deposits are stratiform, representing pyroclastic kimberlite that erupted from a vent with little or no hypabyssal-facies kimberlite remaining (Harvey and others, 2009). The basement geology of central Saskatchewan is similar to that of north-central Montana, raising the possibility that similar stratiform kimberlites could be present, for example, in the Central Montana Alkalic Province.

Sapphire

The bedrock Yogo deposit in central Montana is famous for the spectacular blue sapphires with high color saturation, known simply as Yogo sapphires in the trade (fig. 2). However, the alluvial sapphire deposits in southwestern Montana are by far the largest in the United States (Berg, 2007, 2014; Berg and Landry, 2018). These deposits generally produce pale-colored sapphires that are commonly enhanced by heat treatment and known in the gem trade as Montana sapphires. The largest of the alluvial deposits is the Rock Creek district, 16 mi southwest of Philipsburg, with an estimated historic production of 70 tons mined from an area of only 3 mi². Significant sapphire production continues from these alluvial deposits. Fifty-million-year-old rhyolite is the most likely bedrock source of these sapphires. Farther to the east, the Dry Cottonwood Creek district, 20 mi northwest of Butte, has produced a small quantity of sapphires, also thought to have weathered from Eocene rhyolites and dacites. Sapphires are mined from Pleistocene gravels on strath terraces along Hauser Lake on the Missouri River east of Helena, with estimated total production of 2 to 3 tons. These sapphires may have been derived

by weathering of dikes and sills in the Big Belt Mountains on the east side of the Missouri River.

On the basis of comparison of trace element geochemistry of the Montana alluvial sapphires to that of foreign deposits, Zwaan and others (2015) concluded that the alluvial sapphires in western Montana were derived from metasomatic crustal rocks. Palke and others (2017) suggest partial melting of anorthosites produced a corundum-bearing residuum. However, Berg and Dahy (2002) favored a crustal metamorphic source based on the occurrence of corundum-bearing metamorphic xenoliths in an Eocene sill near Helena, Montana that resemble Archean metamorphic rocks in southwestern Montana.

The Yogo sapphire deposit in central Montana is the only sapphire deposit in the State where these gems are mined directly from the bedrock source, which is an Eocene lamprophyre. Essentially all of the mining of this deposit has been from underground workings (Mychaluk, 1995). Because of their very attractive color, said to be a cornflower blue, and general lack of inclusions, these sapphires command a high price. Unfortunately, large stones are rare and many of the sapphires are flat, which limits their yield when cutting a gem. Cade and Groat (2006) concluded on the basis of the geochemistry of garnet inclusions that Yogo sapphires were of mantle origin. Dahy (1991) favored a crustal metamorphic rock source based on associated minerals and xenoliths. Palke and others (2016) postulated that partial melting of an aluminous protolith at the base of the crust produced a corundum residuum.

Amethyst

Granitic plutons of the Boulder Batholith and other similar-aged intrusive bodies contain scattered, mostly small pegmatite deposits (fig. 1 and Heinrich, 1948, 1949). These pegmatites were evaluated for their potential to supply mica and beryl (Stoll, 1950), but no significant mining of this type has occurred in Montana. Instead, the pegmatite deposits have received considerable attention from mineral collectors, and some small-scale mining has occurred for gemstones, in particular amethyst. The Pohndorf amethyst mine, located in the Highlands Mountains 15 mi southeast of Butte, was operated in the 1920s and 1930s (Childs and Porter, 1989). At Pohndorf, gem-quality amethyst and smoky quartz occur in pockets or vugs within a sill-like pegmatite body. Along with amethyst, the pockets also contain hydrothermal albite and a

green-colored muscovite (Heinrich, 1949; Childs and Porter, 1989). More recently, the Little Gem Mine, located only a few miles from the Pohndorf deposit, has been exploiting a similar occurrence of gem amethyst with associated green muscovite in vugs and pockets within a sill-like pegmatite. A recent fluid inclusion study showed that the Little Gem amethyst formed at relatively high temperature (>200°C) and pressure (>2 kbar), suggesting that the amethyst may have formed during the waning stages of Late Cretaceous magmatism in the Boulder Batholith (Gammons and others, 2016).

Perhaps the best known mineral collecting locality in Montana for smoky quartz and amethyst is Crystal Park, located in the south Pioneer Mountains. Here, collectors dig in weathered, vuggy, granitic rock for euhedral quartz crystals. Interestingly, the Crystal Park mineral occurrence may be related to a shallow porphyry–molybdenum hydrothermal system (Pearson and Berger, 1980).

GRAPHITE

Graphite has been mined at a small scale in the Archean rocks of southwest Montana. The known deposits, all of which are small, typically occur near contacts of Precambrian marble and intrusive rocks.

The Crystal Graphite Mine of the southern Ruby Mountains (fig. 2), the largest such deposit, produced 2,000 tons of graphite between 1902 and 1941 (Ford, 1954). Graphite is also found in hydrothermal quartz veins cutting Precambrian schist, gneiss, and marble. Beginning with Winchell (1911), there have been many attempts to explain the origin of the southwest Montana graphite deposits. These have ranged from *in situ* metamorphism of hydrocarbons, to metasomatism by magmatic fluids associated with pegmatites, to a purely hydrothermal origin. The recent study of Duke and others (1990) provides compelling C-isotope and fluid inclusion evidence that the Crystal Graphite and nearby deposits formed when relatively low temperature (T <350°C) hydrothermal fluids leached disseminated graphite out of marbles that had been previously metamorphosed to T >800°C, and reprecipitated the graphite in structurally controlled veins and lodes.

