GEOLOGIC MAP OF THE CENOZOIC DEPOSITS OF THE UPPER JEFFERSON VALLEY

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Compiled and mapped by
Susan M. Vuke, Walter W. Coppinger, and Bruce E. Cox

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CENOZOIC DEPOSITS OF THE UPPER JEFFERSON VALLEY

Cenozoic deposits are the focus of the Geologic Map of the upper Jefferson Valley. The map is largely a compilation of previous mapping with additional interpretations based on aerial photos and limited additional field work. Older rocks are included to show their relations to the Cenozoic deposits, but they are generalized on the map. Lithologic descriptions of the Cenozoic deposits are given in the map explanation (p. 17). References used for the map compilation are shown on p. 15. The northern and southern parts of the map are discussed separately.

NORTHERN PART OF MAP AREA

Quaternary deposits

A variety of Quaternary deposits blanket much of the slope area of the Whitetail and Pipestone Creek valleys between the flanks of the Highland Mountains and Bull Mountain (Fig. 1). East and southeast of these Quaternary slope deposits are more isolated areas of partly cemented Pleistocene gravels on pediments. One of these gravel deposits near Red Hill (Fig. 1) yielded a late Pleistocene vertebrate assemblage including cheetah, horse, camel, and large mountain sheep. Radiocarbon dates from the lowest part of the sequence range between 10,000 and 9,000 ^{14}C yr. B.P. (Hill, 2001).

Tertiary stratigraphy

Lithostratigraphy for southwestern Montana Tertiary deposits was established in the northern part of the map area by Kuenzi and Fields (1971) partly as a modification of formal stratigraphy established in the Three Forks and Toston, Montana, areas (Robinson, 1963, 1967), east of the upper Jefferson Valley map area. Modifications included restricting the Sixmile Creek Formation (Robinson, 1967) to Tertiary strata that overlie the mid-Tertiary (Hemingfordian) unconformity (Fig. 2), and defining a new stratigraphic unit, the Renova Formation, underlying the unconformity. The Sixmile Creek Formation in the map area is early Barstovian to Hemphillian in age (Kuenzi and Fields, 1971; Lofgren, 1985). Kuenzi and Fields (1971) described the Sixmile Creek Formation as typically coarse-grained (defined as fine sand and coarser) and the underlying Renova Formation as fine-grained (defined as greater than 70 percent terrigenous very fine sand and finer).

The Renova Formation was divided into three members in the northern part of the map area (Kuenzi and Fields, 1971). Two of the members, the Dunbar Creek and Climbing Arrow, were previously formally established as Tertiary formations by Robinson (1963) in the Three Forks, Montana, area. Kuenzi and Fields (1971) changed the stratigraphic rank of these formations to member status in the upper Jefferson Valley. They also introduced a new member of the Renova Formation, the Bone Basin Member. In the map area, the Climbing Arrow Member is Chadronian (Eocene), the Bone Basin Member is Chadronian to possibly Arikareean (Oligocene and early Miocene), and the Dunbar Creek Member is Chadronian (Eocene) to Orellan (Eocene and Oligocene) (Kuenzi and Fields, 1971; Garcia, 1992; Tabrum and Fields, 1980; French, 1988; Tabrum and others, 1996, 2001; Lofgren, 1985) (Fig. 2). The type section of the Renova Formation is near the community of Renova (Fig. 1); three reference sections--Pipestone Springs, Easter Lily, and Palisade Cliffs, are located in the northwestern part of the map area (Fig. 1).

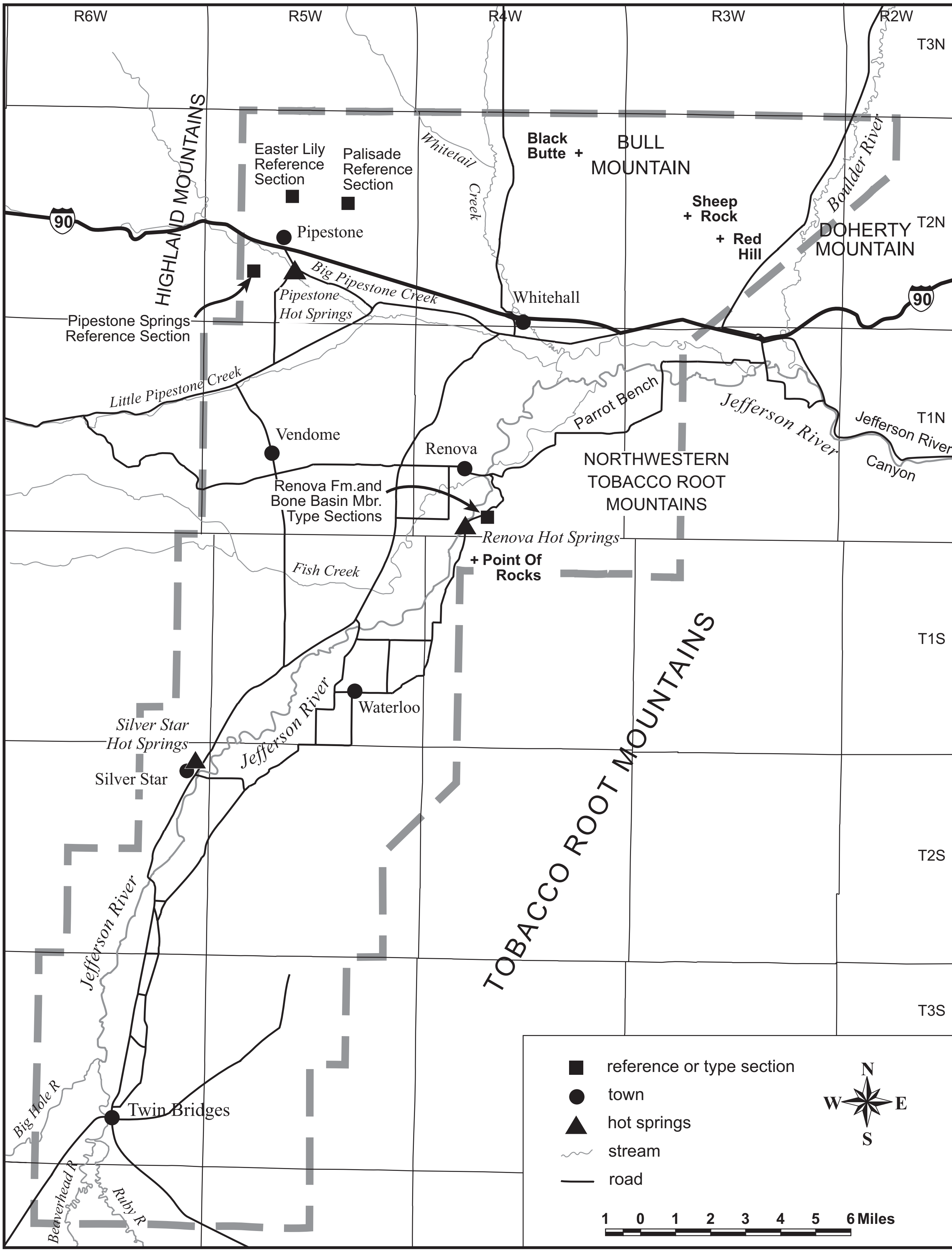


Figure 1. Location Map of study area; map boundary shown by dashed gray line.

