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The Yellowstone and Regal talc mines and their geologic setting in southwestern Montana

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ABSTRACT

We summarize the geologic settings, generalized geology, and inferred conditions of talc formation for two major deposits in southwestern Montana. Imerys Talc operates the Yellowstone Mine in the Gravelly Range. Barretts Minerals Inc., a subsidiary of Minerals Technologies Incorporated, mines talc from two large deposits—the Regal and the Treasure—in the southern Ruby Range. Talc mineralization in southwestern Montana is associated with hydrothermal alteration of Archean dolomitic marbles along fractures in the southern margin of the middle Proterozoic Belt Seaway. Conditions of talc formation appear to have varied across the region and probably range from shallow hot spring systems to connate brine circulation pathways in Belt basin sediments. A road log description of the geology along a loop from Bozeman to Dillon, Montana, to visit both the Yellowstone and Regal talc mines accompanies this paper.

INTRODUCTION

Talc is a hydrous magnesium phyllosilicate [$Mg_3Si_4O_{10}(OH)_2$] that may consist of compact masses of <1μm microcrystalline platelets or crystal sizes >100 μm in platy macrocrystalline talc. In addition, highly lamellar talc has individual macroscopic plates similar to mica. Individual talc platelet size is controlled by conditions of mineral formation, and the size of the talc plates affects surface properties. Talc is recognized for its softness (Mohs hardness of 1) and the ease with which it can be carved with a knife.

The talc deposits mined in southwestern Montana produce some of the purest talc in the world (Van Gosen et al., 1998).

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Many of the Montana talc products are of the compact or microcrystalline variety and are in great demand for manufacturing paper, paints and coatings, plastics, rubber, ceramics, and agricultural products. In addition, cosmetic and personal care products, pharmaceuticals, and selected food industry applications are low volume niches for Montana talc. Two companies, Imerys Talc and Barretts Minerals Inc., currently operate mines and mills in southwestern Montana.

OVERVIEW OF REGIONAL GEOLOGY

All of the talc deposits in southwestern Montana (Fig. 1) are hosted by Archean dolomitic marbles that are associated with high-grade metamorphic sequences, including quartzofeldspathic gneiss, garnetiferous kyanite-staurolite mica schist, quartz-rich gneiss, banded iron formation, amphibolite, and many other lithologies. A late Archean tectonothermal event from continental collision is the postulated cause for the oldest amphibolite grade metamorphism, followed by a ca. 1.7–1.8 Ga upper amphibolite facies metamorphic event (Brady et al., 1998). Both the Yellowstone and Regal talc mines are in the Paleoproterozoic suture zone along the northwestern edge of the Archean Wyoming province (Fig. 2).

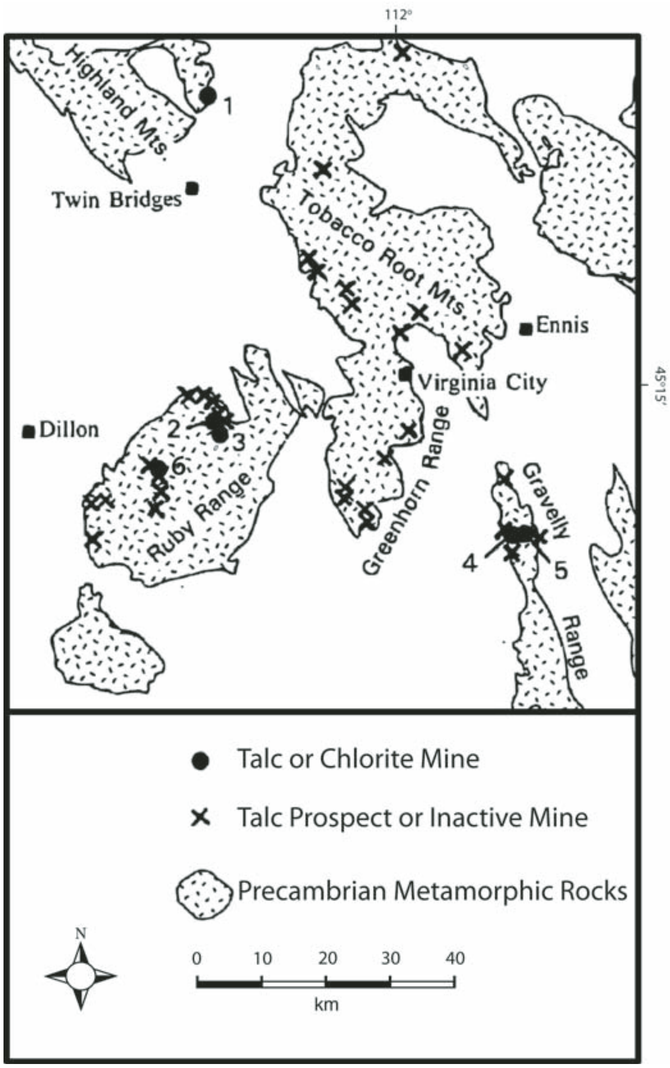


Figure 1. Simplified map for selected chlorite and talc mines in southwestern Montana (after Berg, 1995). 1—Golden Antler Mine (chlorite); 2—Treasure Mine (talc); 3—Beaverhead Mine (talc); 4—Johnny Gulch Mine (talc); 5—Yellowstone Mine (talc); and 6—Regal Mine (talc). X—Other talc and chlorite prospects.

Formation of talc is often associated with faulting and magmatism that occurred during opening of the Belt basin (ca.1.4 Ga), with stable isotope studies of selected minerals in and around talc ore bodies, geochronological data, petrological studies, and fluid inclusions in chalcedony supporting this assertion (i.e., Anderson et al., 1990; Brady et al., 1998; Gammons and Matt, 2002). If Belt seawater was involved in talc formation, it would require that the Belt basin extended across part of the region uplifted as the Dillon Block. Erosion would have removed the resulting Belt sedimentary rocks from the southern Ruby Range while preserving Belt basin sediments to the west and southwest. Presently, the extensive exposures of Belt Supergroup sedimentary rocks are found in the Pioneer Mountains 24 km (15 mi) west of Dillon (Vuke et al., 2007), as well as in the Beaverhead Mountains and adjacent ranges in Idaho farther southwest (Burmester et al., 2013).

The geologic setting of the talc deposits is somewhat enigmatic, and textural relationships can be complex in detail (Fig. 3). For example, diabase dikes postulated as the heat engines for the hydrothermal cells that produced talc, as described below, are not exposed near some of the producing or past producing deposits (i.e., the Treasure and the Beaverhead deposits, respectively). Some talc deposits display thickening and deformation in early fold hinges, e.g., the Regal (Fig. 4), whereas other deposits are in relatively thin marbles and though not within obvious fold hinges, are along major north-to-northwest chloritic fault zones, e.g., the Treasure (Fig. 5) and the Beaverhead. Improving plausible talc formation model(s) must consider these differences.

In the Ruby Range, chlorite appears to have developed in aluminous rocks such as mica schist and quartzofeldspathic gneiss as part of the same process that produced talc in the dolomitic marbles. Berg (1979) described the Nolte chlorite deposit in the Highland Mountains ~48 km (30 mi) north of the southern Ruby Range. Clinochlore, or Mg chlorite, apparently replaced all mineral phases in the quartzofeldspathic gneiss except rutile and zircon. The chlorite at the Nolte deposit, and at least some of the chlorite and associated talc in the southern Ruby Range appears to be associated with north-to-northwest–trending steeply dipping fault zones.

Talc Formation Models for SW Montana

Early models for talc formation in southwestern Montana included a retrograde metamorphic event based on replacement

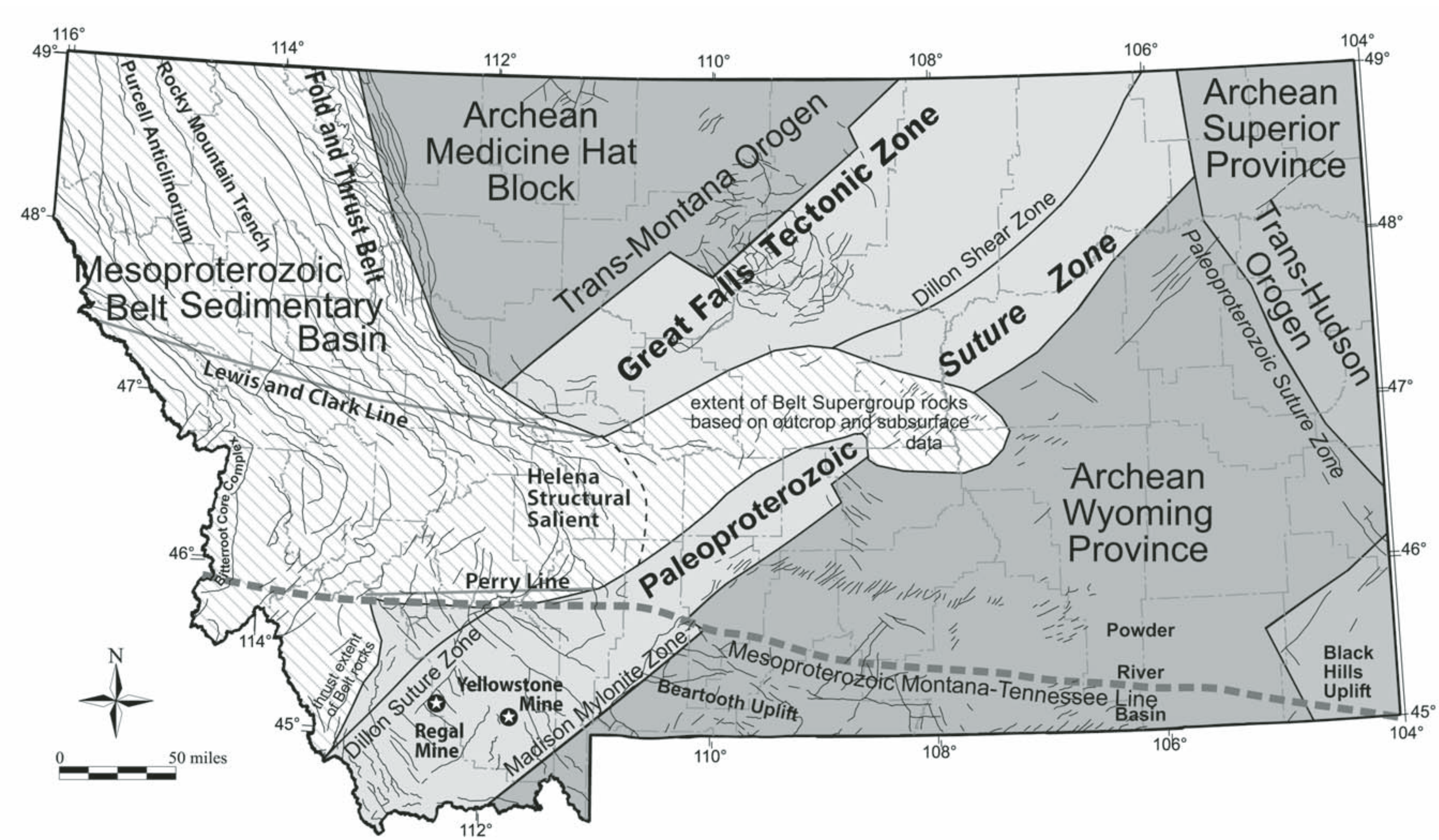


Figure 2. Montana basement rock and tectonic provinces (modified after Vuke et al., 2007). The Yellowstone and Regal Mine localities are each indicated with a star and major faults are delineated with thin gray lines. The Paleoproterozoic fold-and-thrust section southeast of the Dillon suture zone and northwest of the Madison mylonite zone in southwest Montana contains the Dillon Block.

Figure 3. A loose block of ore in the Treasure Mine showing some of the complex relationships between talc and carbonates. The central domain of medium-green chloritic talc is cut by white veinlets <1 cm thick of dolomite or magnesite. These veins terminate at the contact between the chloritic talc and the surrounding coarsely recrystallized white dolomite. The recrystallized dolomite is partially replaced by white coarsely crystalline talc. Hammer and GPS unit provide scale.

of tremolite by talc and biotite by chlorite, and on the restriction of the talc deposits to Archean rocks where radiometric dates had been reset at ca. 1.6 Ga, e.g., Berg (1979). Anderson et al. (1990) suggested a hydrothermal model for the formation of the Beaverhead deposit at ca. 1.4 Ga and, by inference, a similar origin and age for the other talc deposits in the area. Physical-chemical modeling and petrographic evidence developed by Anderson et al. (1990) suggested that the talc was formed in a near-surface hot spring environment and required large volumes of water.

Talc formation in southwestern Montana is probably related to a rifting event, such as the opening of the Belt basin, based on several lines of evidence. A proprietary age date on sericite associated with talc yielded a middle Proterozoic age for the hydrothermal system (Childs, 1984). Furthermore, a Proterozoic age of 1.36 Ga for sericite associated with talc was reported by Brady et al. (1998). Investigations of stable isotopes and Rb/Sr radiometric age dates on Ruby Range talc deposits indicate a middle Proterozoic age for the talc (Childs, 1984; Hurst, 1985).

Northwest-trending Proterozoic diabase dikes, which are common throughout the southern Ruby Range, may have invaded extensional faults related to opening of the Belt basin and are the postulated heat source that drove talc-forming hydrothermal systems (James, 1990). Rose (1984) demonstrated that the trace element geochemistry of the talc, when compared with the unaltered host dolomitic marble, contained elevated Cr and Ni, which could indicate the presence of a mafic or ultramafic component in the talc-forming process. Moreover, Hoy et al. (2000) suggested that diabase sills were emplaced into soft sediment in the northern Belt basin, and heat loss drove hydrothermal cells, with associated hydrothermal vents or sand boils, roughly synchronous with the exposure to metal rich brines that formed the Sullivan massive sulfide deposit and its related tourmaline and chlorite alteration blankets in southern British Columbia.