GYPSUM

The most extensive gypsum deposits in Montana are in the Great Falls–Lewistown area in the west-central part of the State (fig. 3). This mineral has been mined from the Kibbey Formation of the Mississippian Big Snowy Group from a deposit near Raynesford

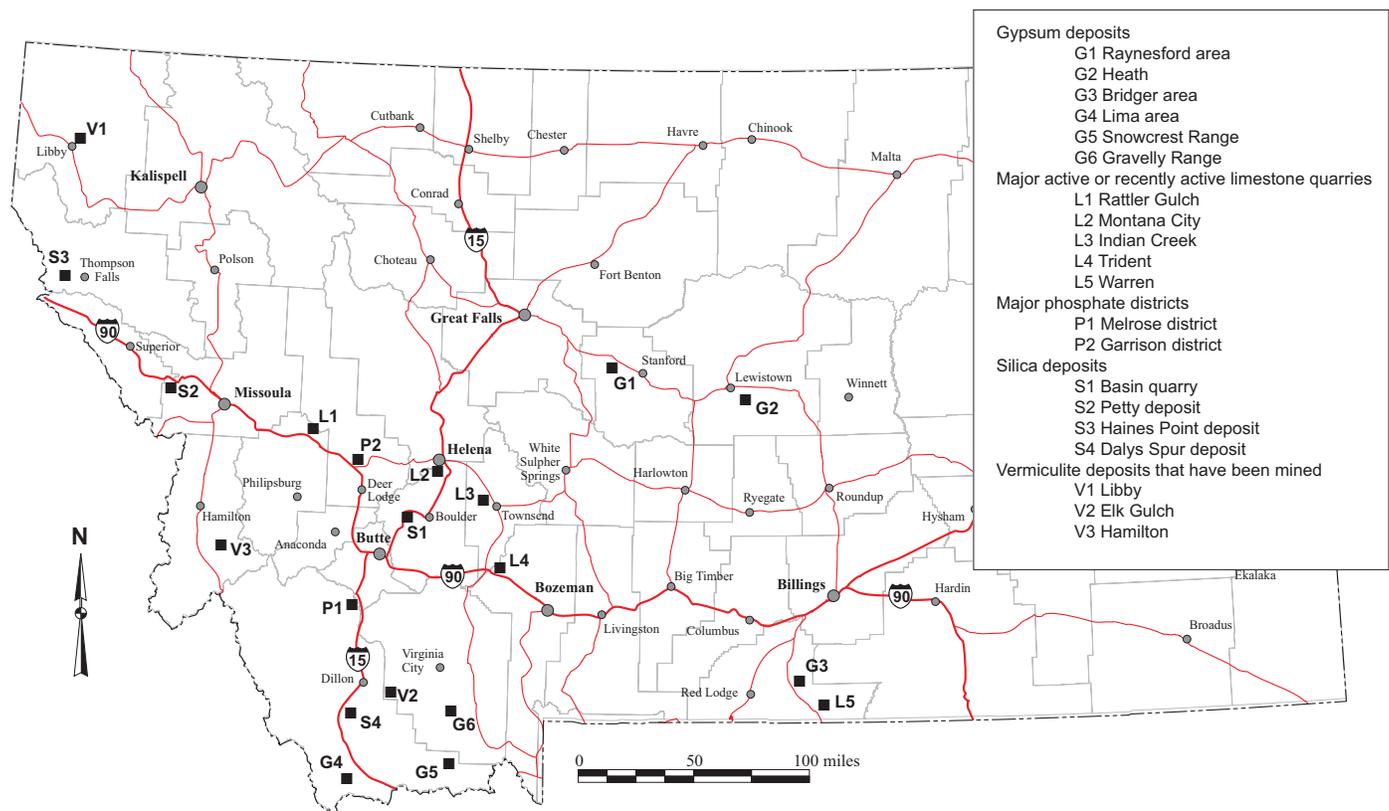


Figure 3. Gypsum, limestone, phosphate, silica and vermiculite deposits.

32 mi southeast of Great Falls. It was also mined a few miles farther southeast from the Otter Formation, also of the Big Snowy Group. Higher in the geologic section, gypsum beds in the Jurassic Piper Formation of the Ellis Group were mined in a large underground mine in the vicinity of Heath east of Lewistown for a wallboard plant (Perry, 1949). Forty miles southwest of Billings near Bridger, gypsum beds were mined from the Triassic Chugwater Formation (Knappen and Moulton, 1930). Forty miles southeast of Dillon in the Snowcrest Range, and also southwest of Dillon, gypsum occurs in the Big Snowy Group (Johns, 1980). The Jurassic Ellis Formation in the Gravelly Range south of Virginia City also contains gypsum (Mann, 1954).

LIMESTONE

The Madison Group of Mississippian age is the largest limestone resource in Montana. Limestone beds of this group are exposed on the flanks of mountains in central and southwestern Montana and in the Disturbed Belt along the Rocky Mountain Front in the northwestern part of the State. The Madison Group is divided into the Lodgepole Formation and the overlying Mission Canyon Formation. The latter contains higher purity limestone and is 880 ft thick in central Montana (Smith and Gilmour, 1980). Much of the Mission Canyon Formation can be classified as a high-calcium limestone containing more than 95 percent CaCO_3 , less than 5 percent MgCO_3 , and less than 3 percent other impurities (Chelini, 1965). At a quarry in Rattler Gulch, 4 mi northwest of Drummond, unusually pure beds in this formation contain 98 percent CaCO_3 (Landreth, 1968). Although the CaCO_3 content of the Lodgepole Formation is lower than in the Mission Canyon Formation, both of these formations are quarried for use in cement manufacture. Analyses of limestone from the Lodgepole Formation at five localities show a range from 72.8 to 88.2 percent CaCO_3 (Chelini, 1965). This formation reaches a maximum thickness of 780 ft in central Montana (Smith and Gilmour, 1980).

The Meagher Formation, a Cambrian limestone exposed in central and southwestern Montana, is also a source of high-purity limestone. Limestone from a quarry at the south end of the Helena Valley contained 93.2 percent CaCO_3 (Perry, 1949). Other potential sources of CaCO_3 are travertine deposits near Lewistown, north of Yellowstone National Park, and along the Montana–Idaho border west of Lima (Berg, 1974).

Limestone in Montana is used in the production of lime and cement.

Phosphate

The Permian Phosphoria Formation of Utah–Wyoming–Idaho–Montana is one of the world's largest accumulations of phosphorite, sedimentary apatite. Popoff and Service (1965) estimated that the southern part of the Montana phosphate field contains 1.2 billion tons of phosphate rock, with another 67.7 million tons in the northern part. Most of this resource would require underground mining. Historical phosphate mining in Montana has taken place in the hills north of Garrison, and in the Maiden Rock area along the Big Hole River, west of Melrose (fig. 3). Ore from the Maiden Rock mines was used to produce elemental phosphorus at a plant at Silver Bow west of Butte. Ore from the Garrison mines was shipped to Trail, British Columbia, where it was combined with sulfuric acid (a byproduct of Pb–Zn smelting) to convert the raw phosphate rock into phosphate fertilizer. Mining of Montana phosphate ceased with the closure of Cominco's Sullivan Mine in southern B.C., the main supplier of ore to the Trail smelter. Nonetheless, mining of the Phosphoria Formation continues at a large scale today in southeast Idaho.