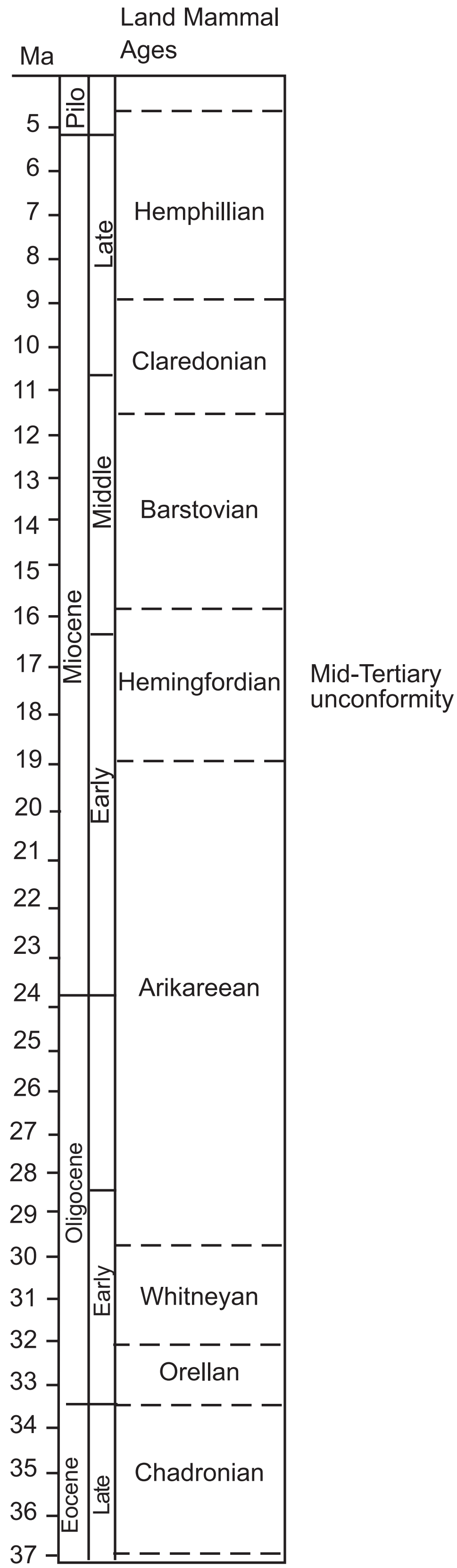


Figure 2. Tertiary dates in map area. Time scale from Berggren and others (1995), and Woodburn (1995).

(Kuenzi and Fields, 1971). The type section for the Bone Basin Member is the same as the type section for the Renova Formation (Kuenzi and Fields, 1971). In addition, an informal late Arikareean unit, the Negro Hollow map unit north of Red Hill, was described by Lofgren (1985) and considered the upper part of the Renova Formation. Red siltstone of the Red Hill map unit may be the oldest sedimentary unit of the Renova Formation in the map area, but it has not been included in the formal stratigraphy. Eocene basalts in the southern part of Bull Mountain record the earliest Tertiary extension in the area.

Five sequences have been recognized in the Cenozoic deposits of the Jefferson Valley and southwestern Montana. These sequences are recognized principally from bounding unconformities rather than than lithology because of the lateral and vertical repetition of lithologies throughout the Tertiary section (Hanneman, 1989; Hanneman and Wideman, 1991). The sequence-bounding unconformities are recognized based on paleosols (primarily stacked calcic paleosols), erosion surfaces, and angular stratal relationships. Some paleosols have been traced from outcrop into the subsurface in the map area where they are recognized as seismic reflectors (Hanneman, 1989; Hanneman and Wideman, 1991). In the map area, the Sixmile Creek Formation is in direct contact with the Renova Formation on the northwestern flanks of the Tobacco Root Mountains near the community of Renova and in the northwestern part of the map area. In both places the contact is erosional.

The lithostratigraphic and sequence stratigraphic approaches to dividing Tertiary deposits in the upper Jefferson Valley have both been greatly augmented by fossil data available throughout the Tertiary section in the northern part of the map area (Kuenzi and Fields, 1971; Fields and others, 1985; Lofgren, 1985; Tabrum and others, 1996; Tabrum and others, 2001; Wang and others, 2004). Of particular note are the world-famous Pipestone Springs fossil beds exposed in the northwestern part of the map area in the vicinity of Little Pipestone and Big Pipestone Creeks that have produced the abundant, well-preserved Pipestone Springs mammal fauna of Douglass (1901), Mathew (1903), and many subsequent paleontologists (see Tabrum and Fields, 1980; Tabrum and others, 1996, 2001).

Tertiary mapping approach

Both the lithostratigraphic and sequence stratigraphic approach to Tertiary deposits recognize unconformity-bounded units. The International Subcommission on Stratigraphic Classification prefers the name *synthem* (Chang, 1975) for unconformity-bounded stratigraphic units (Salvador, 1987). The latest (1983) North American Stratigraphic Code introduced the category of allostratigraphic units that are comparable to synthems (Salvador, 1987). A synthem (or allostratigraphic) mapping approach was informally used for the Tertiary deposits in this report on the upper Jefferson Valley. Rather than lump all of the Tertiary deposits that overlie the mid-Tertiary (Hemingfordian) unconformity into the Sixmile Creek Formation or Sequence 4, for example, separate facies were mapped as informal units that comprise the Sixmile Creek synthem in the map area of this report, and other reports (Vuke, 2004; Vuke, 2003). This approach takes into account intrabasinal and interbasinal facies changes within the unconformity-bounded sedimentary packages and also helps in recognizing faults that may juxtapose a younger part of the synthem against an older part.

Latest Cretaceous, Paleogene, and early Miocene

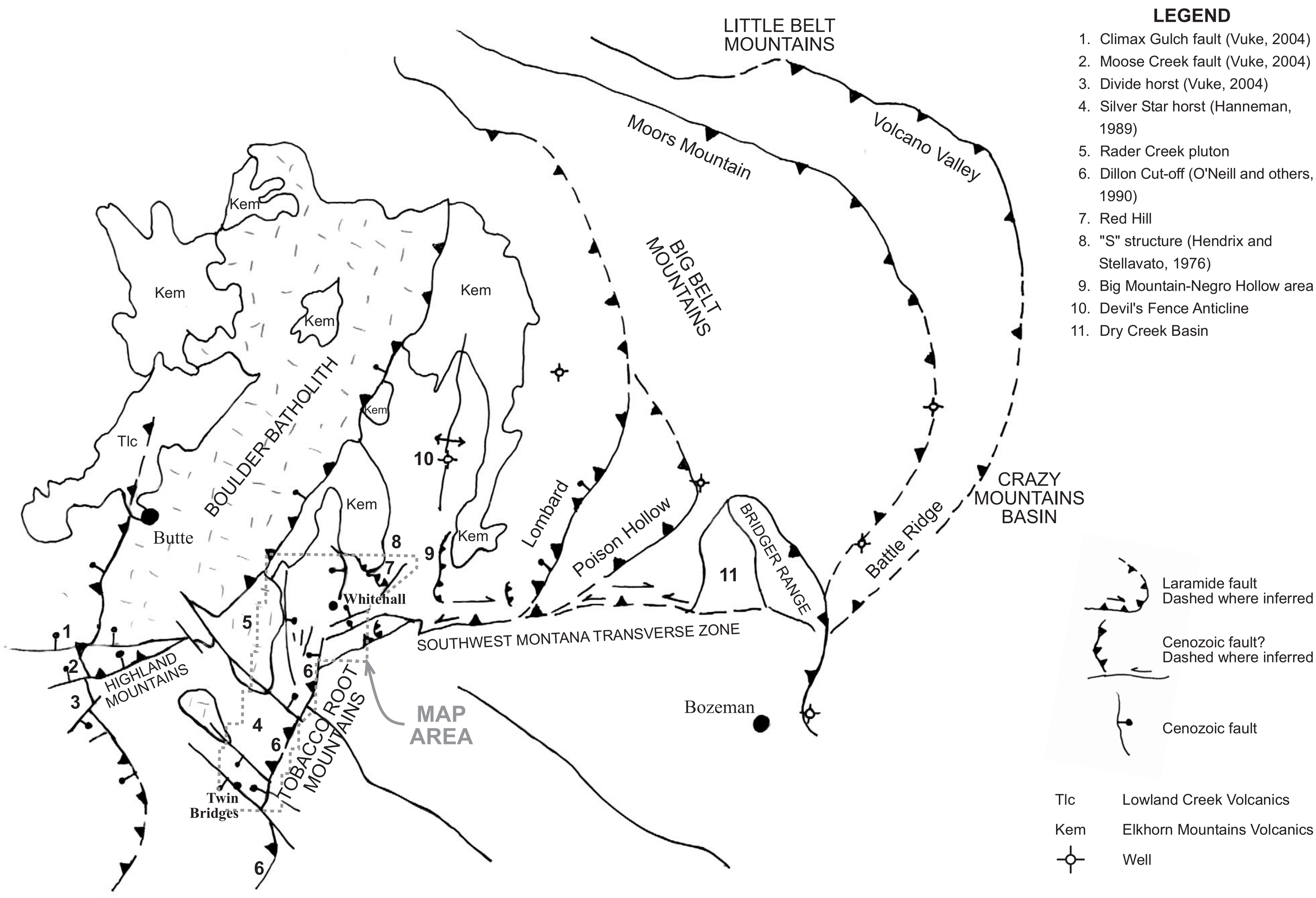
Near the end of the Cretaceous, about 70 million years ago, 10,000 or more feet of Elkhorn Mountains Volcanic rocks overlay older rocks in the area (Klepper and others, 1957). A tremendous volume of the volcanic rocks was eroded from the area during the late Maastrichtian and Paleocene and deposited to the east in the Upper Cretaceous Livingston Group (Lageson and others, 2001) and lower Paleocene Fort Union Formation.