Talc in the Ruby Range and probably talc at the Yellowstone Mine formed in a near-surface environment. Solid support for this assertion is found in field observations: (1) botryoidal talc (Fig. 6), (2) abundant open vugs in veins (Fig. 7), and (3) thinly banded opaline to chalcedonic quartz as vug linings. Investigators generally agree that the timing and characteristics of talc formation support water-rich environments probably related to the Belt basin opening, but details regarding depth of formation in the "plumbing system" are lacking. Talc is stable at temperatures up to 700 °C and pressures of 10 kbar (Evans and Guggenheim, 1988). When water is the dominant fluid component, talc formation reactions and talc stability fields easily extend into low temperature and pressure conditions (Anderson et al., 1990). The mass balance calculations by Anderson et al. (1990) permit further conjecture that the type of shallow environment could have been a local sabkha-type setting proximal to the shore of the Belt Seaway. The crystalizing dikes and sills supplied ample amounts of shallow Mg-enriched water for talc formation. Additional SiO_2 and Mg stripped from the Archean basement rocks by deeply circulating, magma-derived hydrous fluids may have enriched Mg content in dolomite and crystallized magnesite domains in the marble and in the subsequent talc formation. A modern example of this type of environment may be the Guaymas Basin of the Gulf of California, where talc formation is documented adjacent to diabase sills at the seawater interface (Lonsdale et al., 1980).

In the Gravelly Range, Gammons and Matt (2002) suggest that deep brines in the Proterozoic Belt basin were instrumental in talc formation at the Yellowstone Mine. They examined fluid inclusions in hydrothermal quartz contained within talc and developed a model that invokes injection of thick mafic sills into the Belt sedimentary pile. The heat forced connate brines out of the bottom of the basin and into the adjacent basement. This hydrothermal engine would have moved fluids along Proterozoic conduits, which are now "growth" faults in the Yellowstone Mine area, and generated chloritic alteration of mafic dikes that had intruded along the faults. Hydrothermal alteration produced talc in the receptive dolomitic marbles in the basement rocks. Temperatures of talc formation at the Yellowstone Mine ranged from 190° to 250 °C at 1–4 kbar, which corresponds to depths of 3.5–14 km (2.2–8.7 mi) (Gammons and Matt, 2002).

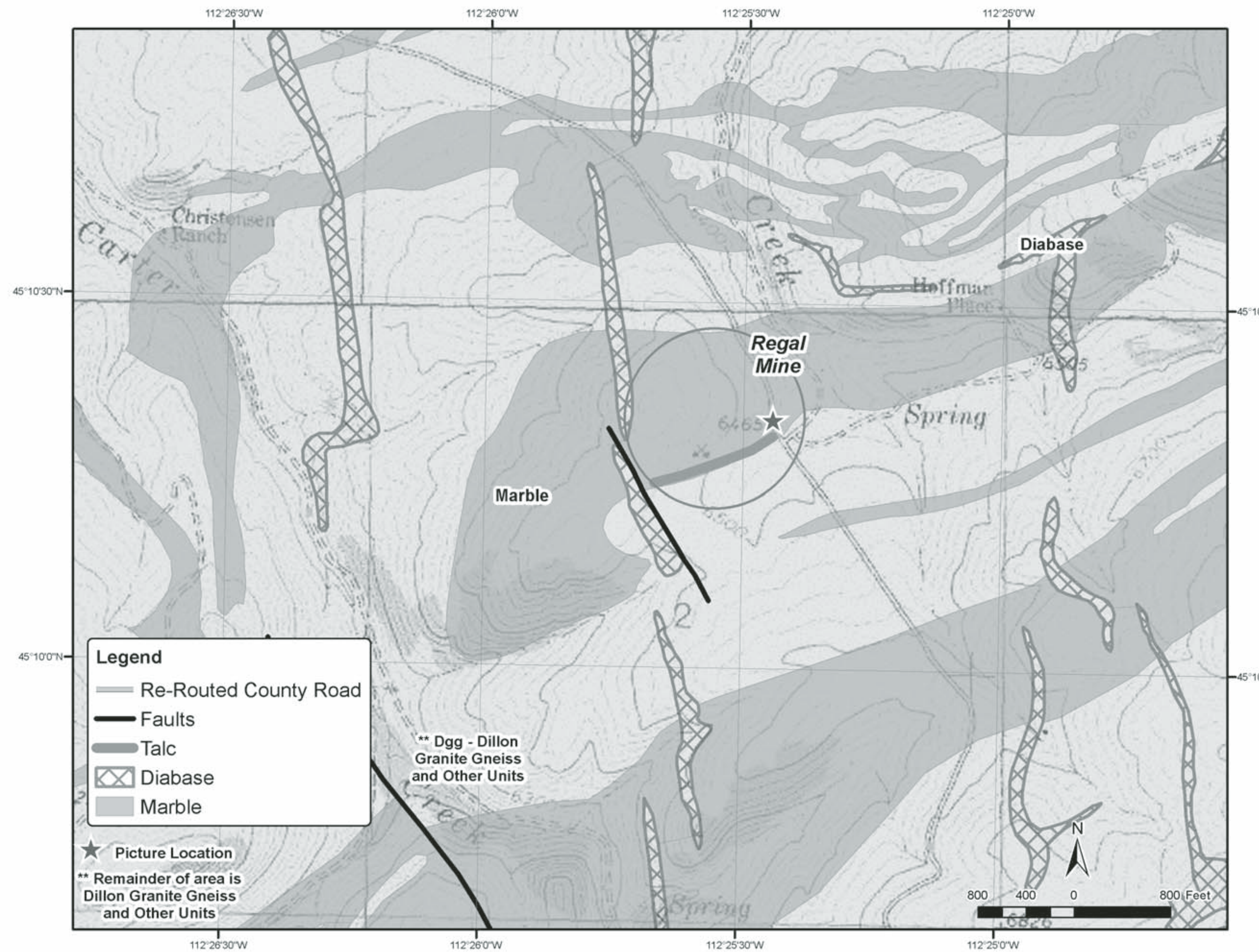


Figure 4. Geologic setting of the Regal Mine, Ruby Range (modified after James, 1990). The original mine locality is indicated by the crossed shovel symbol ~0.2 km west of the original right-of-way for the Sweetwater Road. Expansion of the mine pit necessitated re-routing the road ca. 2006 around a pit within the circle, and the star is the vantage point for Figure 13.

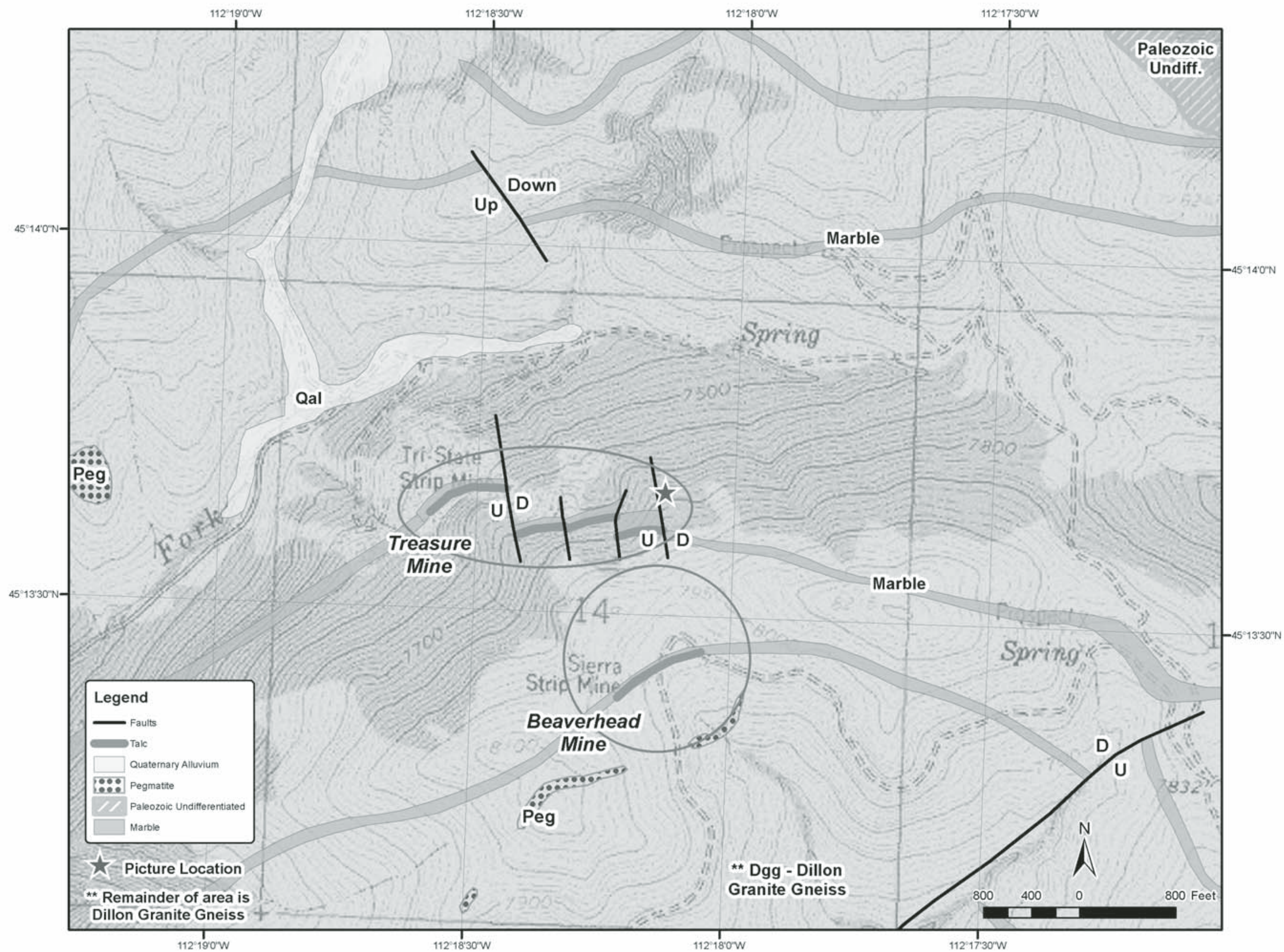


Figure 5. Geologic setting of the Treasure and Beaverhead Mines, Ruby Range (modified after Garihan, 1973). The pre-mining surface geology shown in the map guided placement of the large pits within the indicated oval and circle. The star is the vantage point for Figure 12.

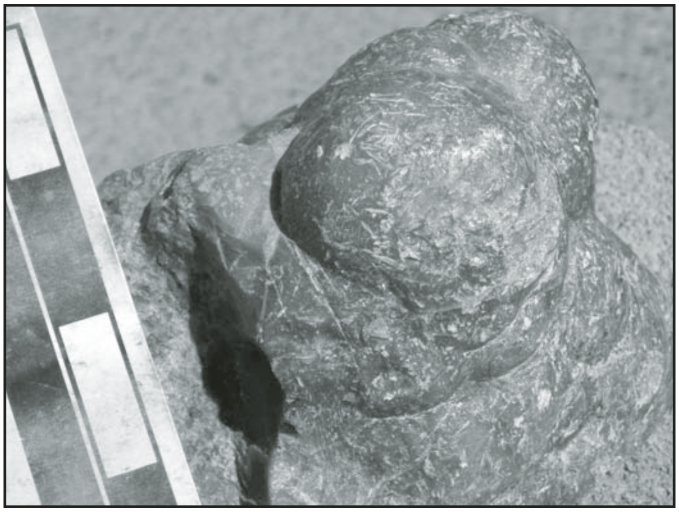


Figure 6. Botryoidal light green talc from the Yellowstone Mine. This texture is strong evidence for open space late in the talc-forming process. Scale is in inches.

Talc Textures

Constant volume replacement of carbonate by talc is indicated by the common occurrence of spectacular coarse dolomite, and possibly magnesite rhomboids, that are partially to completely replaced by talc, while perfectly preserving their rhombic shapes. The Beaverhead and Treasure Mines and the Whitney prospect farther north in the Ruby Range have especially well-developed examples of coarse-grained dolomite pseudomorphically replaced by talc. In addition, talc replaces olivine and diopside formed at amphibolite to granulite metamorphic grades, and tremolite formed during subsequent greenschist-facies metamorphism (Harms et al., 2004). Other evidence of constant volume replacement is found in the quartzofeldspathic gneisses and pegmatites adjacent to the marbles where Mg-chlorite replaces feldspar and mafic minerals and talc replaces quartz ribbons, while the blastomylonitic textures are perfectly preserved (Figs. 8 and 9).

Evidence for a shallow (epithermal) origin of the talc deposits includes the abundant development of botryoidal textures in the talc, possibly resulting from deposition from a colloid (Fig. 6), and other textural evidence cited above. Veins in the talc and the coarse recrystallized carbonate are lined with euhedral quartz and amethyst crystals (Fig. 7) at the Yellowstone Mine, the Whitney prospect, and many other localities. In order to maintain void space now expressed as vugs and common botryoidal textures in the talc zones and the host marble, talc must have formed at depths shallow enough for the rock to have behaved in a brittle manner. Experimental deformation studies on limestones and marbles (Paterson, 1978) suggest that the brittle-ductile transition in these rocks takes place at 0.3–1.0 kbar of pressure or roughly 1–3.5 km (0.6–2.2 mi) in depth. The effects of high heat flow would be expected to further decrease the depths to the brittle-ductile transition.

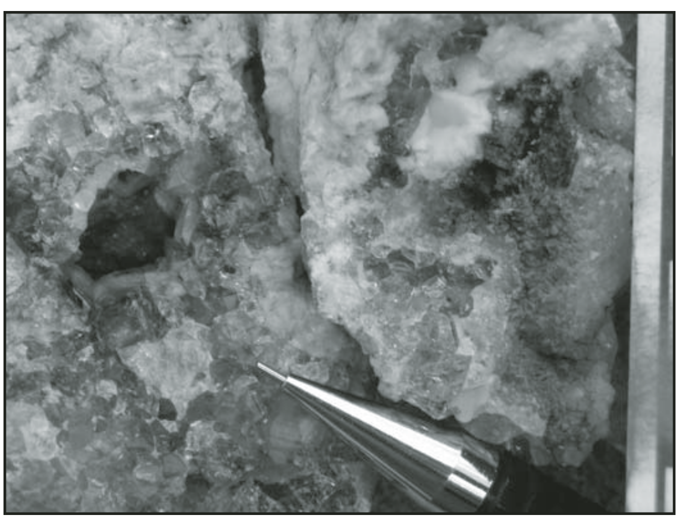


Figure 7. Coarse vugs lined with amethyst, smoky quartz, and locally chalcedonic banded quartz within coarsely recrystallized dolomite and talc. This texture is strong evidence for open space late in the talc-forming process. Samples collected from the Whitney prospect north of the Treasure Mine. Mechanical pencil provides scale.