Although the Phosphoria Formation is up to 800 ft thick in southwest Montana, the phosphate-rich horizons are thin (typically less than 10 ft thick). Important horizons include the Meade Peak Member near the base of the formation (the main ore zone for the Maiden Rock mines) and the Retort Member near the top (the main ore zone for the Garrison mines) (Cressman, 1955). Within each member, phosphate occurs as pellets of carbonate fluorapatite 0.1 to 1 cm in diameter (Gulbrandsen, 1966). The phosphorite beds and associated black shales are rich in other metals and metalloids, including arsenic, selenium, vanadium, and uranium (Perkins and Foster, 2004), which has led to environmental problems. A number of deaths of sheep, cattle, and horses in the 1990s were linked to selenium poisoning from the Idaho phosphate mines. Vast resources of vanadium and uranium are contained within the Phosphoria Formation, but are not now economically recoverable.

Silica

A quartz body in the Boulder Batholith near Basin (figs. 1, 3) has produced more than 250,000 tons of quartz containing 99.5 percent SiO_2 that was used for

the manufacture of silicon and ferrosilicon (Peterson, 1976). Chelini (1966) described four other quartz deposits in the Boulder Batholith between Butte and Helena with purity > 99% SiO₂. Numerous relatively pure quartz bodies northwest of Missoula perhaps resulted from remobilization of quartz from the enclosing quartzites of the Belt Supergroup. The Petty Creek deposit 18 mi northwest of Missoula contains an estimated 960,000 tons of quartz with analyses averaging 99.5 percent SiO₂ (Chelini, 1966). Farther to the northwest, the Haines Point deposit, 18 mi northwest of Thompson Falls, contains at least 100,000 tons of quartz with purity of 99.7% SiO₂ (Burlington Northern, 1972). Quartz sandstone in the Pennsylvanian Quadrant Formation is exposed in southwestern Montana. Duplicate analyses of this sandstone quarried at Daly's Spur 11 mi southwest of Dillon mined for smelter flux show purity of 98.9 and 97.5 SiO₂ (Carter and others, 1962).

Vermiculite

Vermiculite has a unique property in that it expands or *exfoliates* to up to 30 times its original volume when heated. This makes it an excellent thermal insulator. Between 1920 and 1990, an open pit mine and processing plant near the town of Libby, Montana was the largest producer of vermiculite in the U.S. The main commercial product from the Libby mine, marketed as "Zonolite," was used as insulation in homes and businesses throughout the country. The geology of the vermiculite deposit was summarized by Pardee and Larsen (1929), Bassett (1959), Boettcher (1967), and Bandli and Gunter (2006). The deposit is part of the Cretaceous Rainy Creek alkaline-ultramafic igneous complex. According to Bassett (1959), a coarse-grained body of augite-pyroxenite was hydrothermally altered to biotite during intrusion of a younger set of syenite dikes, and the hydrothermal biotite was later altered to vermiculite by supergene weathering. The vermiculite content of the main ore body was unusually high, ranging from 30 to 84% (Pardee and Larsen, 1929). Unfortunately, another byproduct of the hydrothermal alteration of augite was a fine-grained amphibole that crystallized into a shape and size similar to asbestos fibers (Meeker and others, 2003). Miners and their families at Libby were eventually found to have an unusually high incidence of asbestos-related lung disease, which led to the site being added to the U.S. EPA's Superfund list. A number of extremely costly and highly publicized lawsuits ensued, which

continue to this day. Besides closure of the world-class mine at Libby, litigation has resulted in the mandatory removal of Zonolite insulation from all public buildings in the United States. Although originally referred to as "tremolite-asbestos," later mineralogical studies showed that the Rainy Creek amphibole is a mixture of several different amphiboles, including winchite, richterite, tremolite, and magnesioriebeckite (Meeker and others, 2003).

A number of other deposits of vermiculite occur in Montana (Perry, 1948), at least two of which were mined at a small scale. The "Western Vermiculite Project" is located near the headwaters of St. Clair Creek, a tributary to Skalkaho Creek, which flows west out of the Sapphire Mountains toward Hamilton. The second vermiculite deposit of interest is located southeast of Dillon at Elk Gulch, where a small amount of vermiculite was mined. Like at Libby, the vermiculite bodies near Dillon and Hamilton occur as a weathering product of biotite associated with pyroxenite and similar rocks (Berg, 1995).

OTHER INDUSTRIAL MINERAL COMMODITIES

None of the following industrial minerals has been mined in Montana, but they are briefly described because they are known to occur in the State and, within the past 40 or 50 years, there has been occasional interest in them.

Dolomite

Four Paleozoic formations contain substantial dolomite deposits: the Middle Cambrian Meagher Limestone in southwestern Montana, the Upper Cambrian Pilgrim Limestone in southwestern and central Montana (Perry, 1949), the Ordovician Big Horn Dolomite in south-central Montana, and the Devonian Jefferson Dolomite in western and central Montana.

Feldspars

Tertiary alkalic rocks in the Central Montana Alkalic Province (fig. 1) appear to offer the best potential sources of alkali feldspars. The Little Rocky Mountains, Judith Mountains, North and South Moccasin Mountains, Highwood Mountains, and Bear's Paw Mountains all contain syenite or closely related rocks. See the chapter in this volume by Mosolf for more detail (Mosolf and others, 2020).

Marble

Marble formed by metamorphism of limestone beds, mainly in the Madison Group of Mississippian age, adjacent to Mesozoic plutons in southwestern Montana is a potential source of ground calcium carbonate for use as a functional filler.

Potash

Sylvite beds in the middle Devonian Prairie Evaporite in southern Saskatchewan are a major source of potash. These same beds occur in the subsurface in northeastern Montana, but at a greater depth (>9,000 ft below surface). The sylvite beds in Montana are also thinner and of lower grade than those in Saskatchewan (Berg, 2010).

Zeolites

Clinoptilolite formed by alteration of Tertiary volcanic ash is widespread in southwestern Montana in numerous small occurrences. The clinoptilolite deposit along Grasshopper Creek 15 mi southwest of Dillon is the largest recognized zeolite deposit in Montana and has the best development potential (Berg and Cox, 2001). Discontinuous zeolitic alteration in Tertiary beds is also exposed along Muddy Creek 40 mi south of Dillon and in the White Earth area along Canyon Ferry Lake north of Townsend.