This period of erosion must have been followed by sediment accumulation during the Paleocene and/or early Eocene that almost completely buried exposures of Elkhorn Mountains Volcanics in the Bull Mountain area. The Chadronian (Eocene) Climbing Arrow Member on both sides of Bull Mountain, and the Chadronian part of the Bone Basin Member south of Parrot Bench (Fig. 1) contain sinuous channels of immature sandstone and granule and pebble conglomerate that have the appearance of weathered granite that has undergone very little transport. Biotite is relatively abundant. Lithic clasts are almost all granitic, and there are only minor, scattered clasts of Elkhorn Mountains Volcanics. Despite the modern proximity to Bull Mountain, Doherty Mountain, and the Tobacco Root Mountains (Fig. 1), there are only sparse lithic clasts other than granitic rocks.

In contrast, the Chadronian Climbing Arrow Member near Pipestone Springs that rests directly on granodiorite of the Rader Creek Pluton of the Boulder Batholith (Fig. 3), does not contain much sandstone or conglomerate and has only trace amounts of biotite (Kuenzi, 1966). The likely source for granitic rocks was the Boulder Batholith to the southeast which must have been near the basin margin and probably not covered by Elkhorn Mountains Volcanics. Alternatively, there may have been a more local source. A gravity low centered near Whitehall may reflect an extension of the Boulder Batholith gravity low (Hanna and others, 1993). Batholithic rocks may have been exposed in this area during the Chadronian and subsequently down-dropped during Miocene extensional tectonism. Paleochannels trend northeast in the Bull Mountain area and roughly north-south in the area above Parrot Bench (Kuenzi, 1966). Paleocurrent data suggest southwest paleoflow in the Climbing Arrow Member east of Bull Mountain (Richard, 1966; Lofgren, 1985) making it difficult to explain a granitic source with minimal input of volcanic rocks.

The granitic sandstones and conglomerates near Bull Mountain contain biotite and subordinate muscovite (Streeter, 1983). Other two-mica sandstones in the Renova Formation of southwestern Montana are interpreted as derived from the Idaho Batholith to the west (Thomas, 1995). However, the immaturity of the Climbing Arrow Member sandstone and conglomerate in the Bull Mountain area suggests that they were not derived from a distal source. Granitic rocks of the exposed Boulder Batholith contain only biotite (R. Berg, personal communication, 2004). The source of the muscovite is not known.

Chadronian and Orellan deposits of the Dunbar Creek Member rest nonconformably on Elkhorn Mountains Volcanics in the western part of the map area. Although dominantly composed of tuffaceous siltstone, the Dunbar Creek Member also contains both granitic and volcanic clasts.



From Ross (1955), Warne and others (1997), Burton and others (1997), and Vuke (2004).

Figure 3. Regional structural setting of Jefferson Valley map area.

No deposits of Orellan age are present east of Bull Mountain (Lofgren, 1985). The Chadronian Climbing Arrow Member is unconformably overlain by the late Arikareean (early Miocene) Negro Hollow map unit. Conglomerates in this unit are also primarily composed of granitic clasts (Lofgren, 1985), suggesting that Bull Mountain was only minimally exposed.

Middle Miocene and younger

An episode of erosion occurred during the Hemingfordian and was accompanied by the initiation of basin-and-range extension. Clasts in early Barstovian deposits a couple of miles north of the Negro Hollow map unit, outside of the upper Jefferson Valley map area, are almost exclusively composed of Elkhorn Mountains Volcanics (Lofgren, 1985), and probably indicate the exposure of Bull Mountain. East of the Boulder River (Fig. 1) early Barstovian deposits are composed of Paleozoic and intrusive clasts and suggest that Doherty Mountain (Fig. 1) was also exposed (Lofgren, 1985). Red Hill, just east of Bull Mountain (Fig. 1), was also likely exposed at this time.

Red Hill Map Unit

The Red Hill map unit on Red Hill is composed of breccia, red tuffaceous siltstone, and immature granitic sandstone, and has been interpreted several ways, both tectonic and sedimentary (Foster and others, 1993). It both underlies and overlies Paleozoic units at different locations. Although the breccia contains clasts of Paleozoic rocks and Elkhorn Mountains Volcanics, the overlying sandstone or conglomerate in the unit is composed almost entirely of minerals and clasts derived from granitic rock. Except for its local red color, the overlying sandstone and conglomerate closely resemble channel sandstone and conglomerate of the Climbing Arrow Member.

The following observations suggest that the breccia is tectonic:

1. Breccia exposures preferentially overlie or occur within less competent lithologies that are usually overlain by limestone.
2. The breccia cuts across formation contacts locally, suggesting tear faults.
3. The breccia and individual clasts range from unaltered to completely silicified.
4. The breccia unit has a planar upper surface and relatively uniform thickness of approximately 80 to 150 ft.
5. Slickensides are abundant locally.
6. The breccia zone can be traced into an apparent west-vergent thrust fault to the northwest that places the Jefferson Formation over the Elkhorn Mountains Volcanics.
7. Granitic sandstone, apparently the Climbing Arrow Member, that contains only minor clasts of other lithologies, occurs both above and below the breccia; yet the breccia is primarily derived from Paleozoic rocks with subordinate Elkhorn Mountains Volcanics. This suggests that Climbing Arrow Member granitic sandstone occurs both on the hanging wall and footwall of a fault and that the breccia is tectonic. The presence of Elkhorn Mountains Volcanics in the breccia but not in the overlying sandstone suggests that the breccia is younger than the Climbing Arrow Member.
8. The Red Hill map unit both underlies and overlies Paleozoic rock at different localities. This further suggests that the map unit is within a fault zone, with Paleozoic rock in both the hanging wall and footwall.
9. The Red Hill map unit dips as steeply as 45º locally.