GRAVELLY RANGE

The Yellowstone Mine, owned and operated by Imerys Talc, is located in the eastern foothills of the Gravelly Range 5.9 km

Figure 8. Loose block of pink quartzofeldspathic gneiss (i.e., Dillon Granite Gneiss) from the Treasure Mine area. Biotite in the gneiss in the upper part of the photo is partially replaced by chlorite but the feldspar and quartz are unaltered. The gneiss below the sharp boundary extending horizontally across the lower part of the block is strongly altered to chlorite and contains quartz veinlets. Individual foliation surfaces can be followed uninterrupted across the alteration boundary. Bird droppings (white elongated blot) are oblique to boundary. Rock hammer provides scale.

Figure 9. Constant volume replacement of quartz. Light green talc has completely replaced the original euhedral quartz crystal extending right to left across the center of the photo at the pencil point and other quartz grains in the left and upper portions of the photo. In this pegmatite, the talc is a pseudomorphic form after quartz, but feldspar remains relatively fresh even where it is immediately adjacent to quartz that is replaced by talc. Fresh quartz is present in this sample just to the left of the pencil point and exemplifies an abrupt alteration boundary. Pegmatite from the Granite Creek area in the southern Tobacco Root Mountains. Scale is in inches.

(3.6 mi) west of the Madison River (Figs. 1 and 10). Operations consist of an open pit mine, sorting and grading plants, and facilities to maintain heavy mining equipment. Continuous open pit mining operations have occurred since the early 1950s. The reserve base will support mining for decades into the future.

The Yellowstone Mine is situated in medium- to high-grade Archean dolomitic marble of the Wyoming province (Vargo, 1990). Low-grade metamorphic and intrusive rocks, which may be as young as Proterozoic in age, are exposed in the mine area and are separated from the marble by a northward-dipping thrust fault (Kellogg and Williams, 2000). The mine area is capped with volcanic tuffs, ashes, and clays of the Pliocene Huckleberry Ridge Tuff (Pritchett, 1993).

Talc ore bodies are hosted in a siliceous dolomitic marble unit that exhibits complex folding and faulting. The marble was structurally thickened by folding and underlies an area 4 km (2.5 mi) along strike and 2.4 km (1.5 mi) wide. Well-developed quartz rods and mullions are found throughout the dolomitic marble. These lineations are parallel to tight F_2 fold axes that have an average orientation of 15°/S35°W. The average strike of foliation is N35°E with dips ranging from 55° to 75° on both limbs of the primary synform. Foliation dips are to the SE on the north limb of the fold and to the NW on the south limb. Gray dolomitic marbles typically have sucrosic textures that range from fine-grained to microcrystalline. Local alteration of the marble by hydrothermal activity produced coarse crystalline masses stained maroon with hematite.

The primary talc orebody mined at the Yellowstone Mine is known as the Johnny Gulch deposit. This mass of talc is "decoupled" from the host rock, severely deformed, discordant to foliation of the host rock, and likely a replacement of select layer(s) within the massive dolomitic marble. Refolded folds still recognizable within the talc suggest intense deformation within the host dolomitic marble. Evidence of the earlier deformation events is further obfuscated by fault zone brecciation from periodic reactivation.

Of particular interest is the distribution of iron throughout the orebody. Yellowstone talc was formed in a reducing chemical environment with ~1% Fe in the system substituting for Mg^{2+} in octahedral lattice sites. Excess iron in the system combined with sulfur to form pyrite inclusions in the talc, presumably during talc formation. More recently, the pyrite oxidized to limonite and goethite above the water table, with partial mobilization to create rust stain along fracture surfaces. Differential concentrations of iron as FeO_x within the talc zones reveal fold patterns similar to those defined by the larger scale shape of the orebody.

Analysis of drill hole data and surface mapping using 3-D modeling of the talc orebody morphology suggests multiple superposed folding events occurred. Plastic deformation resulting from ductile flow of the carbonate host is indicated by flexures and convolutions in the talc-dolomite contacts. The interference patterns seen in 3-D modeling, i.e., folded hinges of earlier folds, indicate at least three superposed fold sets. The hinge-line of the primary antiform in the deposit plunges to the north. Thickening in the core of the fold nose is responsible for the primary volume of talc ore in the Johnny Gulch deposit.

Three north-south–striking normal faults provide the structural control and the plumbing system for fluids that created the talc mineralization in the Johnny Gulch orebody (Fig. 11). These large faults were invaded by mafic magmas, and periodic reactivation created fluid pathways for talc-forming mineral reactions in the carbonates and chlorite alteration in contacted mafic intrusive bodies. Multiple generations of carbonate minerals, silica, and to a lesser extent talc exhibit cross-cutting relationships at the periphery of these structures, indicating multiple fluid flux events (Cerino et al., 2007). The Johnny Gulch orebody consists of eight separate structural domains that are divided by key faults.

Cenozoic reactivation of the western boundary fault dragged the overlying Huckleberry Ridge ash, tuffs, and clays deep onto the footwall along the western boundary fault and related structures. Karst processes created large embayments into the carbonates along the hanging wall side of the western boundary fault. Karst features and offsets in the ash layers along the reactivated growth fault (Fig. 11B) are observable in the pit walls.

The majority of talc mined at the Yellowstone Mine was formed by a constant volume replacement of dolomite by talc. Relict compositional layering marked by minute amounts of graphite is observed to pass from the dolomitic marble host through pods of talc. This textural continuity indicates a constant volume replacement mechanism that could require a

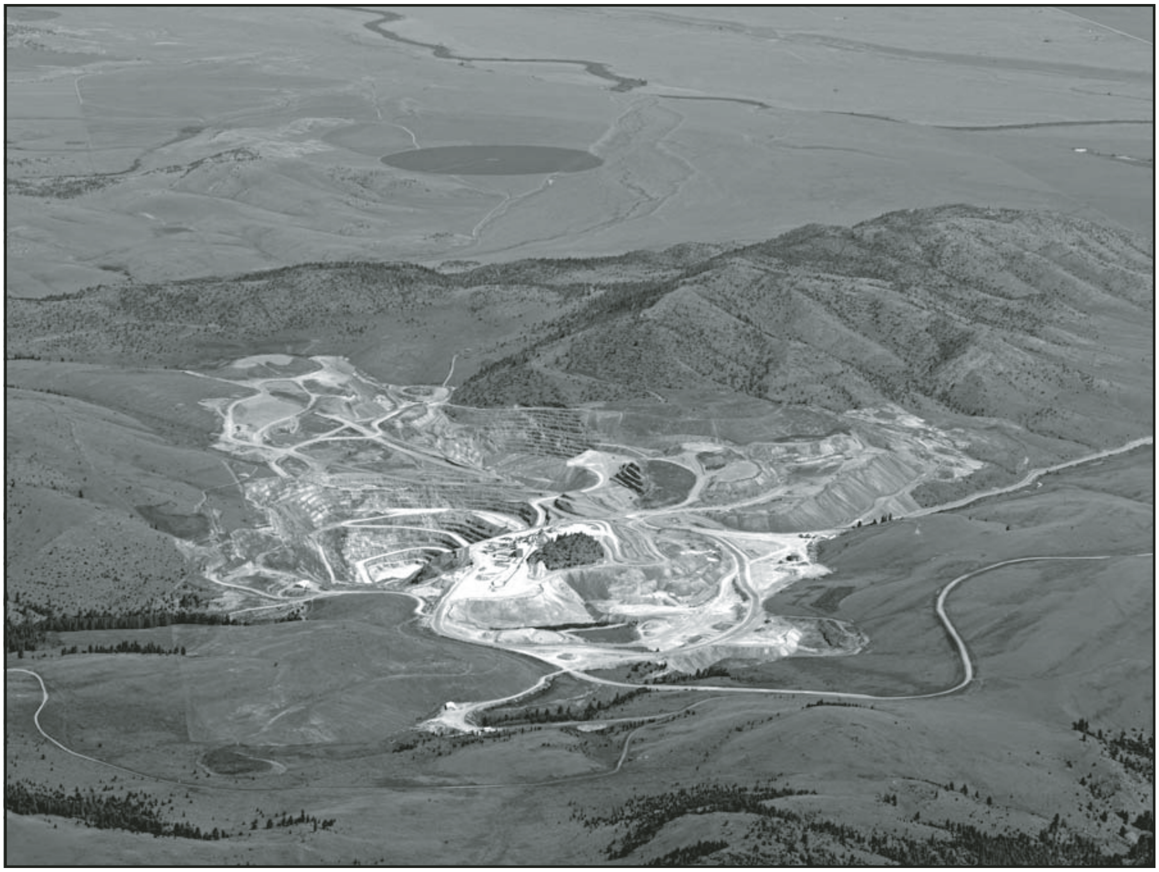


Figure 10. Oblique aerial view of Imerys Yellowstone Mine taken July 2013 looking north-northeast. The Madison River meanders across the upper right-hand portion of the image.

minimum volumetric water/rock ratio of 600 (Anderson et al., 1990). Minor amounts of talc with botryoidal textures exist in the Yellowstone deposit and are indicative of precipitation in open spaces. The botryoidal talc is usually free of iron oxide stain, and it cross-cuts the massive "constant volume" talc. Both the massive and botryoidal varieties are microcrystalline as a result of relatively low temperatures and pressures during talc formation.

Telescoping of the ancient hydrothermal system might explain the significantly different homogenization temperatures in fluid inclusions from the Yellowstone (140 °C) and the Cadillac–Burlington Northern talc deposit (88 °C) located less than one mile to the east in the same marble (Gammons and Matt, 2002). A telescoped hydrothermal system has a steep temperature gradient, such that radically different P-T determinations result depending on which part of the system is tested.

SOUTHERN RUBY RANGE

All of the deposits in the southern Ruby Range share the following characteristics:

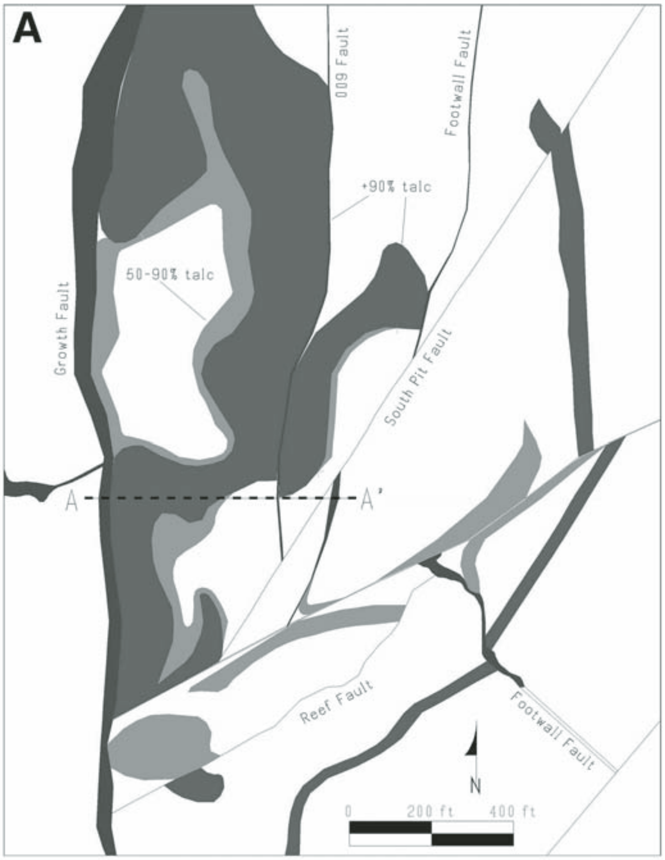
- The host rocks are Archean dolomitic marbles.
- Talc appears to preserve older fabrics developed as part of tight folding of the marbles and development of boudinage.
- Talc and chlorite formation was a constant volume process (Figs. 8 and 9).
- The host marble is strongly recrystallized with development of coarse dolomite with or without magnesite.
- Talc replaces the recrystallized coarse-grained dolomitic marble; chlorite is present as an alteration product of the adjacent gneisses and schists (Fig. 8).
- The talc deposits terminate abruptly both along strike (Fig. 12) and perpendicular to the compositional layering.
- The host dolomitic marble in contact with talc tends to be coarsely crystalline and lighter in color, and late silica veinlets are common (Fig. 3).
- Graphite and pyrite are present as accessory minerals in the talc.

Numerous smaller talc deposits are found in the southern Ruby Range both north and south of the Sweetwater Basin, which transects the southern part of the range southeast of Dillon, Montana (Fig. 1). These smaller talc deposits have had varying levels of exploration and development, and some have produced talc from both underground and surface-mining operations.

The southern Ruby Range has several major talc deposits—the largest of which are the Regal Mine located ~11 km (7 mi) to the east-southeast of Dillon on the Sweetwater Road (Figs. 4 and 13) and the Treasure Mine and the adjacent Beaverhead Mine in the headwaters of Stone Creek (Figs. 5 and 12). In this chapter, the Treasure Mine includes both the formerly active Treasure Chest Mine and the presently operating Treasure State Mine because they are on the same orebody and have been mined with a single open pit. A major north-south fault termed the "Treasure fault" passes through the Beaverhead and Treasure Mines as well as prospects aligned along the fault farther north. This structure was likely the primary conduit for passage of talc-forming fluids, because strongly chloritized zones in gneiss and schist and talc mineralization in marble coincide with probable fault traces. Barretts Minerals Inc. owns and operates both the Regal and Treasure Mines, and ores are processed at a mill located on a rail line ~13 km (8 mi) south of Dillon, Montana, on the east side of Interstate 15.