TALC AND CHLORITE

Introduction

Talc [$Mg_3Si_4O_{10}(OH)_2$] has a wide range of industrial uses, and new applications are constantly being developed. Uses include paper production, paint and other coatings, ceramics, plastics, rubber, agricultural products, cosmetics, pharmaceuticals, and foods. The low hardness (1 on the Mohs scale), platy nature, chemical inertness, and hydrophobic qualities make talc uniquely suited for many industrial applications. The mines in southwestern Montana produce some of the purest and most easily accessible talc in the world (Van Gosen and others, 1998a; fig. 4). Some of the talc deposits of southwestern Montana have been known and studied for 70 years or more, so they are relatively well understood, while smaller occurrences are less well known (fig. 5).



Figure 4. Typical samples of high-grade Montana talc. Massive block on the left and sheared and foliated talc on the right. Shear foliation and rehealed breccia zone in sample on the right is at approximately a 20° angle to the long axis of the scale card.

Current Mining Operations

Two companies, Imerys Talc and Barretts Minerals, Inc., currently operate mines and mills in southwestern Montana (fig. 6). Barretts Minerals operates the Treasure State Mine in the Ruby Range (fig. 7), the Regal Mine in the Sweetwater Valley east of Dillon, Montana, and the Barretts Mill south of Dillon (fig. 8). Imerys Talc operates the Yellowstone Mine south of Ennis, Montana and mills at Sappington and Three Forks, Montana (figs. 6, 9, and 10). With three active mines, Montana was the largest producer of talc in the United States in 2016 (Flanagan, 2017). Both Imerys and Barretts maintain strong quality control and research laboratories, and the parent companies have grown dramatically in recent years through both acquisitions and exploration. Imerys, the parent company of Imerys Talc, is a public company listed on the Paris Exchange. Imerys employs 16,000 people worldwide and brought more than 90 new products to the world market in 2016 alone. Imerys employs approximately 35 people at the Yellowstone Mine and 95 people at its milling and administrative facilities. Both companies have made improvements in their mineral separation and milling facilities in recent years to maximize use of the resource.

Minerals Technologies, Inc. is the parent company of Specialty Minerals, Inc., that is in turn the parent company for Barretts Minerals, Inc. Barretts Minerals employs 85 full-time and contract people at its operations in Dillon, Montana (fig. 8), with an annual payroll in 2015 of over \$5.5 million. Barretts paid more than \$1 million in property taxes in 2016.

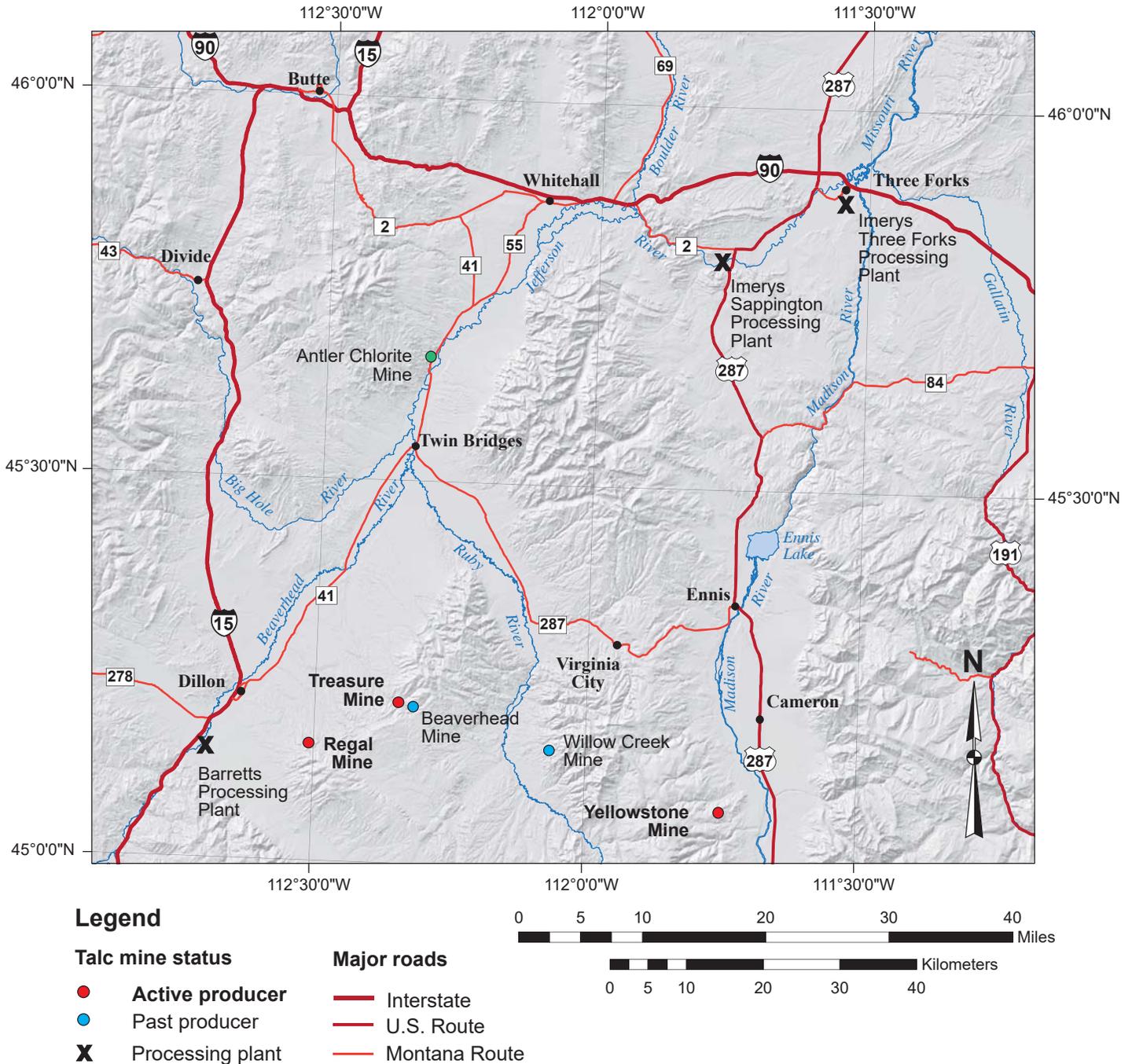


Figure 6. Map of southwestern Montana showing locations of the three active talc mines, two past-producing talc mines (Beaverhead and Willow Creek), and the past-producing Antler Chlorite Mine (green). Three active processing plants (mills) are shown.