The Golden Sunlight gold mine on southern Bull Mountain just west of Red Hill, is developed in a hydrothermal breccia. A hydrothermal origin for the Red Hill map unit, related to the Golden Sunlight Mine system, has been ruled out (Foster and others, 1993). Interpretations of a sedimentary origin for the Red Hill map unit red siltstone have included: 1) red beds associated with karst development or solution breccias (Foster and others, 1993), 2) paleosols (Foster and others, 1993), and 3) paleotalus (Richard, 1966).

Red beds associated with karst breccia in the Mission Canyon Limestone near Livingston, Montana, were distinguished from solution breccia deposits, in part based on clay mineralogy (Roberts, 1966; Sando, 1974). Kaolinite was the dominant clay mineral in the karst deposits whereas illite was the dominant clay mineral in the solution breccia and overlying Amsden Formation. However, the karst deposits were interpreted as paleosols that developed *prior to* Mississippian-Pennsylvanian Amsden Formation deposition, and the solution breccia was interpreted as having developed during the Late Cretaceous or Tertiary. Another study of the Mission Canyon and Lodgepole Limestone at the north end of the Big Horn Basin found illite rather than kaolinite in both solution and karst breccia deposits (McCaleb and Wayhan, 1969; Sando, 1974). These studies suggest that the kaolinitic red siltstone at Red Hill is not a product of either karst or solution breccia development. If the breccia, dominantly composed of limestone, is paleotalus from Red Hill Paleozoic rocks, it is difficult to explain the overlying sandstone and conglomerate beds with clasts almost exclusively of granitic rock, comparable to those in the Climbing Arrow Member.

The following observations suggest that the red siltstone is a product of pedogenic processes during a time of a warm, humid climate:

1. The clay in the red siltstone is kaolinite (Richard, 1966; Kuenzi, 1966), unlike most of the other Tertiary units in western Montana that contain montmorillonite clay (Kuenzi and Fields, 1968a). Kaolinite typically develops in oxisols of warm, humid climates.
2. The siltstones are mottled in patterns that suggest burrows or root casts.
3. The lowest red siltstone may be associated with the unconformity at the base of the Tertiary deposits, a likely place for soil development. Kaolinitic red beds are associated with this surface in other areas (Thompson and others, 1982). However, this soil horizon is not present where the Climbing Arrow Member rests on granodiorite of the Boulder Batholith near Pipestone Springs, possibly because a limestone substrate was more conducive to its development than a granitic substrate.

The breccia is interpreted as having developed on the sole of a low-angle southwest-vergent thrust fault that cuts the Climbing Arrow Member, Paleozoic rocks, and the red soil horizon, with these units both on the hanging wall and footwall of the thrust. A similar Tertiary breccia and red soil overlain by Paleozoic rocks are also present at several other locations to the east, all just north of the Southwest Montana Transverse Zone (Fig. 3)(Vuke, 2003). The age of the Red Hill map unit is shown as Eocene? and Miocene? in the map explanation, reflecting both the interpreted age of the paleosol (Eocene), and the interpreted age of breccia development (Miocene). Alternatively, the red siltstone may have been a product of mid-Miocene tectonism involving Paleozoic limestone during another interval thought to be wet and humid (Thompson, and others, 1981). If this is the case, the entire unit may be Miocene. Pleistocene gravel that locally covers the Red Hill map unit does not appear to be involved in the apparent faulting, but a number of small cross faults, at least some of which are listric, appear to offset the Pleistocene gravels and underlying deposits. These small faults are not shown on the map.

West- and southwest-vergent thrust faults?

Several other apparently west- or southwest-vergent thrust faults are present in the northeastern part of the map area. They are anomalous because Laramide thrust faults, especially north of the Montana Transverse Zone, are generally east-vergent and dip to the west. Some of these apparently southwest-vergent faults in the map area have been interpreted as folded thrust faults (Dixon and Wolfgram, 1998). Similar thrust faults in the Negro Hollow area northeast of the map area have also been interpreted as folded thrust faults (Glaman, 1991). However, slivers of Paleozoic rocks on the west side of thrust plates of Elkhorn Mountains Volcanics suggest that transport direction was to the west. Paleozoic beds are repeated and not overturned. A unit of breccia and red beds, called the Conrow Creek conglomerate (Lofgren, 1985; Streeter, 1983), apparently overlies Mississippian Mission Canyon Formation and underlies Elkhorn Mountains Volcanics. Clasts of Elkhorn Mountains Volcanics are present within the breccia itself. The breccia has been interpreted as deposited in a narrow gorge during Late Cretaceous and early Tertiary (Streeter, 1983) or as a debris flow deposit of unknown age (Lofgren, 1985). The Conrow Creek conglomerate was mapped as part of the Red Hill map unit in this report and is interpreted as a tectonic breccia at a thrust fault contact between Paleozoic rocks and overlying Elkhorn Mountains Volcanics. Alexander (1951, 1955), one of the first to map in this area, also interpreted several west- and southwest-vergent thrust faults in the map area.

Burton and others (1997) pointed out that estimates of eastward translation along the Southwest Montana Transverse Zone, particularly for the Lombard thrust plate (Fig. 3) are low compared to estimates from drill data from the Devil's Fence Anticline to the north (Fig. 3). This discrepancy may be explained by the difference in Laramide fold and thrust style between the Devil's Fence Anticline and the Southwest Montana Transverse Zone, as well as by folding of the Jefferson Canyon-Cave Fault, the main thrust of the Southwest Montana Transverse Zone (Whisner and Schmidt, in preparation). Could Cenozoic reversal of movement on the Southwest Montana Transverse Zone have also accounted for some of the discrepancy?

West-vergent folds and faults on the east side of the Devil's Fence Anticline and in the Big Mountain-Negro Hollow area northeast of the map area have been interpreted as simple-shear-induced parasitic "drag" folds related to upward crowding of Laramide thrust faults in the cores of major depressions in the area (Whisner and Schmidt, in preparation). However, if the Eocene Climbing Arrow Formation is involved in west-vergant thrusting in the map area of this report, as discussed above, there may also be a component of Cenozoic movement that contributed to the apparently anomalous direction in the Devil's Fence Anticline and Big Mountain-Negro Hollow areas as well.

The northern part of the map area is located immediately north of the Southwest Montana Transverse Zone and immediately east of the Boulder Batholith, and in addition, is located at a curve in the Southwest Montana Transverse Zone where the Dillon cut-off begins (O'Neill and others, 1990) (Fig. 3). The thick pile of Boulder Batholith and Elkhorn Mountains Volcanics may have served as a buttress for further Cenozoic westward translation on the Southwest

Montana Transverse Zone causing the development of thrust faults. Thrust movement may have been directed to the southwest where the Southwest Montana Transverse Zone curves toward the Dillon cut-off (Fig. 3).

The "S" Structure, a small anticline and syncline north of Red Hill, is anomalous in that it displays indicators of pervasive strain (Hendrix and Stellavato, 1976) whereas Laramide folds of western Montana generally display brittle deformation. The pervasive strain may have resulted from deep burial under 10,000 ft or more of Elkhorn Mountains Volcanics (Hendrix and Stellavato, 1976). The axial plane traces of the folds trend northwest-southeast and plunge about 60º to the northwest. The "S" Structure may have been thrust to the northeast over less deeply buried rocks near the end of the Laramide, or it may have been thrust to the southwest over less deeply buried Elkhorn Mountains Volcanics and Paleozoic rocks of Red Hill during the Miocene, or possibly both.