Regal Mine

The orebody at the Regal Mine strikes west southwest and dips ~45° to the north. It occupies the footwall of the "Regal" marble, and this marble in the mine area is made up of both limbs of an early isoclinal fold that was subsequently refolded to produce a "fish hook" interference pattern (Fig. 4). The shaft



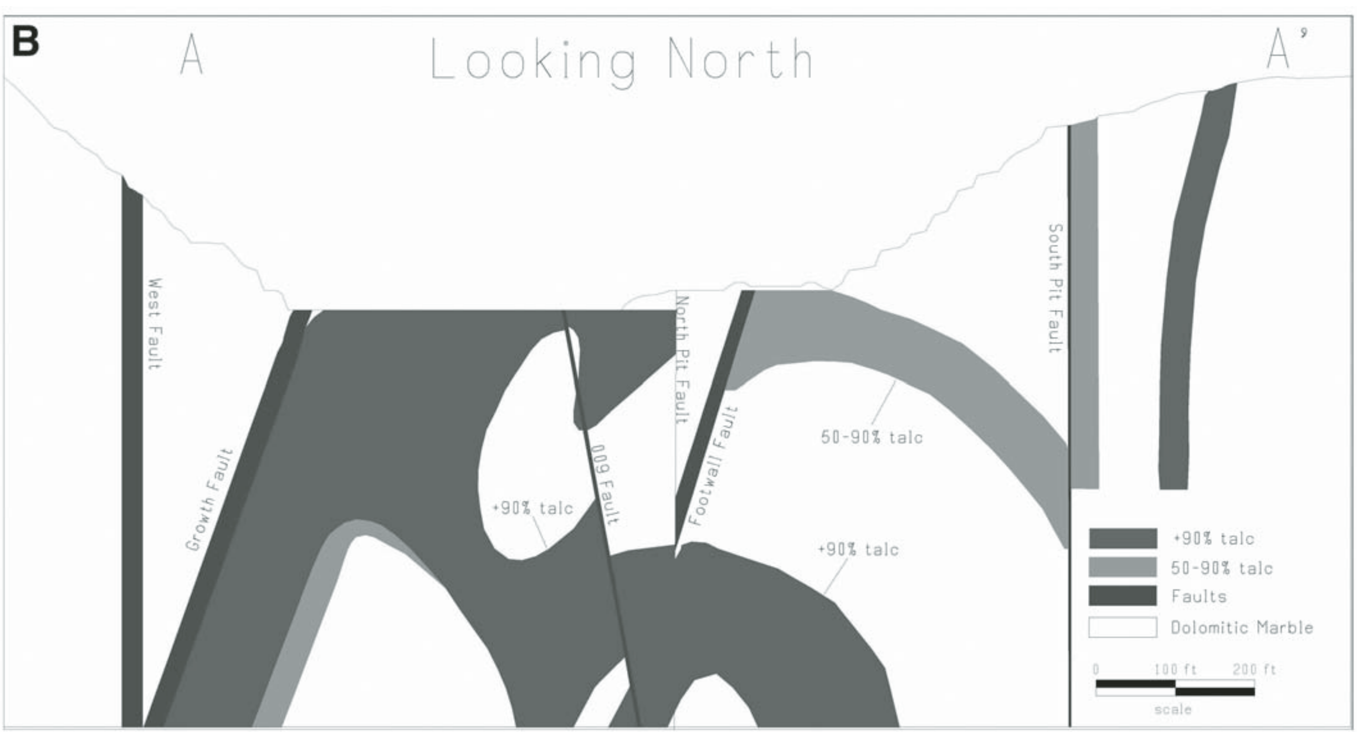


Figure 11. Complex folding and faulting of the Johnny Gulch orebody at the Yellowstone Mine. (A) Plan view geology. (B) Section A–A′ view geology at mine coordinate 7700N. Faults are labeled and fault zones are black sinuous lines. Dark gray regions are >90% talc, light gray are 50%–90% talc, and white areas are dolomitic marble.

Figure 12. View looking west subparallel to the strike of the Treasure orebody from the location indicated in Figure 5. The marble and contained talc orebody dips to the right at ~40° north. The dark gray rocks outlined by two black lines on the mine face in the center of the photo are brown and green footwall schist and gneiss that are locally intensely altered to chlorite (green). The host marble is unaltered where it extends out of the pit to the right in the photo. The host marble visible at the left edge of the photo is unaltered east of the pit.

of the fish hook in the mine passes to the west where it bends sharply to the south and then back to the east, terminating at the end of the "hook."

The Regal orebody is as much as 61 m (200 ft) thick and is immediately underlain by a strongly chloritized garnetiferous sillimanite mica schist. In most places, the hanging wall of the orebody is a fault contact between the orebody and marble. The hanging wall of the marble in the mine includes interlayered biotite gneiss, amphibolite, quartzofeldspathic gneiss, and pegmatite. Subsidiary talc bodies are found in the marble above the main talc zone. The orebody is terminated on the west by a nearly vertical diabase dike that is ~30 m (100 ft) thick, is locally altered to chlorite, and is the inferred heat source for the hydrothermal cell(s) that produced the orebody. The orebody appears to terminate on the east by a major brecciated fault zone with abundant iron and manganese staining, calcite veins, and silicification. This fault strikes north-northwest and is approximately vertical.

To date, only minor talc has been identified by drilling and mapping on the west side of the major diabase dike. The reason for this major difference in talc development east and west of the dike is poorly understood. Thin mafic dikes cut the hanging wall marble and are clearly visible in the west and south wall of the pit. They are probably much younger than the diabase. Potential to expand the talc reserves at the Regal Mine appears to be good.

SUMMARY

The talc deposits in the Gravelly and Ruby Ranges are hosted by Archean dolomitic marbles and are associated with major faults that acted as conduits for hydrothermal fluids thought to be responsible for alteration of marble to talc and of gneisses and schists to chlorite. The source of at least some of the talc-forming fluids appears to have been the middle Proterozoic Belt basin, and the abundant evidence for open space and constant volume talc formation suggests a relatively shallow crustal level for talc formation. Mass balance calculations by Anderson (1987) suggest an open system, possibly under hot spring conditions. The reserve estimates at southwestern Montana mines have significantly increased in recent years, with good potential for discovery of additional reserves.

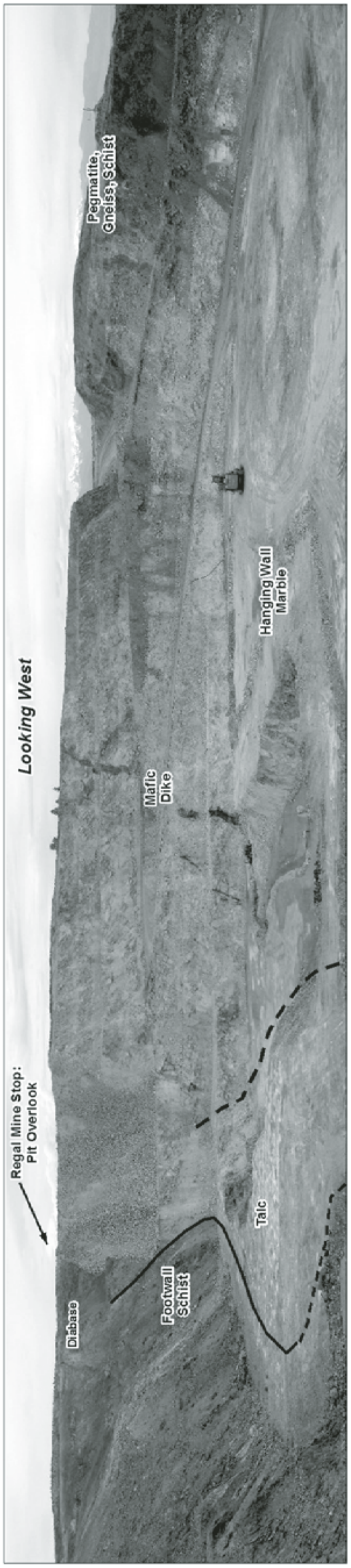


Figure 13. Regal pit view looking west down the fold axis of the re-folded fold from the location indicated in Figure 4. The footwall of the orebody and marble is to the left (south) and the hanging wall of the marble is to the right (north). A thin, continuous mafic dike is visible in the middle of the photograph running from the bottom to the top of the pit wall. The large north-northwest–trending diabase dike shown in map view in Figure 4 is visible to the left (i.e., southwest corner of the pit) in this picture. Pegmatite and gneiss are exposed in the hanging wall on the right side of this picture. Snowy peaks of the Pioneer Mountains are visible where the mine road exits the pit.

ROAD LOG, INTRODUCTION

This road log was generated from a combination of published documents adapted to describe the geology along various segments of the highway routes to, between, and returning from the Yellowstone and Regal Mines in southwest Montana, and are cited below with corresponding road increments. The older road logs were updated and expanded with new geologic information where warranted. The trip length precludes stops other than for tours at the talc mines, but the Archean to Holocene rock exposures and spectacular geologic structures en route are outlined here for geologic interest. The high probability of inclement spring road conditions makes unpaved roads, such as the Sweetwater Road, which traverses the Ruby Range, potentially impassable. However, the Sweetwater Road from Alder to Dillon is a geologically rewarding and scenic road through the Ruby Range, and can provide excellent access to Archean basement and Cenozoic structures.

A route map is provided for reference (Fig. 14). The basic framework of the road log begins with the segment from Bozeman to Norris, Montana, traveling on Montana Highway 84 (McMannis, 1960). From Norris to Ennis along U.S. Highway 287, we updated information from Johns et al. (1981). The road log segment from Ennis to the turnoff of U.S. Highway 287 south of Cameron was created for this trip because this is the access to Imerys Talc Yellowstone Mine. From Ennis to Twin Bridges, we again augmented the road log of Johns et al. (1981). The segment that includes Dillon, Whitehall, and Bozeman along Montana Highway 41, Montana Highway 55, and I-90 follows an updated version of the road log from Schmitt et al. (1995). The commentary for the Sweetwater Road from Dillon to the Regal Mine used Sears et al. (1995) as a template.

A schematic depiction of the lithologies and time and/or spatial relationships is presented in Table 1.

ROAD LOG, DETAILED

Mileage	*Directions and Descriptions*
0.0	Leave Montana State University Student Union Building (SUB). WGS84 datum; UTM 0496292 m E; 5056890 m N. From parking area, turn right onto Grant Street. At stop sign, turn left onto 11th Street.
0.3	At stop sign, turn right onto W. Lincoln Street.
0.8	Turn right onto S. 19th Ave.
1.3	At stop light, turn left onto W. College St.
2.0	Turn left on W. Main St. (U.S. Highway 191). The road name switches to Huffine Lane.

Geographic orientation: On the left, at 8 o'clock, is the Gallatin Range, 10 o'clock is the Madison Range, and on the right at 4 o'clock is the Bridger Range.

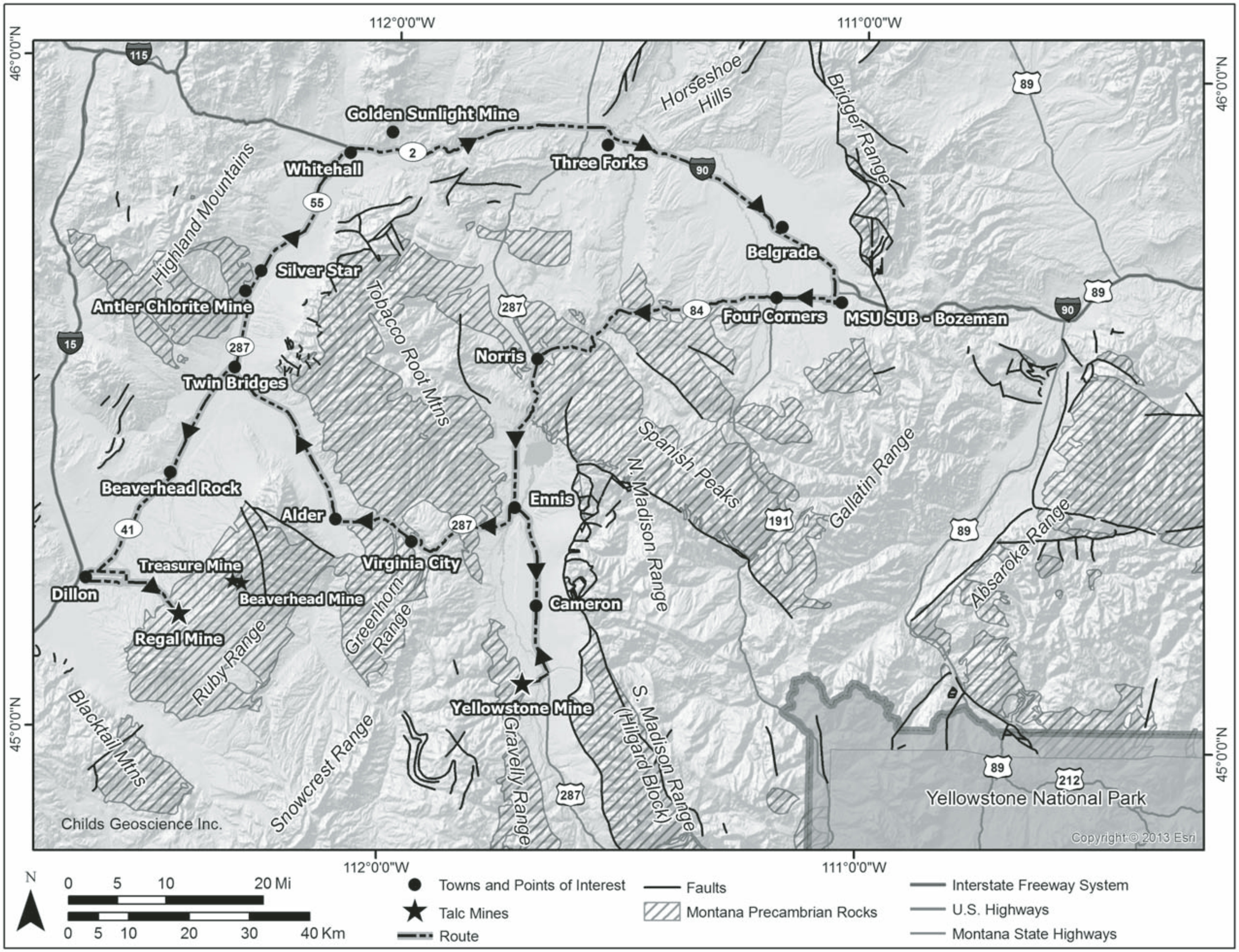


Figure 14. Field trip route map. The Yellowstone Mine (Stop 1) and the Regal Mine (Stop 2) are shown with arrows in the direction of travel. The SUB starting point is on the Montana State University campus.