Talc and marble in red
TFZ, Treasure Fault Zone in yellow

Figure 7. Aerial view looking south across the Treasure Mine in the foreground and the Beaverhead Mine in the background. The talc ore bodies and the enclosing marbles are outlined in red. Quartzofeldspathic gneiss and other rock types make up the iron-stained high wall in the center of the photo. The Treasure fault zone is outlined in yellow. This vertical fault strikes approximately north-south and is up to 100 m (300+ ft) wide with intense alteration to chlorite and lesser talc throughout its extent. The Treasure and Beaverhead talc zones dip steeply toward the camera. Photograph by Julia Gwinn.



Figure 8. The Barretts mill located 8 mi south of Dillon, Montana processes talc from the Treasure State and Regal Mines in the Southern Ruby Range. Photograph by Julia Gwinn.

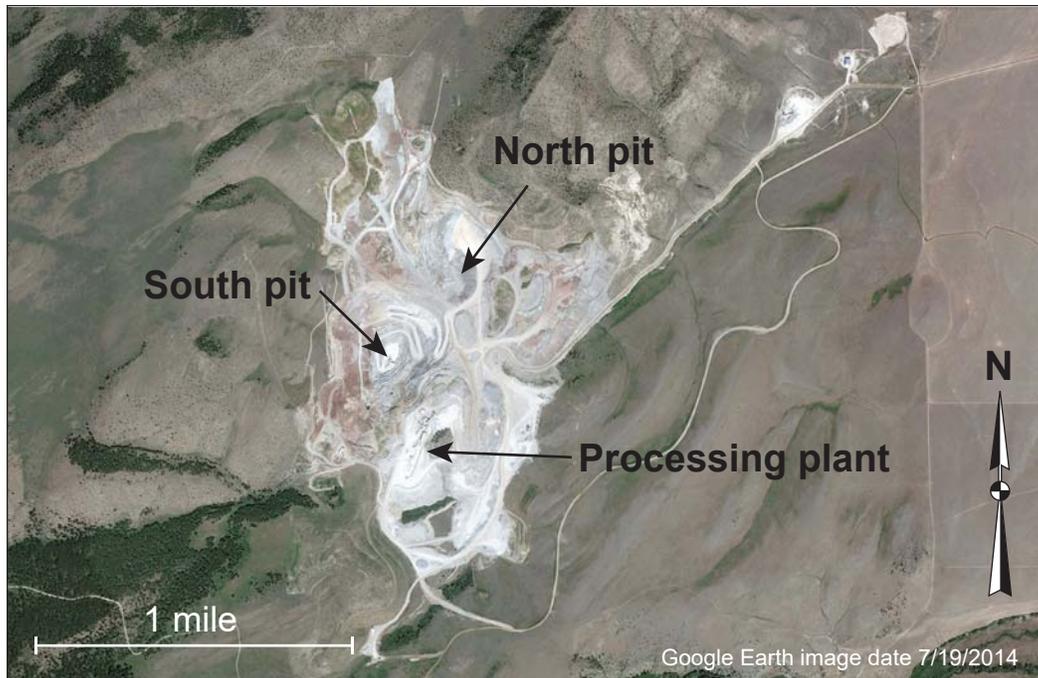


Figure 9. Google Earth imagery covering the Yellowstone Mine in the eastern Gravelly Range approximately 20 miles south of Ennis, Montana. The mine is operated by Imerys Talc. The north pit is no longer active and is being filled with waste rock from the ongoing operations in the south pit.

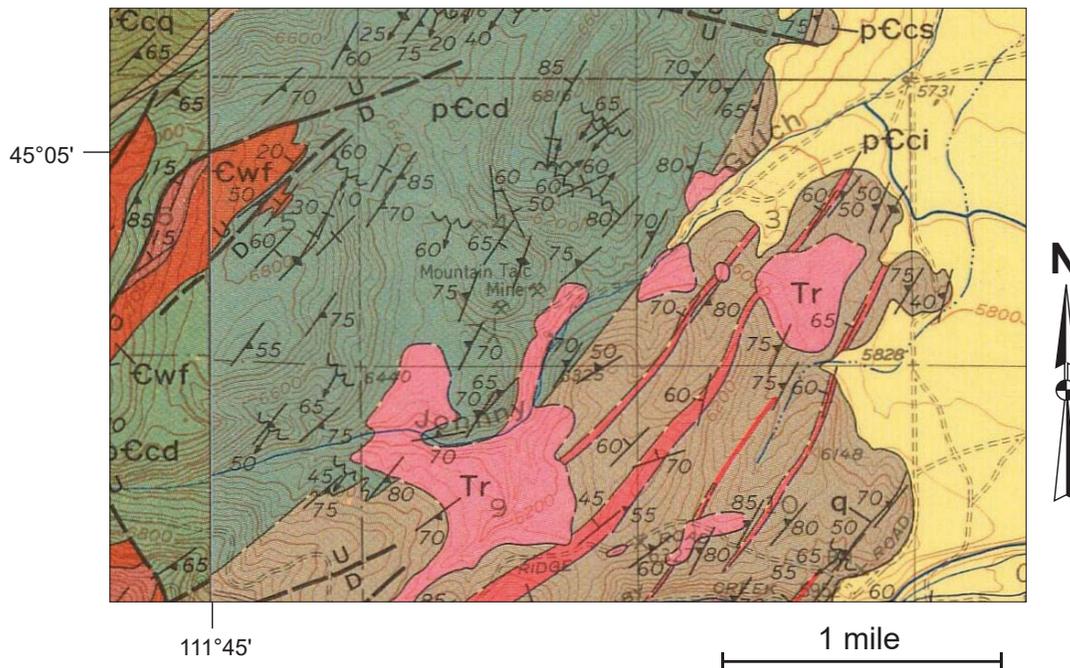


Figure 10. The geology of the same area as that in figure 9. Geology is from Hadley (1969a,b). The Yellowstone Mine has expanded greatly since Hadley mapped the area and the southern pit and processing plant are now in the area labeled “Johnny” on the geologic map. On geologic map: green is marble; brown is phyllite and other low-grade metamorphic rocks; red is iron-rich quartzite (iron formation); orange is Cambrian sedimentary rocks; pink is Tertiary-Quaternary tuff; and yellow is Quaternary alluvium. Marbles and other metamorphic rocks are Archean or Paleoproterozoic.