Early Barstovian deposits of the Parrot Bench map unit are present in the northwestern part of the map, but may be younger to the east of an interpreted fault that appears to drop Tertiary deposits down to the east. Deposits of the basal Parrot Bench map unit in the northwestern part of the map are composed of matrix-supported, unconsolidated to well-cemented breccia with angular to subangular clasts dominantly of locally derived Elkhorn Mountains Volcanics, diorite porphyry, and granitic rocks. Deposits of the basal Parrot Bench map unit rest unconformably with erosional contact on the Dunbar Creek Member and are overlain by interbedded fine-grained sandstone and lenses of sandy matrix-supported pebble and cobble gravel that contain angular to subangular clasts of both granitic and volcanic rock. Recently, a canid fossil, tentatively considered early Barstovian, was discovered in the northwestern part of the map area. This fossil is particularly significant because it represents a previously undescribed species and is the only representative of *Aelurodon* known from Montana (Wang and others, 2004).

On the northwest flank of the Tobacco Root Mountains above Parrot Bench (Fig. 3), early and middle Barstovian deposits are not present. Late Barstovian deposits unconformably overlie the Bone Basin Member. A volcanic fanglomerate facies (Kuenzi, 1966) indicates that local sources of Elkhorn Mountains Volcanics, Proterozoic LaHood Formation, and Paleozoic rocks were being eroded at this time. These source rocks were exposed at the northwest end of the Tobacco Root Mountains, probably at the basin margin.

Many of the faults in the northern part of the map area, particularly the north- and northeast-striking faults, developed following deposition of the youngest Tertiary strata in the area. Point-of-Rocks Cave (Fig. 1) on the northwest flank of the Tobacco Root Mountains in the map area, contains Blancan (Pliocene) fossils (Hill, 2001; Rasmussen, 2003), but Pliocene deposits are otherwise not known from the map area.

East of Bull Mountain and immediately south of Red Hill (Fig. 1), Pleistocene gravel deposits and adjacent hills and valleys curve. This may reflect deflection from late Pleistocene or Holocene movement on faults in the area. The Jefferson River is thought to have become entrenched in the canyon east of the northeastern part of the map area during this time (Schmidt and others (1987).

SOUTHERN PART OF MAP AREA

The east side of the upper Jefferson Valley is almost entirely covered by alluvial fan deposits except for a few exposures of Tertiary beds. The alluvial fans are mostly middle Pleistocene or younger in age (Bartholomew and others, 1990). A large alluvial fan is also present at the mouth of Fish Creek on the west side of the valley. Unlike the fans on the east side, the Fish Creek fan is strewn with large boulders thought to have been deposited by glacier outburst floods (Bartholomew and others, 1990), sudden release of glacial meltwater from either a glacier or a glacier-dammed lake.

Tertiary deposits in the southern part of the map area are younger than the mid-Tertiary unconformity except for Arikareean deposits that crop out east of the Jefferson River near Silver Star (Fig 1). An ash from these deposits has been dated as 21.7 $\pm$ 0.9 m.y. (Hanneman, 1989). Other Tertiary deposits in the southern part of the map area, the Parrot Bench, Silver Star, and Twin Bridges map units, are interpreted as part of the Sixmile Creek synthem (p. 4).

Seismic and gravity data indicate that the southern (uppermost) Jefferson Valley is divided by a structural arch (Rasmussen and Fields, 1985), interpreted as a basement high (Hanneman, 1989; Brunsvold, 1989; Hanneman and Wideman, 1991). Varying interpretations of the thickness of basin fill over the basement high have been made including 600 m (Brunsvold, 1989), 1200 m (Vane, 1972), sea level (about 1500 m) (Wigger, 1985; Hanna and others, 1993), and over 3000 m (Rasmussen and Fields, 1985).

The area of the basement high is mappable at the surface as a horst between the Silver Star and Twin Bridges faults. Offset on the bounding faults involves both Tertiary and Quaternary units. Late Quaternary uplift of the horst has been interpreted from observed changes of channel pattern, dimension, and shape, and from associated hydraulic conditions of the Jefferson River across the area of the horst (Jorgensen, 1990). The Jefferson River channel in the uplifted area is straighter, less laterally active, has a greater flow capacity, and contains less sediment in the form of within-channel bars. These fluvial responses are attributed to accommodation of the effects of Quaternary uplift in the area (Jorgenson, 1990). Tertiary uplift of the basement high is also suggested because part of the Tertiary section (interpreted as Arikareean) present in the basins north and south of the basement high is missing over the high (Hanneman, 1989; Hanneman and Wideman, 1991).

Gravity data from two lines perpendicular to the Jefferson Valley on the east side of the valley indicate that the depth to the bottom of the Jefferson Basin changes from sea level near Dry Boulder Canyon over the basement high, to -3000 ft near Hellroaring Canyon north of the high (Wigger, 1985). This abrupt change is interpreted to be the result of a northwest-striking fault that bounds the north side of the high and is down-dropped to the northeast (Wigger, 1985). This subsurface fault is probably the Silver Star fault shown on the upper Jefferson Valley map.

Generally northeast-trending seismic transect lines that cross the Silver Star and Waterloo faults suggest a 9,500-ft (2900-m) offset of Cenozoic deposits across a fault zone (Brunsvold,

1989) in the area of the Silver Star Fault. These faults have also been called the Bismark and Cherry Creek faults, respectively (Hanneman, 1989).

The upper Jefferson Valley is asymmetrical, with large, steep, west-dipping faults on the east flank and at least one east-dipping fault of smaller magnitude on the west flank (Rasmussen and Fields, 1985). Tertiary strata abutting the large west-dipping basin faults show dip reversal caused by drag-folding during basin subsidence, and contain numerous small faults, many of which are antithetical, that cut the deeper strata (Rasmussen and Fields, 1985). Both the Tertiary and Quaternary deposits thicken toward the east basin-bounding faults (Rasmussen and Fields, 1985). Many of the basin-bounding faults have also been interpreted as right-lateral strike-slip faults (Ruppel, 1993).

Several Quaternary faults in the map area have been trenched and logged. The Georgia Gulch fault in the southwestern part of the map area postdates Pinedale outwash, so is latest Pleistocene or possibly earliest Holocene (Bartholomew and others, 1990). A trenched fault in the Vendome fault zone offsets gravel deposited by Bull Lake(?) outburst floods from Fish Creek to the west. The latest movement on this fault was determined to be late Pleistocene (Bartholomew and others, 1990).

HOT SPRINGS

The upper Jefferson Valley has a concentration of geothermal systems that include Silver Star, Renova, and Pipestone Hot Springs (Fig. 1), as well as unnamed small hot springs, warm springs, and thermal ground water intercepted by drilling. Thermal water probably circulates in fractures in the Boulder Batholith at Silver Star Hot Springs, and within folded sedimentary rocks on the flanks of the Tobacco Root Mountains at Renova Hot Springs (O'Haire, 1977).