TABLE 1. SCHEMATIC REFERENCE SECTION OF MAJOR LITHOLOGIC UNITS AND AGES OF OUTCROPS ALONG THE SOUTHWEST MONTANA FIELD TRIP ROUTE FROM BOZEMAN TO DILLON, VIA NORRIS, ENNIS, AND VIRGINIA CITY, AND FROM DILLON TO BOZEMAN VIA WHITEHALL

Eon	Era	Period	Epoch	Thickness (m, avg.)	Sedimentary unit	Igneous unit	Abbreviated lithology	Source
Phanerozoic	Cenozoic	Neogene	Holocene		Recent or active sediments		Recently or actively depositing fluvial, lacustrine, aolian, glacial systems; includes colluvium.	
			Pleistocene				Fresh till of the Pinedale Glaciation, partly weathered till of the Bull Lake Glaciation, and deeply weathered till of a Pre-Bull Lake Glaciation.	J. Montagne, 1989, personal commun.
			Pliocene	3–170		Huckleberry Ridge Tuff	Fine- and coarse-grained facies containing tuffaceous siltstone, conglomeratic sandstone, and brown to gray conglomerate, as well as common exposures of the lithologically varied Six Mile Creek Formation.	Kellogg, 1994; Vuke et al., 2002; McDonald et al., 2012;
			Miocene			Basalt flows		
		Paleogene	Oligocene	300	Dunbar Creek Fm.		Tuffaceous siltstone, fine-grained sandstone, poorly sorted coarse-grained arkosic sandstone, and matrix-supported conglomerate beds of the Dunbar Creek Formation (Renova equivalent).	Marvin et al., 1974; Vuke et al., 2002
			Eocene (middle)	300+	Undiff.	Virginia City volcanic field and Absaroka Volcanics	Pale olive to reddish-brown bentonitic, sandy clay and claystone, yellowish-gray coarse-grained argillaceous sand and sandstone, and tuffaceous siltstone and fine-grained volcanic glass sandstone of the Climbing Arrow Formation (Renova equivalent), atop the intercalated gray, fine-grained tuffaceous limestones and conglomerates of the Milligan Creek Formation.	Vuke et al., 2002
			Eocene (early)	—	Red Bluff Fm.	Andesite, latite, and dacite sills	Pale siltstone, sandstone, conglomerate, and brick-red mud and siltstone overlying subrounded to well-rounded, matrix-supported, bouldery diamictite.	Vuke et al., 2002
	Mesozoic	Cretaceous		600	Undiff.	Tobacco Root batholith, Boulder batholith and its satellite plutons (including Hells Creek pluton), Elkhorn Mtn Volcanics	Cretaceous sedimentary rocks include the Sphinx Conglomerate, Beaverhead Conglomerate, Livingston Formation (Sedan equivalent), Everts Formation, Virgelle Sandstone, Eagle Sandstone, Telegraph Creek Formation, Cody Shale, Frontier Formation, Mowry Formation, Muddy Sandstone, Thermopolis Formation, and Kootenai Formation.	Vuke et al., 2002; Kellogg et al., 2007
		Jurassic	Upper	200	Undiff.		Jurassic sedimentary rocks include the Morrison Formation, Swift Formation, Rierdon Formation, and Sawtooth Formation.	J.Montagne, 1989, personal commun.
		Triassic		0–30	Dinwoody		Brown sandy limestone and calcareous shale.	J. Montagne, 1989, personal commun.
	Paleozoic	Permian		0–30	Shedhorn S.S. (Phosphoria equiv.)		Brown to greenish-brown, laminated or thin- to thick-bedded chert, interbedded with oolitic phosphatic sandstone, siltstone, and yellowish-gray dolomitic limestone.	
		Penn.	Upper	40	Quadrant		Pale cream-colored clean washed dolomite cemented quartz arenite.	J. Montagne, 1989, personal commun.; Kellogg and Williams, 2005
			Lower	88	Amsden Group		Brick-red, reddish-brown, and pink calcareous siltstone.	
		Mississippian		130	Snowcrest Range Group		Dark gray thin- to medium-bedded limestone of the Lombard Formation overlying thin- to medium-bedded, yellow-gray to maroon, friable Kibby Sandstone.	J. Montagne, 1989, personal commun.; Kellogg and Williams,
				135–275	Big Snowy Group		Thin- to thick-bedded, pale olive gray, locally fossiliferous limestone atop red and green-gray shale, calcareous sandstone, and cherty limestone.	
				440	Madison Group		Light gray, locally fossiliferous, thick-bedded to massive limestone of the Mission Canyon Formation atop thin- to medium-bedded limestone and argillaceous limestone of the Lodgepole Formation.	

(*Continued*)

TABLE 1. SCHEMATIC REFERENCE SECTION OF MAJOR LITHOLOGIC UNITS AND AGES OF OUTCROPS ALONG THE SOUTHWEST MONTANA FIELD TRIP ROUTE FROM BOZEMAN TO DILLON, VIA NORRIS, ENNIS, AND VIRGINIA CITY, AND FROM DILLON TO BOZEMAN VIA WHITEHALL (*Continued*)

Time units				Thickness (m, avg.)	Sedimentary unit	Igneous unit	Abbreviated lithology	Source
Eon	Era	Period	Epoch					
Phanerozoic	Paleozoic	Devonian		40–60	Three Forks Fm.		Thin-bedded, yellowish siltstone and silty limestone.	Kellogg and Williams, 2005
				110	Jefferson Dol. and Maywood Fm.		Thin- to thick-bedded, dark gray to light gray, petroliferous, locally fossiliferous Jefferson Dolomite overlying pale yellow sugary dolostone of the Maywood Formation.	Vuke et al., 2002; Kellogg and Williams, 2005
		Ordovician		3	Bighorn Dol.		Scarce occurrences only in the northwestern Madison Range. Thin- to medium-bedded light gray dolostone.	Kellogg and Williams, 2005
		Cambrian		40–60	Red Lion Fm. (Snowy Range equiv.)		Thin-bedded tan to gray siliceous dolostone intercalated with orange-tan to reddish-tan cherty ribbons. Lower portion contains intraformational clasts up to 5 mm.	Kellogg and Williams, 2005
				30–120	Pilgrim Fm.		Medium-bedded to massive, light gray, locally oolitic dolostone.	
				30–75	Park Shale		Greenish-gray to tan, fissile shale.	
				50–150	Meagher Fm.		Thin-bedded to massive, light gray micritic limestone.	
				30–65	Wolsey Shale		Thin-bedded, greenish-gray, olive, micaceous sandstone, siltstone, and shale.	
				15–75	Flathead Formation		Thin- to medium-bedded, medium- to coarse-grained, reddish-brown, tan, and purplish-tan arkosic sandstone. Basal conglomerate contains rounded pebbles of metamorphic rock.	
Proterozoic	Neoprot.			~30		Diabase	Sets of mafic dikes, ferrobasaltic to tholeitic composition.	Kellogg and Williams, 2005; McDonald et al., 2012
	Mesoproterozoic			up to 20,000	Belt Supergroup		A truly venerable assemblage of siliciclastic and carbonate rocks deposited in the Belt Basin from 1.47 to 1.4 Ga. Argillite and quartzite of the Missoula Group overlie the Middle Belt carbonate units, which in turn overlie the argillite and planar- and cross-bedded sericitic quartzite of the St. Regis, Revett, and Burke Formations. At the base of the Belt Supergroup lie the laminated siltite and argillite couplets of the Prichard Formation. LaHood Formation is a basal syntectonic coarse conglomerate along Perry Line and Willow Creek fault.	Schmidt et al., 1988; Ross and Villenueve, 2003; McDonald et al., 2012
Archean				Unknown	Meta-igneous and meta-sedimentary rocks		Quartzofeldspathic gneiss, amphibolite and hornblende-plagioclase gneiss, biotite schist, dolomitic marble, aluminous gneiss and schist, banded iron formation, and ultramafic rocks.	Kellogg and Williams, 2005; McDonald et al., 2012

Bozeman to Four Corners

This road log segment is adapted from Schmitt et al. (1995).

Bozeman was named for John M. Bozeman, who scouted the route from the Oregon Trail near Ft. Fetterman (Douglas), Wyoming, to the gold camps of western Montana. In 1864, he successfully guided fortune seekers over the route from Ft. Laramie. Bozeman was platted in 1864 through his efforts. Early growth of Bozeman was based on the rich agriculture of the Gallatin Valley. In 1893, Montana State College was founded as the state's land-grant institution of higher education, with emphases in agriculture and engineering.

Geologic Setting of the Gallatin Valley

The valley is surrounded by mountains on all sides, and lies at the juncture of four major tectonic provinces including: (1) the south margin of the middle Proterozoic Belt basin; (2) the Sevier fold-and-thrust belt, where the south margin of the Helena salient reactivated Belt basin faults); (3) thick-skinned Laramide deformation; and (4) eastern limit of Neogene "Basin and Range" extensional deformation (Lageson, 1989). Laramide uplifts include the Bridger Range to the east, the Beartooth and Gallatin Ranges to the south, the Spanish Peaks–Madison Range to the southwest, and Tobacco Root Mountains to the west. The north end of the Gallatin Valley is framed by the Horseshoe Hills and Big Belt Mountains, both lying within the Belt basin and Sevier fold-and-thrust belt. Lageson (1989) describes the Bridger Range as "a perched basement wedge of Archean and Proterozoic rocks overlain by steeply east-dipping Paleozoic-Mesozoic strata." In addition, a high-angle normal fault bounds the north flank of the Gallatin Range at the south end of the valley, and several normal faults within the Gallatin Valley are antithetic to range front normal faults.

Between Bozeman and Four Corners, U.S. Highway 191 traverses poorly consolidated Tertiary sediments that fill the Gallatin Valley. Based upon a local anomaly of approximately –30 mGals in gravity data (Kucks, 1999), Schmitt et al. (1995) state that as much as 1525 m (5000 ft) of Tertiary fill is locally present. The crest of the ancestral Laramide Bridger Range lies beneath the valley to the north, having been down-dropped by a listric normal fault(s) that bounds the west flank of the range. Inasmuch as basement rocks are overlain by Tertiary strata along the west margins of the valley, the crest of the ancestral Bridger Range was probably eroded to the basement before being displaced by normal faulting. Thus, the presence of Paleozoic or Mesozoic rocks at depth in this part of the valley is unlikely.

To the south, the Gallatin Range is capped by Eocene volcanic rocks genetically related to the Absaroka and Challis volcanic fields.

Four Corners to Norris

This road log segment is adapted from McMannis (1960).

7.3	Four Corners: Junction of U.S. Highway 191. Landmarks are Korner Club and gas stations. Proceed west to Norris on Montana 84.
8.4	Gallatin River crossing.
9.2	Immediately west of Cottonwood Golf course lies a gravel pit north of the highway. Outcrop of Neogene valley-fill sediments?
11.1	Amsterdam Road on right.
12.7–13.0	Excellent outcrops of Miocene thin-bedded lake sediments, part of the sedimentary fill in the Gallatin Valley (Vuke et al., 2002).
16.0	On right, outcrops of garnetiferous hornblende-biotite gneiss, schist, and amphibolite of the Archean basement.
16.2	Intersection of Camp Creek Road on north with renovated Anceney grain elevator on south side of road and former railroad terminus. This was a center for grain shipment to mainline railroads farther north into the 1980s. The elevator was sold in ~1993 and is now a residence. The ranch that Charles Anceney Sr. established, the Flying D, was purchased by Ted Turner and is where he raises bison.
16.4	Exposures of fine-grained Miocene beds in roadcuts. These strata are unconformable on the Precambrian basement along a surface of strong relief.
17.4	Geographic orientation: At 11 o'clock the crest of the Tobacco Root Mountains is visible. The name, Tobacco Root, is reportedly derived from the habit of local Native Americans, who collected mullein plants in the area and mixed them with kinnikinnick as a substitute for smoking tobacco (Schmitt et al., 1995).
18.8–19.2	Archean gneisses cut by pegmatites are exposed on the right.
21.3	Highway crosses Elk Creek. This valley is the surface topographic expression of one of many northwest-trending oblique reverse faults in the area similar to the fault along Cherry Creek of mile ~26.8.
24.6	Black's Ford Fishing Access to the Madison River and Madison River Road on right. Wildfire swept over the area in June 2012.

High metamorphic grade Archean rocks of the Spanish Peaks region ~10–20 km to the southeast are within the same structural block and experienced the same general geologic history as rocks exposed here (Kellogg, 1994). Mogk et al. (1989) report a U-Pb zircon age from Spanish Peaks quartzofeldspathic gneiss of 3.3–3.2 Ga. Voluminous melts, mostly trondhjemitic and tonalitic, were injected in the Spanish Peaks area at 3.2–3.1 Ga, which is the suggested age of peak metamorphism (Mogk et al., 1989).

25.1	Madison County line.
25.3–25.5	Two old base metal mine portals visible on the left explored veins in Archean gneiss.

26.0 On the right, across the Madison River, is a prominent exposure of Archean quartzofeldspathic gneiss that is a popular rock climbing venue called "Neat Rock Crag" by locals.

26.8 Turn off to Damsel Fly Fishing Access to Madison River and bridge over Cherry Creek. The road crosses a northwest-trending reverse fault similar to the Spanish Peaks fault zone, which offsets Precambrian rocks on the north against Paleozoic rocks to the south in the area immediately east of the highway. West of the Madison River, that same fault zone appears to have recently undergone minor reactivation as a normal fault. Across the river at 2 o'clock is Red Mountain, which is underlain by Tertiary rhyolitic volcanic rocks (rhyolitic vitrophyre, Vuke et al., 2002).

27.9 Cliffs at 3 o'clock across the river are underlain by Archean gneiss at their base and overlain by the Cambrian Flathead Formation (Paleozoic).

28.2 Bear Trap Canyon access road on left. The road ends at a trailhead and fisherman's access.

28.4 Highway crosses Madison River.

29.7 Excellent outcrop of migmatitic quartzofeldspathic gneiss and amphibolite cut by steeply dipping pegmatite dikes in cliff on south shore of Madison River.

30.2 To the left, across the river, a rock fall occurred in ~1990, which blocked the Bear Trap Canyon access road, stranding a number of recreationists to the south. Numerous pegmatitic dikes cut the Archean gneiss.