Eighteen Year Trend—Talc

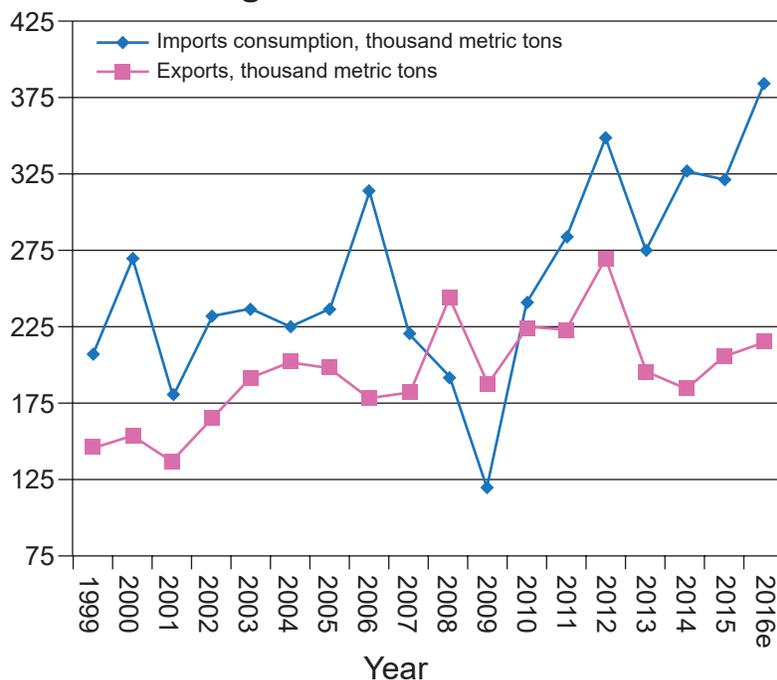


Figure 11. Eighteen-year trend data for talc production (thousands of long tons) and consumption (thousands of long tons), 1999 to 2016 for the United States (estimated). From Tomaino, 2017.

Generalized Geology

Overviews of the talc deposits of southwestern Montana include Berg (1979), Cerino and others (2007), and Underwood and others (2014). The regional geology and the three producing mines are shown in figure 12. Metasomatic replacement of the host rock by Mg- and Si-enriched fluids is thought to have produced talc deposits from dolomitic marble (fig. 13) and chlorite deposits from quartzofeldspathic gneiss (Anderson and others, 1990; Berg, 1983).

The talc deposits of the Ruby Range are hosted in Archean and possibly in Paleoproterozoic high-grade metamorphic rocks within the Trans-Montana fold-and-thrust belt and Dillon Shear Zone as defined by Sims and others (2004). In contrast, the Yellowstone deposit in the Gravelly Range (fig. 10) is hosted in lower grade marbles, which are interstratified with metabasalts, iron formation, and other sediments. Metabasalts in this sequence retain relict pillow structures and pelitic rocks here have been metamorphosed to phyllite rather than coarse mica schist. The rock assemblage in the Yellowstone Mine area may be Paleoproterozoic in age rather than Archean (Sims and others, 2004), although more work will be required in order to have certainty about the age of these low-grade metamorphic rocks. The Antler (Nolte) chlorite deposit (fig. 6) resulted from alteration of quartzofeldspathic and biotite gneiss to chlorite (Berg, 1983).

Development of chlorite rather than talc is thought to be a function of the composition of the host rocks with production of chlorite in the gneiss and talc in the dolomitic marbles. Otherwise, the similarities between the Antler chlorite deposit and the talc deposits farther south are striking. In both types of deposit, the alteration is quite localized and grades outward into unaltered host rock over a few feet to a few tens of feet; both deposit types follow steeply dipping, north-striking fault zones, and both are developed in areas inferred to have been part of the Proterozoic Belt Basin (Anderson and others, 1990).

If the areas containing the talc deposits were once part of the Belt Basin, the Belt sediments have now been eroded and evidence for the extension of the basin into these areas is only indirect (fig. 12). This evidence includes Mesoproterozoic radiometric dates on sericite genetically associated with the talc (Hurst, 1985; Brady and others, 1998); stable isotope data that suggest origin from brines of the Belt Basin (Brady and others, 1998); a mafic trace element signature in the talc possibly related to the extensive diabase dikes and sills spatially associated with the talc deposits and the Belt Basin (Rose, 1984); the presence of major talc bodies in rocks thought to be of Paleoproterozoic age that were affected by the Big Sky Orogeny at 1.7–1.8 Ga (Sims and others, 2004) and the absence of talc in Paleozoic dolomites in the same areas; the occurrence