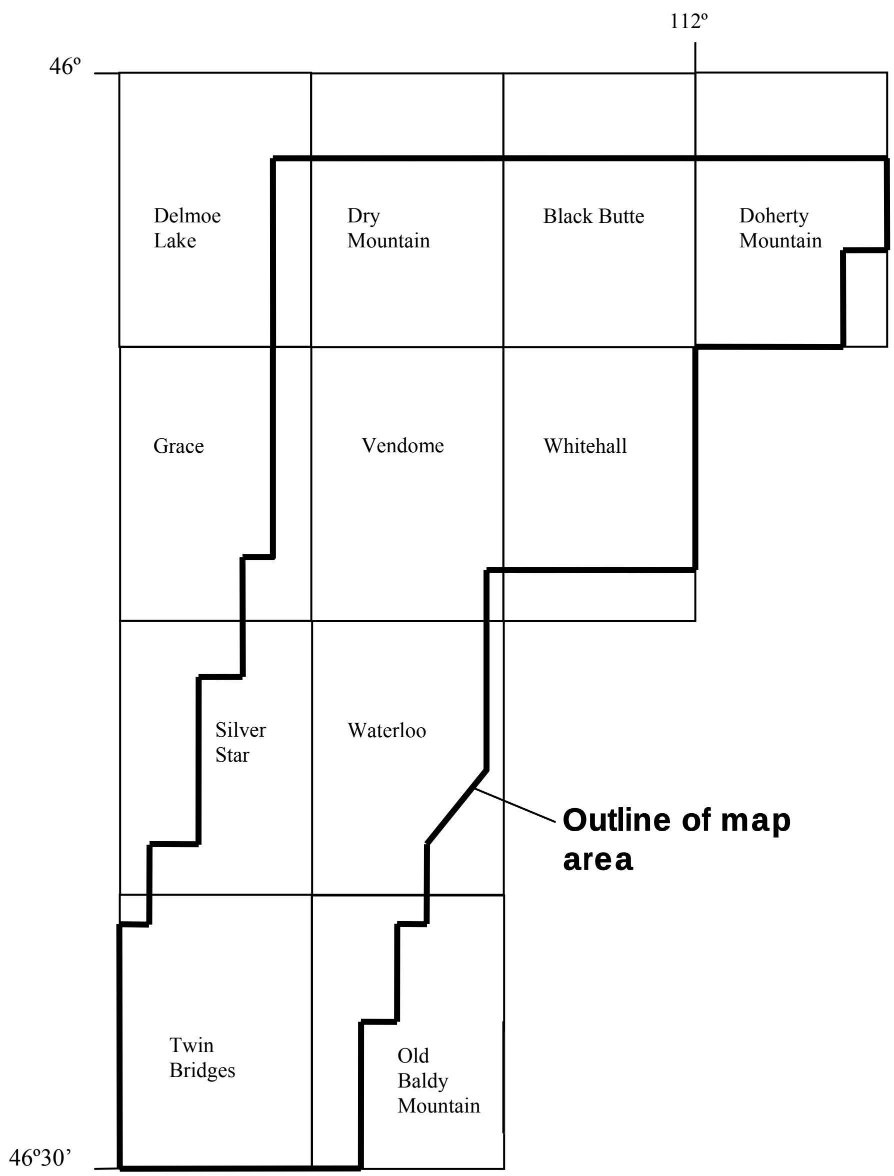
The Pipestone Hot Springs area is one of five areas in the Tobacco Root Mountain region with clusters of earthquake epicenters (Stickney, 1993). Thermal water probably circulates in igneous rocks of the Elkhorn Mountains Volcanics or Boulder Batholith that underlie Cenozoic deposits at Pipestone Hot Springs (O'Haire, 1977). Northeast-striking faults through this hot springs area have been postulated by Prostka (1966), O'Haire (1977), Chadwick and Leonard (1979), and Vice (1982). A northeast-striking concealed fault was interpreted on the present map arbitrarily connecting Pipestone Hot Springs with a warm spring 2 miles to the southwest. In addition, lineaments from thermal infrared imagery suggest a set of east-west-striking faults through the Pipestone Hot Springs area (Vice, 1982), not shown on the present map.

The water in all of the hot springs in the map area is meteoric, warmed by heat associated with the regional geothermal gradient of this area that has above-average crustal heat flow. The numerous faults in the area serve as local conduits for sinking cold water and rising hot water (O'Haire, 1977).

Deposits of an older, but probably Holocene hot spring underlie Tertiary deposits near Silver Star and include banded quartz, banded calcite, geodes, and quartz and calcite crystals (McMillan, 1939). In addition, tufa, probably of hydrothermal origin, is exposed in the Climbing Arrow Member near a fault on the east side of Red Hill.

The map area lies within a seismically active part of Montana called the Intermountain Seismic Belt (Stickney and others, 2000), and although modern surface-rupturing faults are rare, the area continues to experience numerous small- and moderate-magnitude earthquakes (Stickney and others, 2000).

INDEX OF 7.5-MINUTE QUADRANGLES FOR
GEOLOGIC MAP OF THE UPPER JEFFERSON VALLEY



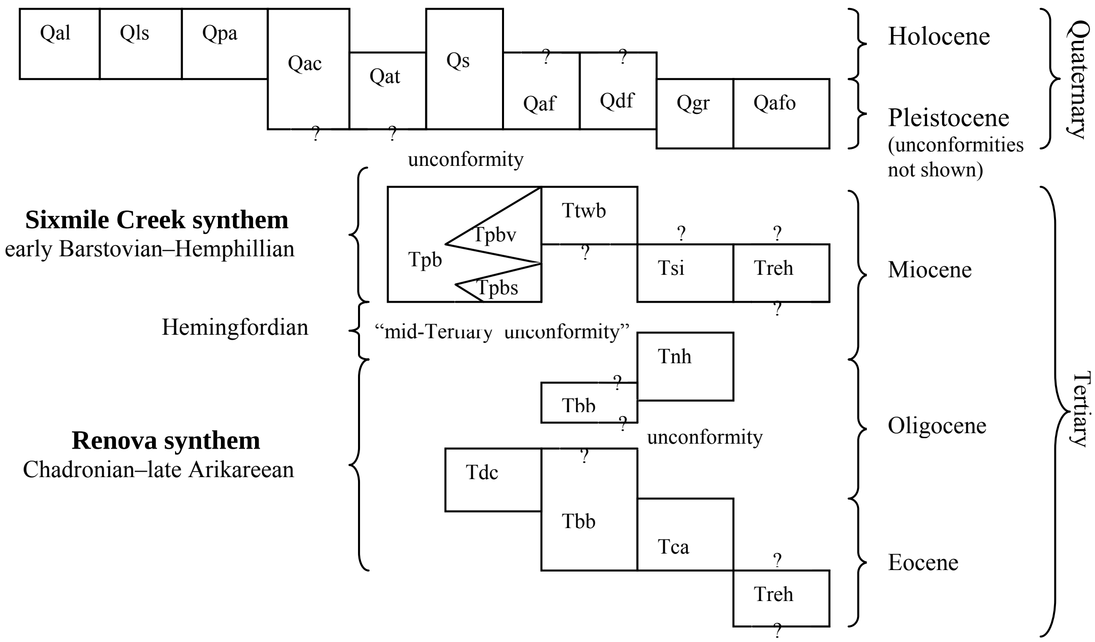
SOURCES OF GEOLOGIC MAPPING FOR GEOLOGIC MAP OF THE UPPER JEFFERSON VALLEY

Alexander, 1955; Plate 1; 1:31,680 scale.
Axelrod, 1984; Plate 1; 1:24,000 scale.
Bartholomew and others, 1990; Figures 2 and 4; 1:100,000 scale.
Berg, 1959; Plate 1; 1:12,000 scale.
Dixon and Wolfgram, 1998; 1:24,000 scale.
Hanneman, 1989; 1:63,360 scale.
Hanneman and Wideman, 1991; 1:500,000 scale.
Hendrix and Stellavato, 1976; Figure 10-1; 1:62,500 scale.
Kuenzi, 1966; Plate 1; 1:24,000 scale.
Lofgren, 1983; Plate 1; 1:24,000 scale.
O'Haire, 1977; Figures 3, 4, and 12; 1:39,370 scale.
Prostka, 1966; 1:24,000 scale.
Reid, 1957; 1:95,000 scale.
Reshkin, 1963; Plate 1; 1:24,000 scale.
Ripley, 1987; Figure 3; 1:24,000 scale.
Ruppel and others, 1993; 1:250,000 scale.
Schmidt, 1975; 1:24,000 scale.
Streeter, 1983; 1:24,000 scale.
Vitaliano and Cordua, 1979; 1:62,500 scale.