31.1 Parking area for the Warm Springs Creek Fishing Access and mouth of Bear Trap Canyon to south, where the incised Madison River flows from the Madison Dam 16 km (10 mi) south of here. In August 2010, a semi-truck–sized boulder dropped off the canyon wall and onto the concrete dam. The hydroelectric company PPL Montana, who oversees the dam and associated powerhouse, reported some crushed spill gates, but the lower dam structure apparently was deemed sound.

Tertiary Red Bluff conglomerate caps the hill that lies across Warm Springs Creek to the east. For the next several miles, the highway follows the general east-northeast trend of this creek, which flows across Precambrian metamorphic rocks. Many excellent exposures of these rocks are seen in roadcuts and canyon walls. Shoulders on ridges to the south of the road suggest an ancient mature valley was incised by Warm Springs Creek.

31.6 Severe erosion visible on the right was a result of a wildfire in 2012. Continue up Warm Springs Creek through Archean gneisses.

33.7 On the left, Montana Agricultural Experiment Station.

33.9 Bradley Creek Road turnoff to the south and the Lower Hot Springs Mining District. From 1870 to 1948, lode gold was the primary commodity with byproducts of silver, copper, and lead (Kellogg, 1994). Oxidized sulfide-bearing quartz veins cutting Archean gneiss were the typical mining targets. The richest gold-bearing veins in the Lower Hot Springs district (e.g., Boaz and Grubstake Mines) are parallel to a regional set of northwest-striking, northeast-dipping to nearly vertical, Late Cretaceous to earliest Tertiary reverse faults. The Boaz Mine workings are located at 9 o'clock; a large mine dump is just visible in the upper part of the valley. There are spectacular views of the Tobacco Root Mountains at 12 o'clock. Low hills to the south are underlain by diamictite and fine sediments of the Eocene Red Bluff Formation. Hot spring activity has locally silicified this unit.

Norris to Ennis

This road log segment is adapted from Johns et al. (1981).

36.5 Norris. Junction of U.S. Highway 287 and Montana 84. Turn south up Burnt Creek to McAllister and Ennis. Hills to the west are capped by Miocene basalt, which overlies Miocene siltstone and sandstone (Kellogg, 1994). Miners leaving Virginia City/Alder Gulch following the peak in placer gold production in 1865 located lode gold mines in the Norris area in the late 1860s, and by 1900, load gold mining largely ceased (Montana Abandoned Mine Reclamation, 2014).

39.4 Archean gneiss is visible in roadcuts on the left.

39.7 Roadcut exposes the eastern margin of the Late Cretaceous Tobacco Root batholith, which intrudes Archean gneiss and amphibolite in the central Tobacco Root Mountains. This batholith is a zoned granodioritic pluton (medium-gray, coarse-grained, porphyritic) located at the northwest end of the Spanish Peaks–Gardiner fault system (Schmitt et al., 1995). Left-reverse motion on splays of the Spanish Peaks–Gardiner fault system may have accommodated intrusion of magma into a transtensional pull-apart (Schmidt et al., 1990).

41.9 Summit of Norris Hill. High country to the west is underlain by Archean rocks and the Tobacco Root batholith. The Madison Valley opens to the south.

43.9 Crossing northwest extension of Spanish Peaks fault. This fault is believed to be a continuation of the northwest-trending Gardiner thrust zone, visible at the north entrance to Yellowstone National Park. In this area, the Spanish Peaks fault cannot be readily identified along the road.

Multiple pediment surfaces in this area include the prominent surface that approximately coincides in elevation with that of the Cameron Bench, which lies to the south of Ennis. Fluvial gravels exposed in roadcut to the right (west) are imbricated, indicating flow to the south; beds now dip 10–12 °N.

46.5 McAllister Post Office. Continue south across floodplains of North and South Meadow Creeks, which are slightly incised into the Ennis terrace.
49.8 Highway crosses to higher, slightly older terrace. To the west is a still higher general level named the Cameron Bench, which is ~76 m (250 ft) above the present floodplain of the Madison River. There are excellent views of the Spanish Peaks Wilderness at 8 o'clock, Jack Creek at 10 o'clock, and Fan Mountain at 10:30.
53.0 Junction of U.S. Highway 287 and Montana Highway 287 in Ennis. Bear east into downtown Ennis and south on U.S. Highway 287.

We shall return to this junction following our visit to the Yellowstone Mine, which is ~34 km (21 mi) south. The road log contains information for traveling both directions.

53.5 Rest stop at Lions Club Park on south side of Ennis prior to crossing Madison River.
54.1 Odell Creek bridge. The Gravelly Range, visible at 11 o'clock, lies on the eastern limb of a large southwest-plunging syncline. Phanerozoic sediments exposed in this syncline separate the pre-Belt metamorphic rocks exposed in the Gravelly Range from those exposed in the Greenhorn Range to the west (Johns et al., 1981).
59.8 Ennis airport road (east). The fault-bounded Madison Range is visible on the left, and the Gravelly Range on the right.
62.9 Sphinx Mountain is at 10 o'clock. A syncline that formed during the Cretaceous age by progressive crustal loading during thrust faulting was filled with coarse sediments that lithified into conglomerate (cf. Beaverhead Formation) that caps Sphinx Mountain. Hendrix (2011) provides a nice geology hiking trail guide for up close inspection of fault surfaces and lithologies of the Helmet and Sphinx Mountain areas.
64.3 Cameron Post Office.
68.5 River terraces are visible to the west as we descend from the Cameron Bench.
70.0 To the right, a prominent extension of the Gravelly Range juts eastward into the Madison Valley. This nose is underlain by Archean dolomitic marble that hosts the talc in the Yellowstone Mine, which is coming into view on the south side of the hills.
71.6 Turn right onto the road leading to McAtee Bridge Fishing Access and the Yellowstone Mine operated by Imerys Talc (signs). An aerial photograph of the mine site (Fig. 10) may aid orientation.
72.3 Cross Madison River.
72.8 Note the rugged Hilgard block, which forms a portion of the southern Madison Range at 7 o'clock. The Yellowstone Mine is located at 11 o'clock.
74.5 The public road goes left; stay right. The old Burlington Northern Talc Pit is at 3 o'clock.
74.6 Turn right to visitor check-in at Imerys Talc Yellowstone Mine office. We will take a site tour led by mine personnel.

STOP 1

The southwest pit overlook is located along the Growth Fault (mine name only, not a genetic term), which is stained maroon by hematite, and cuts dolomitic marble. The Growth Fault can be traced northward along strike to where it cuts altered chlorite; and at the northern end of the structure, stratified deposits of distal Pliocene Huckleberry Ridge volcanic rocks are visible. The North Pit and Footwall faults are visible on the north pit wall at about N30°E and the South Pit fault can be seen along the eastern margin of the pit. As of January 2014, activity in the pit is focused in the southern portion of the talc body, south of section A–A′ in Figure 11A, as well as on upper benches to the north.

74.8 Leave the Yellowstone Mine and retrace route north to Ennis, Montana.
75.0 Recent fault scarps cutting alluvial fans at 2 o'clock formed at the western margin of the Hilgard Block. At 12:30, a large moraine at the mouth of Indian Creek drains west out of the Hilgard Block. Immediately north of this moraine at 12 o'clock is a possible debris flow.
75.3 At 11 o'clock, there is an excellent view of Sphinx Mountain on the right and lower Helmet Peak on the left. Similar to the Sphinx, Helmet Peak is Sphinx Conglomerate underlain by Cretaceous sedimentary and volcanic rocks.
77.1 Re-cross the Madison River.
77.8 Turn left heading north on U.S. Highway 287.
77.9 Indian Creek.
80.5 Start climb from lower bench up onto the Cameron Bench.
85.1 Cameron Post Office.
86.4 Mill Creek alluvial fan at 3 o'clock. Tan and/or gray Mesozoic and Paleozoic rocks with various dips are visible along the western flank of the Madison Range.
89.1 Descend into the modern drainage incised into Cameron Bench.

Ennis to Twin Bridges via Virginia City

This road log segment is adapted from Johns et al. (1981).

96.5 Junction of U.S. Highway 287 and Montana Highway 287 in Ennis: Turn west on Montana Highway 287 toward Virginia City. At this junction, the road lies at the edge of the Ennis terrace, a recent level of stabilization of the ancestral Madison River, ~15 m (50 ft) above the present floodplain.

98.7 Highway rises to the terrace level below the Cameron Bench. The slightly higher Cameron Bench can be seen to the north.

99.4 Cameron Bench.

100.5 South end of the Tobacco Root Mountains is visible at 12 o'clock, and the northern Gravelly Range at 10 o'clock. This is approximately the nonconformity of Tertiary sediment over Precambrian metamorphic rocks. Pre-Belt schists and gneisses are exposed intermittently in roadcuts and surface exposures.

104.0 Sphinx Mountain scenic turnoff: This observation point provides a magnificent view of the Madison Valley and Madison Range. At the western base of the Madison Range (below Lone and Fan Mountains) is a broad alluvial fan spreading both north and south. This alluvial fan covers older pediment surfaces. No recently formed fault scarps are discernible along this portion of the mountain front, but they are well developed along the range front to the south. About 914 m (3000 ft) of the Sphinx Conglomerate caps Sphinx Mountain.

~105.0 Summit of Ennis Hill: Pegmatite dikes are exposed in Precambrian metamorphic rocks.

105.2 Early Oligocene volcanic flows overlie Precambrian metamorphic rocks. Marvin et al. (1974) suggest a K-Ar age of 34–33 Ma for these volcanic flows.

106.7 Top of grade and commencing down-slope approach to Alder Gulch and Virginia City. A red clay band marking an old erosional surface overlying the volcanic units may no longer be distinct in the roadcut. An overlying andesite flow contains carbonate and zeolite nodules filling vesicles in the flows and the interstices in the breccia.

108.2 The Ruby Range appears at 11 o'clock. Cenozoic faulting has cut this range into three distinct blocks trending southwest to northeast. These blocks are a succession of half-grabens; the faults that bound each block trend west-northwest, roughly orthogonal to the northeast trend of basin and range faulting in the region.

110.7 Don't forget to check out the Brewery Follies live comedy show.

110.8 Virginia City: Madison County Courthouse on left (south), Boothill to right on Skyline ridge. The Virginia City placer deposits were discovered in May 1863 by prospectors panning gravels in Alder Gulch. Within a year, there was an estimated population of 10,000 people in the area and the Virginia City Mining District (VCMD), along with numerous subdistricts (Granite Creek, Fairweather, Highland, Browns Gulch, Pinegrove, Summit, and Barton Gulch) was established. The placer deposits in the area became the richest single stream placers in the United States. The last major dredging operation was shut down in 1933. In total, over 2.6 million ounces of gold and 350,000 ounces of silver were recovered from placer operations in the VCMD between 1863 and 1963 (Barnard, 1993). Lode deposits contributed another 170,000 ounces of gold and >2.4 million ounces of silver. Figures for base metal production (Cu, Pb, and Zn) were not accurately recorded.

110.9 Jackson Street intersection: To reach the original discovery site for Alder Gulch placers along Alder Creek, drive 1.2 km south (Jackson Street becomes Alder Gulch Road). Bill Fairweather and others discovered gold at this site on 26 May 1863. The U.S. Grant flotation mill is located ~0.4 km (0.25 mi) up (south) Alder Gulch from this point.

111.1 Bummer Dan's bar, the highest placer bar on the west edge of town, was one of the fabulously rich deposits of Alder Gulch. Bummer Dan, aka Dan McFadden, a ne'er-do-well who was caught stealing a pie, was given an ultimatum that he was to work the unclaimed ground or get out of town. With due persuasion he was left scratching at the gravels, but the gleam of gold soon turned perfunctory efforts to feverish labor.

A large placer gold-bearing cavity in volcanic rocks reportedly lies adjacent to the highway. Initially, the placer was too deep 21 m (69 ft) to be recovered during early dredging operations in 1896–1897. However, when the pocket was eventually mined, possibly between July 1935 and June 1937 by more powerful dredges, $1 million in gold was reportedly recovered (Lyden, 1948). The Virginia City district still has intermittent production of gold and silver from both placer and lode deposits.

Placer gravel spoils banks are visible in Alder Gulch. Tertiary volcanic rocks are exposed in a roadcut.

112.3 Nevada City: This is the site at which George Ives, the first of the criminal gang known as the "Innocents" was convicted and hanged, paying the supreme penalty in 1863 for murdering Nicholas Thiebalt for the sum of $200 in gold dust (www.virginiacitymt.com/Nevada.asp). The Nevada City Hotel on the right has a two-story outhouse.

112.7 Browns Gulch enters Alder Gulch from the south: Sometime during the 1860s, five men reportedly extracted $30,000 in gold nuggets in 11 working days from this drainage. A placer operation started in 1967 after test drilling gave encouraging shows from gravel beneath a clay "false bedrock." This operation has been recently reclaimed.

114.5 Granite Creek: Junction City, a flourishing mining town of the 1860s, was probably located a short distance up the gulch. The roadcut contains Archean metamorphic rock including metaquartzite, veined amphibolite, gneiss, biotite schist, hornblende schist, and pegmatite.

114.9 McNeal Gulch: The roadcut just ahead exposes Archean metasediments. Important lithologies are amphibolite, gneiss, and schist.

115.3 Placer operation on the left.

115.4 Water Gulch: The ridge-forming metaquartzite or vein quartz of the Archean sequence contains locally massive rose quartz.

116.2 The highway descends through Archean metamorphic rocks with exposures of thin marbles.

117.3 Northern Ruby Mountains at 12 o'clock: Pre-Belt metamorphic rocks in the core of northern Ruby Range are flanked by Paleozoic and Mesozoic rocks.

119.0 Garnet USA has a mill facility within the ~early 1900s placer dredge tailings on the north side of the road. The plant requires a ready water source for the concentration of almandine alluvial garnet product. A hardrock mine is planned in Archean garnetiferous gneiss from a location ~6 km (3.7 mi) to the southeast.

We are entering the Ruby River Valley.

119.6 To the right is an area of dredge tailings. These extensive piles of gravel were deposited by the stackers of the large dredges, which began operation during the late 1890s and continued unti1 1922. One source estimates the value of gold extracted by this method at about $30 million. The largest of these dredges cost half a million dollars and handled 7645 m^3 of gravel per day.