Regional Geology of Southwest Montana

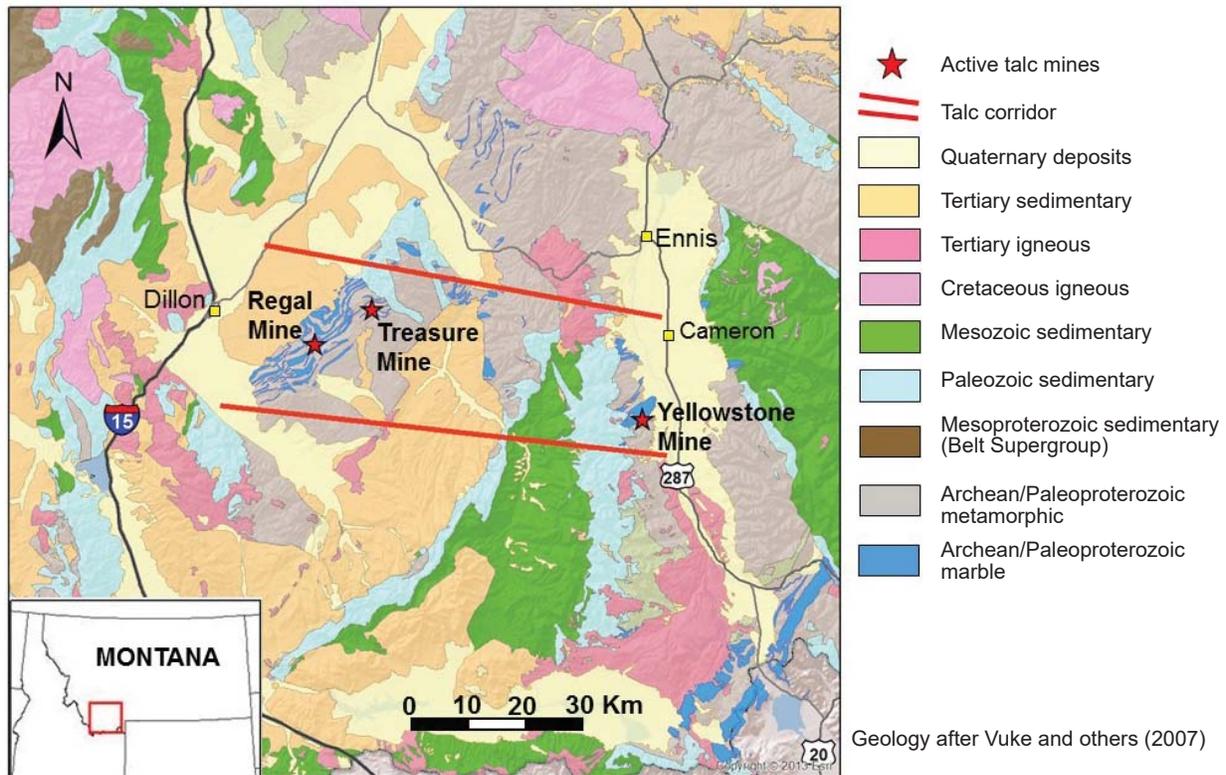


Figure 12. Map similar to Figure 5 but showing the regional geology. The three producing talc mines and the talc corridor are shown for reference.

of a talc prospect in Belt rocks in northern Montana (Berg, 1979); evidence for an open system with high water-to-rock ratios at the Beaverhead Mine (Anderson and others, 1990); and restriction of the commercial talc deposits to a roughly east–west “corridor” extending from the Yellowstone deposit on the east to the deposits in the vicinity of Dillon, Montana on the west (figs. 5, 12). Belt sediments are present well to the south of this corridor in eastern Idaho (fig. 12) and the corridor is parallel with major growth faults farther north in the Belt Basin (Winston, 1986).

On a district scale, some talc occurrences and mines are aligned along east–west, steeply dipping dike swarms and fault zones (fig. 12) approximately parallel with major growth faults within the Belt sediments such as the Southwest Montana Transverse Zone (Schmidt and O’Neill, 1982), and the Jocko and Garnet Lines of Winston (1986). On the scale of individual deposits, talc is commonly controlled by north- to northwest-striking faults and diabase dikes within the more regional east–west zones. West–northwest, northwest-, and north-striking, steeply dipping diabase dikes are common in the Tobacco Root and Highland Mountains and the Ruby and Gravelly Rang-

es. Many of these are probably the result of opening of the Belt Basin and would have provided channel ways for deeply circulating, magnesium-enriched brines that produced talc from the dolomitic marbles in the crystalline basement. It is interesting to speculate that the abundance and orientation of these dike swarms and the associated talc deposits could indicate a relatively rapid rate of extension and fluid infiltration in this part of the Belt Basin. Additionally, rocks tentatively identified as Paleoproterozoic in age are found along the postulated east–west zone of commercial talc deposits in the southern Ruby Range (Alcock and Muller, 2012), suggesting the presence of a structural and depositional corridor that was active in the Paleoproterozoic and controlled talc in the Mesoproterozoic (Childs, 2017).

The significant producing talc deposits are located in a roughly east–west corridor extending from Dillon, Montana on the west to south of Cameron, Montana on the east (fig. 5). The talc deposits are hosted in regional calcitic to dolomitic marbles in the Archean Dillon structural block, and the northeast-trending Trans-Montana Fold and Thrust Belt and Dillon Shear Zone (Sims and others, 2004). All of the marbles that

host the talc in southwestern Montana are considered to be Paleoproterozoic rather than Archean by Sims and others (2004), although the marbles in the Ruby and Tobacco Root Ranges are intimately interfoliated with quartzofeldspathic gneisses long thought to be Archean (Roberts and others, 2002).

The talc deposits are characterized by development of coarse-grained dolomite and magnesite along with talc (fig. 13) and are localized along north- to north-west-striking, steeply dipping faults and diabase dikes. The faults typically have strong chloritic alteration where they cut quartzofeldspathic gneiss, amphibolite, and schists adjacent to the marbles. The diabase dikes are also more or less altered to chlorite. Brecciation and shearing is common in and adjacent to the talc (fig. 4). Botryoidal talc coatings and vugs indicate talc development under relatively shallow depths of burial, possibly having developed in the root zones of hot spring systems (fig. 13). Radiometric dates of 1.14 and 1.03 Ga were obtained on sericite associated with talc at the Beaverhead Mine in the Ruby Range (Childs, 1984), and Rb-Sr age dates on talc from the Ruby Range also suggested a Mesoproterozoic age (Hurst, written commun., 1985). Brady and others (1998) published an age of 1.36 Ga for similar hydrothermal

sericite from the Ruby Range. These ages and other lines of evidence have led to the hypothesis that the talc deposits formed during development of the Mesoproterozoic Belt Basin and associated high heat flow, syndepositional growth faulting, and emplacement of diabase sills and dikes at approximately 1.4 Ga (Anderson and others, 1990; Brady and others, 1998; Gammons and Matt, 2002; Cerino and others, 2007; Underwood, 2015, 2016; Childs, 2017).

Early work by Cyprus Industrial Minerals Company (Rose, written commun., 1984) identified a geochemical footprint involving enrichment of mafic-associated elements in the talc such as Ni, and Cr relative to the marble protolith, accompanying metasomatic influx of magnesium, and recrystallization and coarsening of the host marble (Anderson and others, 1990; and fig. 13). Fluid inclusion studies by Gammons and Matt (2002) and Hill and Gammons (2017) suggest that the talc-forming fluids were Ca-Si-Mg-rich brines and that talc formation occurred at pressures between 1 and 4 kbar. Based on O- and H-isotope analysis of talc, Underwood (2016), using stable isotope fractionation models developed by Saccocia and others (2009), has postulated that the fluids responsible for talc formation were likely some com-