SOURCES OF SUBSURFACE INFORMATION

Abdul-Malik, 1977
Burfeind, 1967
Brunsvold, 1989
Hanna, and others, 1993; 1:250,000 scale.
Hanneman, and Wideman, 1991
O'Haire, 1977
Reshkin, 1963
Richard, 1966
Wigger, 1985

CORRELATION DIAGRAM
CENOZOIC DEPOSITS OF THE UPPER JEFFERSON VALLEY



DESCRIPTION OF CENOZOIC DEPOSITS
UPPER JEFFERSON VALLEY

Note: Thicknesses are given in feet because original maps were on 7.5’ quadrangles with contour intervals in feet. To convert feet to meters (the contour interval unit on this map), multiply feet x 0.3048.

Thickness of many Quaternary deposits was not determined.

Qal ALLUVIUM (Holocene)—Gravel, sand, silt, and clay in channels and floodplains of modern rivers and streams.

Qls LANDSLIDE DEPOSIT—(Holocene) Two mass wasting deposits on east side of Golden Sunlight Mine. Older landslide now covered with mine waste. A 1994 landslide was caused by reactivation of an older landslide and was initiated by weighting from mine waste dumps. A relatively competent part of the Tertiary section slid 2 to 4 ft on montmorillonite-rich mudstone of the Climbing Arrow Member. Earlier natural movement of the landslide was about 1,800 ft (Foster and Smith, 1995).

Qpa PALUDAL DEPOSIT (Holocene)—Sand, silt, and organic matter deposited in swamp environment. Taken from pattern on topographic base. May be related to a concealed fault or faults.

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Qac ALLUVIUM AND COLLUVIUM (Holocene and Pleistocene?)—Dominantly sand, silt, and clay, and subordinate gravel deposited on relatively gentle slopes primarily by sheetwash and gravity processes. Variable thickness, generally less than 30 ft thick.

Qat ALLUVIAL TERRACE DEPOSIT (Holocene and Pleistocene?)—Gravel, sand, silt, and clay in deposits that extend for about one mile along Little Pipestone Creek about 40 ft above the creek. Gravel clasts are subangular to subrounded, as large as boulder size, and composed of volcanic rock, quartzite, and granitic rock in a matrix of calcium carbonate-cemented sandstone and granule conglomerate. Thickness about 5 ft.

Qs SEDIMENT, UNDIVIDED (Holocene and Pleistocene)—Variety of surficial deposits not individually mapped including loess, sheetwash alluvium and colluvium, alluvium in small channels, debris-flow deposits, pediment gravel, and small landslide deposits. Sediment size ranges from clay and silt to boulders. Sediment generally locally derived, although loess is both locally derived and from distal sources. Ash beds from distal sources to west. Larger clasts (pebble size and larger) angular to subangular in unconsolidated fans and fanglomerates. Thickness generally less than 20 ft and in many areas only about 1 inch thick, but locally 50 ft thick or greater.

Qaf ALLUVIAL FAN DEPOSIT (Holocene? and Pleistocene)—Gravel, sand, silt, clay, and ash beds, poorly sorted with larger clasts both matrix-supported and clast-supported. Deposits have retained at least some evidence of original alluvial fan morphology. Alluvial fan of Fish Creek strewn with numerous large boulders that may have been deposited by glacier outburst floods (Bartholomew and others, 1990).

Qdf DEBRIS FLOW DEPOSIT—(Holocene? and Pleistocene)—Matrix-supported gravel with clasts as large as boulder size but generally cobble size and smaller, in a matrix of sand, silt, and clay. Clasts angular to subrounded, derived from Elkhorn Mountains Volcanics, quartz veins, and granitic rocks of the Boulder Batholith.

Qgr GRAVEL DEPOSIT (Pleistocene)—Gravel, sand, silt, clay, and ash on the flanks of Bull Mountain and the northwestermost Tobacco Root Mountains. Composed of locally derived rock, mostly of Elkhorn Mountains Volcanics near Bull Mountain, with subordinate Paleozoic rocks. Southeast of Sheep Rock, unit contains abundant blocky boulders of Cambrian Flathead Sandstone that may have undergone very little transport. Adjacent to Tobacco Root Mountains above Parrot Bench, the gravel is composed of subangular to subrounded clasts of quartzite, and subordinate granitic rocks and Elkhorn Mountains Volcanics. Near Bull Mountain, lower part brown and moderately cemented; upper part unconsolidated (Foster and others, 1993). Overlain by Holocene and Pleistocene loess that contains calcareous paleosols (Foster and others, 1993). Thickness as much as 40 ft.

Qafo OLDER ALLUVIAL FAN DEPOSIT (Pleistocene)—Gravel, sand, silt, and clay, poorly sorted with larger clasts generally matrix-supported. Deposits lack original alluvial fan morphology.

Tpb PARROT BENCH INFORMAL MAP UNIT (Miocene)—Grayish-orange and yellowish-brown fine- to coarse-grained, crossbedded sand or sandstone and subordinate siltstone and mudstone, interbedded with dominantly matrix-supported pebble or cobble conglomerate and breccia. Locally breccia clasts are boulder size. Coarser clasts are generally in channels and lenses with scour bases. Sandstones are typically poorly sorted texturally with coarser granules and small pebbles floating in a sand matrix. Clast composition is that of local sources, including monzogranite of the Boulder Batholith, Elkhorn Mountains Volcanics, Paleozoic rocks, Proterozoic Belt quartzite and shale, and Archean metamorphic rocks. Basal part of member in northwestern part of map area composed of angular to subangular small boulder-, cobble-, and pebble-size clasts dominantly of Elkhorn Mountains Volcanics in a matrix of unconsolidated to cemented granules and smaller clasts. Above Parrot Bench basal part of member lies in erosional contact with the underlying Bone Basin Member with as much as 50 ft of relief on the contact (Kuenzi and Fields, 1971). The basal Parrot Bench map unit contains numerous lenses with clasts of Elkhorn Mountains Volcanics as large as small boulder size, in contrast to the Bone Basin Member that has only rare granule- or pebble-size clasts of the volcanics. A volcaniclastic fanglomerate facies occurs above Parrot Bench in the northeastern part of the map area (Kuenzi, 1966). Age determined by fossils (Kuenzi, 1966; Kuenzi and Fields, 1971; Wang and others, 2004). Thickness approximately 3200 ft (Kuenzi, 1966).

Tpbs SHALE BRECCIA OF PARROT BENCH INFORMAL MAP UNIT (From Kuenzi, 1966) (Miocene)—Local facies of the Parrot Bench map unit at the south end of Bull Mountain. Pale-yellowish-brown, unimbricated breccia composed of texturally poorly sorted, angular clasts dominantly of Proterozoic Belt shale, with subordinate Belt sandstone, Paleozoic limestone and sandstone, and Cretaceous latite. Breccia grades into coarse sandstone, finer sandstone, and siltstone. Clast size as much as 2 ft across decreases away from Bull Mountain. Sporadic conglomerate lenses with rounded pebbles and cobbles generally 1 or 2 inches in diameter, composed of quartzite, gneiss, volcanic rock and limestone cemented by calcium carbonate. Age determined by a paartial tooth of *Merychippus* (Kuenzi, 1966). Generally less than 30 ft thick, but locally as much as 100 ft thick.