119.9 Alder Post Office: Stay right and continue on Montana Highway 287. To the west is an excellent view of the Ruby Range. The Tobacco Root Mountains are to the north. A north-trending fault parallels the eastern front of the Ruby Range. However, the scarp is covered by alluvial fans. Talc from the Beaverhead Mine in the southern Ruby Range (Cyprus Industrial Minerals Company) was shipped overseas for processing from a railroad spur in Alder.

121.9 Turn off to Laurin is on the left. Copper Mountain (iron and copper deposits) is at 2 o'clock (fringe of trees on mountaintop below skyline). Refolded folds defined by Archean dolomitic marbles (Cordua, 1973) similar to those hosting the talc deposits at the Yellowstone and Regal Mines are found throughout the Tobacco Root Mountains to the right. Several talc prospects up California, Harris, and Bivens Creeks were mined by small-scale operations.

122.0 Turn right on the road to California Creek and Mill Gulch Station to reach a lunch stop with good exposures of Archean marbles and other lithologies. Proceed east for 0.3 km (0.2 mi) to where the California Creek road intersects on the left, but continue straight ahead past the IMOC Lumber building for 0.5 km (0.3 mi) to a tee in the road. Turn left on Mill Gulch Road and continue 0.15 km (0.1 mi). The road bends sharply to the right. The lunch stop is in an open valley 1.4 km (0.9 mi) farther up the road.

Pull off on the road to the right for lunch. Please restrict your lunch traverses to the south side of the road because the land north of the road is private property. While enjoying lunch, a stroll to the southeast rewards the hungry geologist with excellent grassroots outcrops of Archean quartzofeldspathic gneiss, and farther east, grassroots outcrops of light gray, dolomitic to calcitic marble and minor hornblende gneiss and other lithologies are found. The regionally metamorphosed amphibolite- to granulite-grade marbles seen in these exposures contrast sharply with the strongly recrystallized marbles at the talc mines we are visiting today.

Investigation of the rocks and minerals in hand specimen: The marble is fine to medium grained, has light green calcsilicate and gray quartzitic interlayers and pods, and contains disseminated grains of diopside and olivine. Graphite and phlogopite are common. Iron oxides are abundant on fracture and layering surfaces and as weathering products of diopside and olivine grains. The calcsilicate layers contain phlogopite, diopside, calcite, tremolite, graphite, and other fine grained phases. Calcite veins are common.

After lunch, we will retrace our route 2.4 km (1.5 mi) back to Montana Highway 287 and turn north, resuming our mileage log northward toward Sheridan, Montana.

With this side trip, the mileage log should be incremented 3.0 miles.

122.6 Alder Creek: The highway is built on Tertiary sediments.

123.4 California Creek.

124.9 The Highland Mountains are at 12 o'clock.

125.2 Robber's Roost Historical Marker, formerly Pete Daly's place: The building served as a stage stop and the second floor once served as a dance hall. When a lower partition was removed recently on the first floor separating the bar from the living quarters, several pounds of lead bullets were recovered from the wall, which apparently was used as a target by the more boisterous patrons. The stage stop served as an incubator where Henry Plummer

(1832–1864), notorious sheriff of Bannack, and his criminal gang—the "Innocents"—hatched many of their plots. Some of the loot was reported to have been cached on the property.

127.1 Horse Creek road: The low foothills on the right are metamorphic rocks.

130.1 Sheridan Post Office: Mill Creek drainage from Tobacco Root Mountains to the east. A number of productive gold-bearing quartz veins occur in a marble layer of the Archean metamorphic rocks in the Mill Creek area. One recent producer is the Red Pine Mine near the head of Indian Creek.

132.3 Mine workings in upper slopes to the left of rounded Mount Baldy at 3 o'clock are part of the Tidal Wave mining district that produced gold and silver.

136.4 Wet and Dry Georgia Creeks road turnoff. Continue on Montana Highway 287.

138.6 At 3 o'clock, light gray–colored cliffs of Madison Limestone are visible.

139.7 Twin Bridges. Turn west toward Dillon at junction with Montana Highway 41.

139.8 Just across the bridge, on the west bank of the Beaverhead River is the Jessen Park rest area, which is open for the summer, usually beginning on Memorial Day weekend.

Twin Bridges to Dillon

This road log segment is adapted from Schmitt et al. (1995).

150.9 Point of Rocks Cemetery on the right (west): The route traverses the outer floodplain of the Beaverhead River. Low hills visible to the left and right above the floodplain are composed of the Tertiary "Bozeman Group," consisting of Eocene(?) through Pliocene, poorly consolidated, basin-fill sediments. From here, one has a good view to the east of the north end of the Ruby Range, the Ruby Valley, and the south end of Tobacco Root Mountains.

152.3 A warm spring is on the west side of the road on Beaverhead River floodplain.

152.9 Crossing Beaverhead River: Mississippian carbonates to the west form Beaverhead Rock. A good section of the Tertiary Bozeman Group strata is visible to the west, unconformably overlying Paleozoic and Triassic strata.

153.7 Turnout for Beaverhead Rock historic site: Beaverhead Rock was named by Native Americans and first recorded by the Lewis and Clark expedition on 10 August 1805. However, the real Beaverhead Rock, as recognized by locals, is south of Dillon at the entrance to the Beaverhead River Canyon and is composed of Tertiary volcanic rocks. That beaver is best viewed traveling north on I-15.

Overview of the north flank of the collapsed Laramide Blacktail-Snowcrest uplift: The Blacktail-Snowcrest uplift trends northeast and is basement cored. It is bounded along its southeastern margin by the Snowcrest-Greenhorn thrust system and related sub-Snowcrest thrust. The remnant high portions of the Blacktail-Snowcrest uplift form the southern portion of the Blacktail Mountains immediately south of Dillon, Montana, and the adjacent Snowcrest Range to the south. The central portion of this Laramide-style uplift has been down-dropped by Tertiary normal faulting to form the Sage Creek basin.

Ruby Range (to the east): According to Tysdal (1976), the Ruby Range consists of Precambrian metamorphic rocks, which include dolomite marble, quartzofeldspathic gneiss, hornblende-rich gneiss, sillimanite schist, and minor banded iron formation, overlain by Phanerozoic sedimentary rocks. The Archean dolomitic marbles that host the talc deposits in the Dillon area are a component of this basement complex. Mid- to late Tertiary sediments overlap older rocks along the range margins.

The central part of the Ruby Range comprises a series of northwest-plunging, basement-cored Laramide folds associated with high-angle reverse faults. The present margins of the uplift, which are buried beneath Quaternary alluvial fans, could be some reactivated Laramide high-angle reverse faults inverted to accommodate Tertiary extension. Normal faults here have been active since Oligocene time.

153.9 Madison-Beaverhead County line: Traveling on Tertiary conglomerate and sandstone.

155.0 To the west lie the high peaks of the Pioneer Mountains cored by the Cretaceous Pioneer batholith. McCartney Mountain is in the middle distance.

158.6 Crossing Stone Creek.

The highway crosses the top of a pediment surface, above the Beaverhead River floodplain to the west. This upland surface has been moderately dissected by intermittent streams flowing down to the Beaverhead River. Loess deposits are locally exposed adjacent to the road. Roadcuts expose sections of tuffaceous Tertiary sandstone and siltstone with resistant calcareous interbeds, which are overlain by matrix-supported channel conglomerate containing abundant Proterozoic quartzite cobbles and other mixed lithologies. The cobbles and pebbles are likely reworked from conglomerates in the Beaverhead Group. Beaverhead River floodplain lies to the west.

166.5 Entering Dillon on Montana Highway 41: Airport road lies to the east. We are traveling south on the upper floodplain of the Beaverhead River (to west in the forested area); this is a Quaternary surface that has been cut laterally into Tertiary strata by the Beaverhead River. Water treatment lakes are north of roadway and armory on south.

167.3 Intersection with I-15 Interchange.

167.5 Junction of Montana Highways 91 and 41: Continue south into Dillon.

167.7 Turn east-southeast on Johnson Ave./Vine St. Turn south on Vine St. before reaching the entrance to the Safeway parking lot.

168.1 Turn east on Kentucky Ave. At the eastern city limit 0.6 km (0.4 mi), Kentucky Ave. becomes Sweetwater Road (Rd 206). The road starts as a two-lane blacktop, but shortly after passing the cemetery (mile 169.3) becomes a two-lane improved gravel road. Inquire locally about conditions.

Dillon to Regal Talc Mine

This road log segment is supplemented from entries by Sears et al. (1995).

170.4 Sweetwater Estates subdivision: Dump material from the Treasure talc mine is visible on the horizon at 12 o'clock. The Sweetwater Road proceeds due east out of Dillon, across the East Bench, a pediment cut on Miocene Six Mile Creek Formation. The Six Mile Creek Formation here includes thin tephra beds, an indurated conglomerate, and garnetiferous sands. The conglomerate is 3–5 m (10–16 ft) thick near the northwest margin of the East Bench. The clasts are well-rounded and imbricated, indicating fluvial transport to the northeast. Pebbles include veined chert and jasper-bearing pink feldspathic quartzite, suggesting a central Idaho provenance. The conglomerate passes southeast into poorly sorted, angular, feldspathic gravel made up of metamorphic and igneous clasts. The clasts were derived from the Ruby Range Archean metamorphic rocks and Eocene volcanics, and the deposit laps onto the source rocks. The Sweetwater Road crosses onto Archean bedrock ~16 km (10 mi) out of Dillon.

171.6 Canal crossing.

172.4 Intersection with Carter Creek Road. Continue east on Sweetwater Road.

173.9 The Regal Mine dumps are visible at 1 o'clock. Forested hills at 3 o'clock mark the location of the Mineral King talc prospect. The Smith-Dillon talc mine is out of sight on the south side of these hills.

174.7 On the right is the talc ore transfer facility for the Regal Mine.

177.9 The Regal Mine is visible at 12 o'clock. Near the turnoff to the Christensen Ranch, Sears et al. (1995) report a basin-bounding, Miocene age fault, down to the northwest, passing through this area. The location of the fault is based on gravity data. The bedrock surface near Sweetwater Pass is an exhumed, dissected, erosional surface of Eocene age; it is overlain by an Eocene lava flow dated at 41.5 Ma (K-Ar whole rock) just north of Sweetwater Road.

179.6 Entering Regal Mine property: Go straight through underpass.

179.9 Turn right, through gate, into Regal Mine. Office is ahead at 10 o'clock.

180.0 Arrive at the Regal Mine office and check-in. Mine personnel will provide site tour.

STOP 2

From the pit overlook, the Regal orebody is visible directly east in the southwest corner of the Regal pit. The orebody strikes west and dips ~45° north, to the left as viewed from the overlook. A major north-northwest diabase dike, a potential heat source for talc formation at the Regal, is in subcrop below the overlook. The Regal marble is the host for the talc ore. The marble is deformed into a hook-shaped, refolded fold hinge (Fig. 4) that is west-southwest of the overlook and is not visible from this point. Furthermore, where the rerouted Sweetwater Road curves on a ridge southwest of the mine property, the road is on the refolded marble of the hook fold, yet the subtle expression of the hook cannot be fully appreciated. Vegetation on the undisturbed land surrounding the mine is a good indicator of lithology.

The return segment from the Regal Mine may follow the Sweetwater Road to the intersection with the Carter Creek Road. Turn north on Carter Creek Road. At the intersection with Nissen Lane, a left turn will allow us to reach Montana Highway 41 north of Dillon. The total distance from the mine to Twin Bridges is 60 km (37.3 mi). The road log for this trip resumes at Twin Bridges.

Twin Bridges to Bozeman

This road log segment is adapted from Schmitt et al. (1995).

Reset odometer at the intersection of Montana Highways 41 and 287.

Mileage	*Directions and Descriptions*
0.0	Turn north on Montana Highway 41 toward Whitehall at the main intersection in downtown Twin Bridges.

The Rochester Mining District is 21 km (13 mi) west in the Highland Mountains.

Tobacco Root Mountains to the east: A spectacular sloping alluvial fan complex lies at the base of the Tobacco Root Mountains. The fan complex is moderately dissected at the top.

The Tobacco Root Mountains form the eastern boundary of the Jefferson River Valley. They extend for 55 km (34.5 mi) southward to Virginia City. South of Virginia City, the general structural trend continues and forms the Greenhorn and Gravelly Ranges. The west flank of the Tobacco Root Range is characterized by a west-dipping Laramide thrust system that has been mostly down-dropped on a normal fault system of similar trend. The rise of the range along the normal fault has tilted the block eastward.

3.6 *Historic point:* Meriwether Lewis camped here when scouting ahead of William Clark in the Jefferson River valley. In this area, the Jefferson River hugs the west side of the valley, probably the result of depositional "crowding" by the young alluvial fan complex along the east side of valley.

Low on the hills to the west, dissected Tertiary and Quaternary alluvial and pediment gravels are preserved along the southeast flank of the Highland Mountains. These older deposits are mostly unconsolidated sediments of deeply weathered, granitic clasts in a sandy matrix, commonly capped by eolian silt (Ruppel et al., 1993).

Highland Mountains to the west: Most faults in the Highland Mountains strike northwest, except for the northeast-striking range-front normal fault on the east flank of the range and the east-west Camp Creek fault in the south-central part of the range. The Camp Creek fault dips gently northward and places Belt Supergroup strata (Newland and LaHood Formations) over the basement rocks to the south. Schmidt and O'Neill (1982) interpreted the Camp Creek fault to be a reactivated middle Proterozic normal fault.

Rugged canyons on the left dissect Archean crystalline rock. Chloritic alteration in Cottonwood Canyon along major west-northwest–trending faults was explored as a possible source of commercial chlorite.

4.5 The Highland Mountains host several plutons of granodioritic (e.g., Rader Creek pluton) and monzogranitic (e.g., Hells Canyon pluton) composition that intrude a faulted metamorphic basement complex containing wedges of Phanerozoic strata. The Hells Canyon pluton is cut by deep Hells Canyon to the west. It is a southern satellite intrusion of the Cretaceous Boulder batholith, which hosts the Butte porphyry copper-molybdenum system ~48 km (30 mi) to the north.