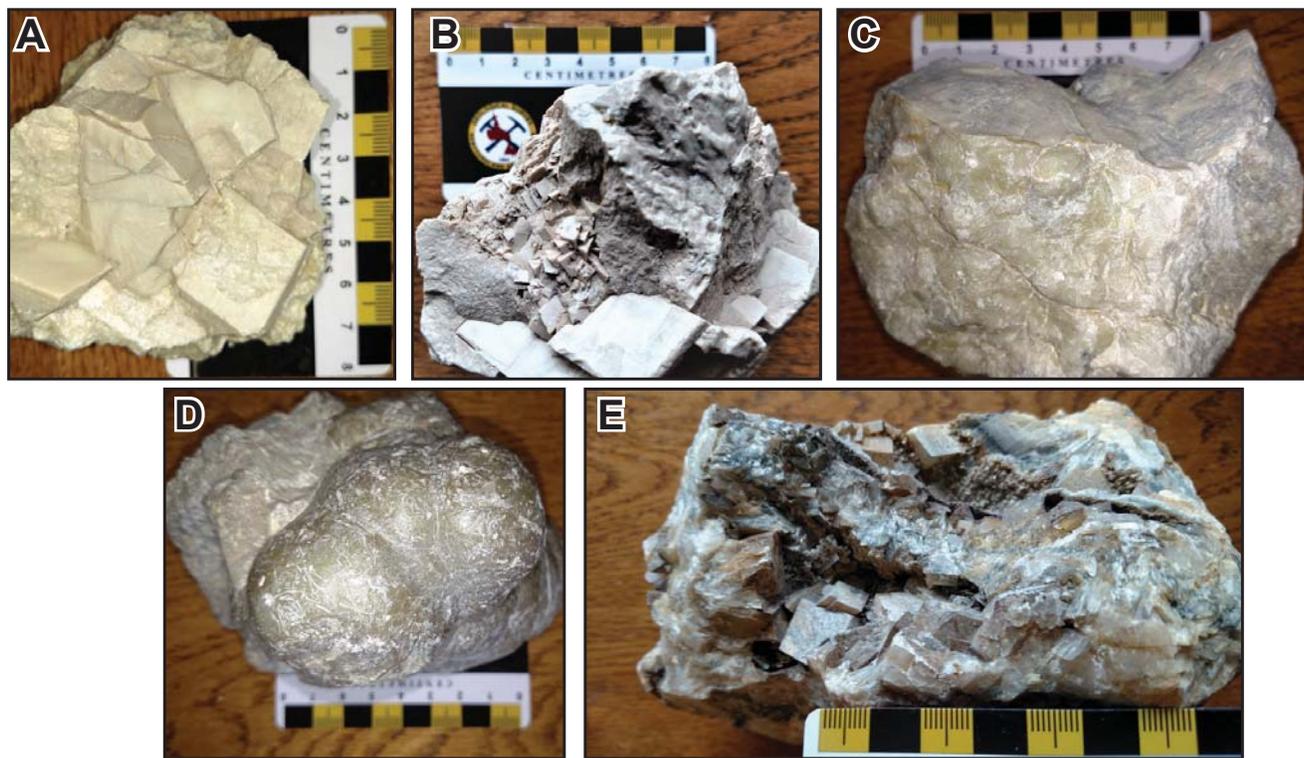


Figure 13. Examples of textural variations in Montana talc deposits. (A and B) Entire samples consist of talc pseudomorphs after coarse rhombs of dolomite or magnesite. Early development of coarse magnesite and dolomite is a characteristic of the Montana talc deposits. (C and D) Botryoidal texture from the Yellowstone Mine (C) and the Beaverhead Mine (D). This texture indicates open space filling during talc development. (E) Coarse hematite-stained dolomite rhombs lining vugs in marble from the Yellowstone Mine. Note quartz-calcite veins on the right cutting the dolomitic matrix.

bination of seawater, sedimentary-basin brines, and meteoric water. Underwood (2015, 2016) also postulated that the talc may have formed over an extended period and in more than one event rather than as a single pulse. All of these authors have concluded that there is a relationship between the talc-forming event and the development of the Belt Basin.

Recent mapping by the Montana Bureau of Mines and Geology and the Idaho Geological Survey has extended the Belt Basin well to the south and west of the talc deposits although, as discussed above, no Belt sedimentary rocks have been identified in the immediate area of the talc deposits. An overlying capping section of Belt sediments would have provided the temperature and pressure conditions necessary for formation of the talc deposits due to burial under a stratigraphic and water column. Clearly, more research needs to be done on the structural setting, including proximity to diabase dikes, geochemical and isotopic signature, and other aspects of the geology of the Montana talc deposits.

Industry Trends

Advances in the Montana talc industry have been made in recent years in both exploration and beneficiation methodologies. Both of the major producers have been very successful in discovering extensions and offsets of known orebodies by drilling around the existing mines. As with other mineral commodities, it is likely that most of the orebodies exposed at the surface have already been discovered. New methods such as fluid inclusion studies (Hill and Gammons, 2017), geochemistry (Anderson and others, 1990), stable isotopes (Underwood, 2016), geophysics, multispectral and hyperspectral remote sensing (Harris and others, 2012), LiDAR imagery, and statistical prospectivity modeling (Kenex, 2015) will all play a more prominent role in future discoveries.

New processing and analytical techniques have been developed to support advances in quality control. In the production pits and mills these include optical and mechanical sorting of the ore, more detailed geologic mapping at the mine face, and 3-D deposit modeling. In the laboratory, both companies have taken leadership roles in requiring new analytical methods and analytical standards for certification of talc for Absence of Asbestos (Block and others, 2014). This includes certification of U.S. Pharmacopoeia talc through CERCLA, the EPA, ASTM, the FDA, the U.S. Pharmacopoeial Convention Expert Talc Panel,

and cooperative programs with academic institutions. Specificity testing and detection limits for absence of asbestos has improved by employing state of the art techniques such as improved sample preparation/concentration methods to increase feasible detection limits, and X-ray diffraction followed by one or more microscopy methods such as Polarizing Light Microscopy, Transmission Electron Microscopy, and Scanning Electron Microscopy.

It is hoped that new research and methods of beneficiation will allow recovery of potential co-products such as magnesite, dolomite, chlorite, and graphite. New research on the use of nano-talc products is likely to lead to dramatic new uses for talc. Innovation to develop new co-products will maximize the use of the available resources. As present industrial mineral resources become depleted, production of alteration minerals such as chlorite, talc, clays, and pyrophyllite that previously have been considered waste during mining of other types of deposits such as porphyry copper–molybdenum systems may also expand.

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