6.9 Crossing Jefferson River. To the far east, coalescing alluvial fans occur along base of the Tobacco Root Mountains.

7.7–7.9 The highwall of the reclaimed open-pit Golden Antler mine is just visible west of the highway above the road. This mine produced high-quality magnesian chlorite from an orebody discovered by local prospector Bob Nolte. Cyprus Industrial Minerals and Luzenac America mined chlorite for ceramic products from this mine in the ~1990s. Chlorite formation was localized along a series of northwest-trending high-angle faults and fractures (O'Neill, 1995). Sericitic alteration of Precambrian basement rocks presently exposed in the Highland Mountain gneiss dome produced magnesium-rich chlorite (clinochlore) via complete chemical replacement reactions (Berg, 1983). Veins of pure chlorite as much as 8 m (25 ft) thick in a zone of alteration of ~80 m (260 ft) wide were described by Berg (1983).

9.3–9.5 Intensely deformed Paleozoic rocks are juxtaposed against Cretaceous granodiorite along the Green Campbell thrust.

10.0 Silver Star Hot Springs. This hot springs may be associated with a north-northeast–trending normal fault parallel to range-front faults that exist along the west side of Jefferson Valley.

The town of Silver Star is located along the southern exposed edge of the main Boulder batholith. The batholith intrudes a south- and west-dipping sequence of Cambrian through Pennsylvanian strata. A roadcut just south of Silver Star exposes the Pennsylvanian Quadrant Formation, which is overlain by porphyritic andesite, probably equivalent to the Elkhorn Mountains volcanics. The mines of the Silver Star district were developed in Paleozoic carbonates adjacent to the batholith and in veins in Precambrian metamorphic rocks. The principal metals sought were gold, silver, lead, and copper. In the heyday of mining in the 1870s, Silver Star was the only town between Helena and Virginia City.

10.3 In the town of Silver Star, Lloyd Harkins' private mining museum on the west side of the highway is adorned with a man cage, huge compressor wheels from underground mines at Butte, and a caboose. A road entering the highway (on the west) is from the Silver Star mining district, where the reactivated Victoria gold mine ships high-grade copper oxide ores to China and gold ore to the Golden Sunlight Mine.

North of town, the highway traverses Quaternary alluvium and talus deposits that were shed off the Highland Mountains to the west. To the east, Paleozoic and Mesozoic strata crop out on the west and northwest flanks of the Tobacco Root Mountains.

11.9 Possible fault scarps cutting the alluvial fans are visible (if the lighting is favorable) at 3 o'clock along the fault-controlled western range front of the Tobacco Root Mountains. Point of Rocks Hot Spring, at the northern end of the Tobacco Root Mountains, is located at ~1:30.

14.3 Junction of Montana Highways 41 and 55. Continue straight (Montana Highway 55) toward Whitehall.

16.4 Silver Bow County line.

16.7 Jefferson County line.

16.7 Road to Waterloo, Montana, takes off on the right. At 3 o'clock, one can see flat irons of Paleozoic carbonate rocks at the base of the Tobacco Root Mountains. The dark shrub dominating these slopes is mountain mahogany, which grows prolifically on carbonate rocks.

18.3 Fish Creek Bridge: Boulders in alluvium adjacent to Fish Creek are interpreted to have been catastrophically deposited in middle to late Pleistocene time in response to the breaching or breaking of a glacially dammed lake along the upper reaches of Fish Creek in the Highland Mountains (O'Neill, 1995). The east flank of the Highland Mountains lies to the west (left) and the west flank of Tobacco Root Mountains lies to the east (right). Traveling on the outer floodplain of the Jefferson River, the road traverses a Quaternary pediment surface. This surface has been dissected to form the current valley floor and floodplain of the Jefferson River (to the east). As we approach Whitehall, the road skirts the eastern margin of a large outcrop of the Miocene Six Mile Creek Formation (low hills to the north).

18.5 Large dumps visible on the skyline at 1 o'clock are from the Golden Sunlight Mine (Barrick Gold Corp.) at the south end of Bull Mountain.

Bull Mountain is a horst composed of Belt Supergroup rocks covered by Late Cretaceous Elkhorn Mountains volcanics farther north. Mineralization occurs within a large (213 m diameter) hydrothermal breccia pipe, which likely formed in an epithermal environment above a molybdenum porphyry system, based upon the increase in potassic alteration and molybdenite mineralization with depth (Foster and Chadwick, 1990). The breccia pipe is believed to have been contemporaneous with Late Cretaceous latite porphyry magmatism. Lamprophyre dikes and small hypabyssal intermediate mafic intrusions (with mantle-derived chemical signatures) may be similar in age to the dominant silicic intrusive and extrusive igneous rocks (DeWitt et al., 1996). Gold is hosted by the latite, and open-pit mining began in the early 1980s. The Golden Sunlight orebody is one of many porphyry-related systems that occur within the Great Falls tectonic zone (O'Neill and Lopez, 1985), a long lived, deep-seated zone of crustal weakness that appears to have controlled late Mesozoic and early Cenozoic magmatism in Idaho and Montana. The Golden Sunlight Mine is the subject of another field trip included in this field guide volume (Oyer et al.).

26.0 Crossing Pipestone Creek.

26.2 Junction with Montana Highway 2. Turn east onto Montana Highway 55 to I-90.

26.6 At stop sign in downtown Whitehall, turn north on Montana Highway 55 and continue through Whitehall.

27.2 Turn east on I-90 ramp (toward Bozeman).

28.2 At 11 o'clock, a prominent ridge is underlain by a Late Cretaceous latite sill that intrudes Proterozoic Belt sedimentary rocks and forms part of the intrusive complex at the Golden Sunlight Mine.

30.4 Tertiary sediments on left are part of the valley-fill marginal to the Bull Mountain block. Tertiary/Quaternary debris flows farther north along the range front are derived from erosion of the Golden Sunlight breccia pipe and contain enough gold-mineralized clasts to have been mined in recent years.

31.1 Triangular valley fill on left is reclaimed dump material from the Golden Sunlight gold mining operation.

32.2 Buttress of a mill tailings dam visible at 9 o'clock is currently being used by the Golden Sunlight Mine.

34.2 Cardwell and Boulder (Exit 256). Continue eastward to Bozeman. Poorly consolidated Neogene strata lie to the north adjacent to long straightaway in highway.

35.0 Boulder River crossing and base of Doherty Mountain Pass: This area is the north end of the Tobacco Root Mountains. Doherty Mountain (to the north) is a large, north-plunging anticline cored by Belt Supergroup rocks (LaHood Formation), and flanked by steeply dipping Cambrian and younger strata. The sedimentary strata are intruded by greenish-black weathering dikes and sills of probable Late Cretaceous age.

46.9 Crest of Doherty Summit between Three Forks and Whitehall: This broad saddle is capped by the "Ballard gravels," a deposit of locally occurring, late Tertiary and/or Quaternary(?) well-rounded, cobble-sized sediment. This saddle may mark the ancestral drainage of the Jefferson River, or some other river, prior to late Tertiary and/or Quaternary extension and basin excavation. Alternatively the Ballard gravels may represent a remnant of a regionally extensive blanket of late Cenozoic, high-elevation pediment gravel.

49.7 Jefferson-Broadwater County line.

52.6 Helena (Exit 274). Continue eastward to Bozeman.

53.2 Gallatin-Broadwater County line. Jefferson River crossing.

54.0 Three Forks, Montana (Exit 278): The early settlement of Gallatin City, founded in 1862 and situated east of the confluence of the Madison, Jefferson, and Gallatin Rivers, was moved in 1882 to a location a mile to the southwest (a locality north of I-90 and marked as Oldtown on modern maps) and named Three Forks. In 1912, the community was relocated to its present site, and in 2012, the population was 1182.

Gallatin City, the first settlement in Gallatin County, was platted in 1862 on the west bank of the Missouri River, opposite the mouth of the Gallatin River. The first cabin was built by Frank Dunbar. People bought lots under the *impression* that the site would become a head of navigation for steamers coming up the Missouri. However, no boats came up the river, because of the Great Falls and other falls and rapids downstream. The town site was abandoned in part and moved to the east bank of the Madison River. At this site stood several cabins and stores, a grist mill, Dunbar's hotel, and a horse-racing track. The hotel still stands today although rooms are not available.

The confluence of the Jefferson, Madison and Gallatin Rivers (named by Lewis and Clark in 1805) to form the Missouri River lies three miles to the north. After traveling up the Missouri, Lewis and Clark camped at the confluence (in present-day Missouri Headwaters State Park) and decided to take the Jefferson Fork to continue their exploration of a route to the Pacific. Their party was guided by a Shoshoni woman named Sacajawea. Her French Canadian husband, Toussaint Charbonneau, was the interpreter for the party. She had been captured by the Minnetaree subgroup of the Dakota Nation in this region five years earlier and, on the trip west, recognized familiar landmarks.

At Trident, which is ~0.8 km farther north of the confluence, Holcim (U.S.) Inc. operates the Trident cement plant. Holcim is an international company that operates 12 cement plants in the United States with 1800 employees. The Trident cement plant was built in 1910, and some of the current 74 employees are third-generation employees. In recent years, the Holcim (U.S.) Inc. Trident plant has received several safety awards.

The mine is in Paleozoic carbonate rocks in the Trident syncline, which is bounded by the Green thrust on the east and the Trident thrust on the west. The cement plant obtains lime from Madison Group limestones at the plant site, shale from nearby, and iron ore from Radersburg and White Sulfur Springs. These ingredients are crushed, ground, blended (in slurry form), and fed into a rotary kiln, where the mixture is burned to partial fusion. The sintered product is ground with gypsum into Portland cement and shipped.

56.5 Madison River crossing.

58.1 Madison River bluffs to the south consist of Tertiary tuffaceous and calcareous siltstones, sandstones, and ash beds. Originally called the "Bozeman lake beds" by A.C. Peale (1896), these cliffs now constitute the Bozeman Group, defined as "... Tertiary fluvial, eolian, and lacustrine rocks which accumulated in the basins of western Montana after the Laramide orogeny" (Robinson, 1963). Kuenzi and Fields (1971) identified two lithostratigraphic units in the Bozeman Group, the Renova and Six Mile Creek Formations. The lower cliffs are mostly lacustrine deposits equivalent to the Eocene–Oligocene Renova Formation, overlain by dominantly fluviatile deposits of the late Miocene Six Mile Creek Formation (Hackett et al., 1960).

A few miles to the south, these Tertiary cliffs were used by early Native Americans as a "buffalo jump" mass kill site (Madison Buffalo Jump State Park at Exit 283).

63.6 Logan-Trident (Exit 283): The limestone cliff directly across the Gallatin River at Logan is the type section of the Madison Group (Sando and Dutro, 1974). Peale (1893) proposed the name "Madison Formation" in the Three Forks area of southwest Montana for carbonates underlain by shales of the Three Forks Formation and overlain by sandstones of the Quadrant Formation, although he never specified a type section. Sloss and Hamblin (1942) reviewed and synthesized previous work on the Madison Group and proposed the stratigraphic nomenclature now used by most geologists throughout Montana (Sando and Dutro, 1974). The Madison was divided into the Lodgepole and Mission Canyon Formations. Sando and Dutro (1974) established a detailed type-section description of the Madison Group at Logan, with a reference set of fossils permanently housed at the U.S. National Museum in Washington, D.C.

67.5 Manhattan (Exit 288): The Horseshoe Hills are well-exposed to the north across the Gallatin River, consisting of northwest-dipping arkose and shale of the middle Proterozoic LaHood Formation (in the bluffs along the river), overlain by a Phanerozoic succession that crops out farther north in the hills. Here, I-90 runs approximately parallel to the old southern margin of the Belt basin, variously known as the Perry line (Winston, 1986), Willow Creek fault (Robinson, 1963; Harrison et al., 1974), Central Park fault (Hackett et al., 1960), and/or the southwest Montana transverse fault zone (Schmidt and O'Neill, 1982).

The Perry line is a major cross-strike structural discontinuity in the Northern Rocky Mountains that is generally delimited by middle Proterozoic normal faults that were reactivated as right-oblique thrust faults during Cretaceous and Paleogene contractional orogenesis (Sevier and Laramide orogenies). As such, the Perry line is one of several fault zones in western Montana that have structurally inverted the Belt basin. During the middle Proterozoic, arkosic debris was eroded from Archean metamorphic highlands across southwest Montana (Dillon Block) and deposited in the Belt basin. These strata are preserved as the LaHood Formation along Montana Highway 2 near the old Lahood station in the Jefferson River Canyon. Prominent northwest-dipping exposures in the Horseshoe Hills north of the river are from east to west: Cambrian (Pilgrim Limestone), Devonian (Maywood, Jefferson, Three Forks, Sappington Formations) and Mississippian (Lodgepole and Mission Canyon Formations)—principally carbonates, except for the Sappington Sandstone.

The structure of the Horseshoe Hills consists of a series of northeast-trending, tight, sigmoidal folds with steep NW-dipping axial surfaces, and right-oblique thrust faults. The Horseshoe Hills were originally mapped by Verrall (1955). Parts of the hills have been subsequently remapped in great detail by field camp students at Montana State University over the years. Lageson (1992) has interpreted the structure of the Horseshoe Hills as being the result of transverse lateral ramping along the old Perry line, coupled with megascopic dextral simple shear.

72.7 Gallatin River crossing.

75.2 Belgrade-Amsterdam (Exit 298): The Bridger Range is well exposed to the east, and Ross Pass is the prominent saddle on the skyline in the middle of the range. Ross Pass is the trace of the Pass Fault, a reactivated middle Proterozoic fault that juxtaposes the Belt Supergroup (LaHood Formation) in the core of the northern Bridger Range and the Archean basement complex south of this fault (e.g., southern Bridger Range). Cambrian strata nonconformably overlie the entire range. The topographic crest of the Bridger Range consists of steeply east-dipping to overturned Mississippian carbonate rocks of the Madison Group, which strike the length of the range. These Phanerozic strata represent the steep east limb of the ancestral (Laramide) Bridger Range (Lageson, 1989).

79.9 Gravel pit north of the highway is in thick Quaternary alluvium of the Gallatin Valley. The bulk of the gravel is composed of rounded cobbles of andesite and dacite derived from the Eocene volcanic rocks of the Gallatin Range to the south.

84.7 Take Exit 305 N. 19th Avenue, Bozeman, south to return to Montana State University.

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