Tpbv VOLCANIC FANGLOMERATE OF PARROT BENCH INFORMAL UNIT (From Kuenzi, 1966) (Miocene)—Texturally poorly sorted breccia composed dominantly of angular pebble- to boulder-size clasts of locally derived Elkhorn Mountains Volcanics and of Proterozoic LaHood Formation, with subordinate amounts of Paleozoic quartzite and limestone interbedded with tuffaceous sandstone.

Ttwb TWIN BRIDGES INFORMAL MAP UNIT (Miocene? and/or Pliocene?)—Yellowish-gray to orangish-brown unconsolidated to weakly cemented gravel, sand, silt, and clay with clasts generally cobble size and smaller, subangular to subrounded and locally derived. Thickness east of the Jefferson River not known. Maximum thickness west of the Jefferson River about 100 ft.

Tsi SILVER STAR INFORMAL MAP UNIT (Miocene?)— Clast-supported gravel or breccia with tan, light-tan, or reddish-brown matrix of angular clasts ranging to pebble size. Gravel clasts angular, locally derived, and as large as boulder size, unconsolidated to cemented with calcium carbonate. Not dated, but likely late Miocene. Thickness about 120 ft.

Treh RED HILL INFORMAL MAP UNIT (Eocene? and Miocene?)—Reddish-brown, poorly sorted locally silicified breccia in sand matrix generally cemented by calcium carbonate. Clasts in breccia as large as boulder size. Clast composition that of adjacent Paleozoic rocks (dominantly limestone, dolomite, shale, and chert) with subordinate clasts of Elkhorn Mountains Volcanics. Overlain by kaolinitic red tuffaceous siltstone that is locally brecciated, and beds of red or brown, immature coarse-grained sandstone or granule conglomerate derived almost exclusively from granitic rock with locally abundant biotite; notably with no Paleozoic clasts. See text for explanation of age interpretation. Thickness 80–150 ft.

Tnh NEGRO HOLLOW INFORMAL MAP UNIT (From Lofgren, 1985) (Miocene)—Poorly sorted, unconsolidated to cemented, matrix-supported pebble conglomerate with dominantly granitic clasts and subordinate clasts of Elkhorn Mountains Volcanics in a tuffaceous silt matrix. Conglomerate locally crossbedded. Lenses of clast-supported conglomerate generally at top of beds. Matrix-supported conglomerate grades laterally into, or is interbedded with, tabular beds of thinly laminated vitric silt and ash. Late Arikareean age determined by fossils (Lofgren, 1985). Thickness north of map area about 900 ft.

Tdc DUNBAR CREEK MEMBER OF RENOVA FORMATION (Eocene and Oligocene)—Orangish-tan to pinkish-tan fine- to coarse-grained, tuffaceous sand and silt, interbedded with ash beds, local lenses of granule- to cobble-size, matrix-supported to clast-supported conglomerate and breccia, and subordinate beds of reddish- or brownish-gray ash-bearing montmorillonite mudstone. Clast composition dominantly monzogranite and rocks of Elkhorn Mountains Volcanics. Planar, tabular bedding visible from a distance, but dominantly low-angle channels apparent in outcrop, many with scour bases and coarse sand, granule, and pebble and cobble breccia and conglomerate. Chadronian to Orellan age based on fossils (French, 1988; Tabrum and others, 1996). Thickness about 1000 ft (Kuenzi, 1966).

Tbb BONE BASIN MEMBER OF RENOVA FORMATION (Eocene, Oligocene, and early Miocene?)—Very light-gray, yellowish-gray, and olive-gray, fossiliferous and locally oölitic or pisolitic limestone, marl, montmorillonite mudstone, and thin beds and stringers of chert and silicified limestone interbedded with matrix-supported granule or pebble conglomerate, sand, silt, and ash. Fossils include algal structures, gastropods, ostracodes, pelecypods, diatoms, and vertebrates that suggest a paludal environment (Kuenzi, 1966) and root casts that indicate subaerial exposure. Silicified limestone interpreted as caliche (Ripley, 1987). Paleosols abundant (Hanneman, 1989). Sedimentary structures include crossbedding and ripple marks. Contains an elongated north-northwest-trending belt of cross-bedded coarse sandstone and granule conglomerate about one-half to 4 ft thick, one-eighth to one-half mile wide, and 1½ miles long, composed almost exclusively of granitic rock fragments (Kuenzi, 1966). Chadronian age determined by fossils, but may extend to as young as Arikareean (Axelrod, 1984). Composite thickness of map unit approximately 1700 ft, but thickest section 965 ft (Kuenzi, 1966).

Tca CLIMBING ARROW MEMBER OF RENOVA FORMATION (Eocene)—Greenish-gray volcanic glass- and pumice-bearing montmorillonite mudstone and tuffaceous siltstone and sandstone or conglomerate in large channels in Red Hill area or in interbeds or smaller channels in the northwestern part of the map. Channel sediment is immature sandstone and granule and pebble conglomerate, generally clast-supported, almost entirely derived from a granitic source. Lithic clasts are almost all granitic, although locally there are scattered clasts of Elkhorn

Mountains Volcanics in the Bull Mountain area. Mudstones contain abundant root casts and zones of calcareous concretions. Light-gray tuffaceous siltstone or mudstone is most abundant north and east of Red Hill and appears to overlie the part of the sections described above. This tuffaceous unit has been called Dunbar Creek Member (Lofgren, 1983), but is considered part of the Climbing Arrow Member on this map because of the similarity of the channel deposits both in composition and orientation. A small exposure of the tuffaceous unit was involved in the 1994 landslide east of the Golden Sunlight Mine (Foster and Troy, 1995). Chadronian age in Pipestone and Cactus Junction areas determined by numerous paleontological studies (summarized in Tabrum and Fields, 1980, and Tabrum and others, 1996). Chadronian age near Bull Mountain determined by fossils (Kuenzi, 1966; Lofgren, 1985). Thickness 175 ft (Kuenzi, 1966).

MAP SYMBOLS

Contact between geologic units–Dashed where approximately located; dotted where concealed

Linear Feature–Possibly controlled by fracture or fault

Fault–Dashed where inferred, dotted where inferred fault is concealed. Bar and ball on downthrown side where relative displacement known

Fault, thrust–Dotted where concealed; teeth on upper plate

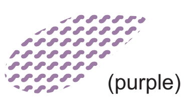
Strike and dip of beddding–Number indicates angle of dip in degrees

Strike and dip of foliation–Number indicates angle of dip in degrees

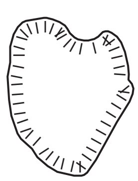
Syncline–Showing trace of axial plane and direction of plunge; dotted where concealed. Plunge arrow omitted where not plunging or plunge direction unknown

Anticline–Showing trace of axial plane and direction of plunge; dotted where concealed. Plunge arrow omitted where not plunging or plunge direction unknown

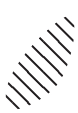
Zone of tectonic brecciation. Tectonic breccia also interpreted, but not shown in Red Hill map unit



Zone of shearing



Golden Sunlight Mine, Inc., pit



Golden Sunlight Mine, Inc., mine dump

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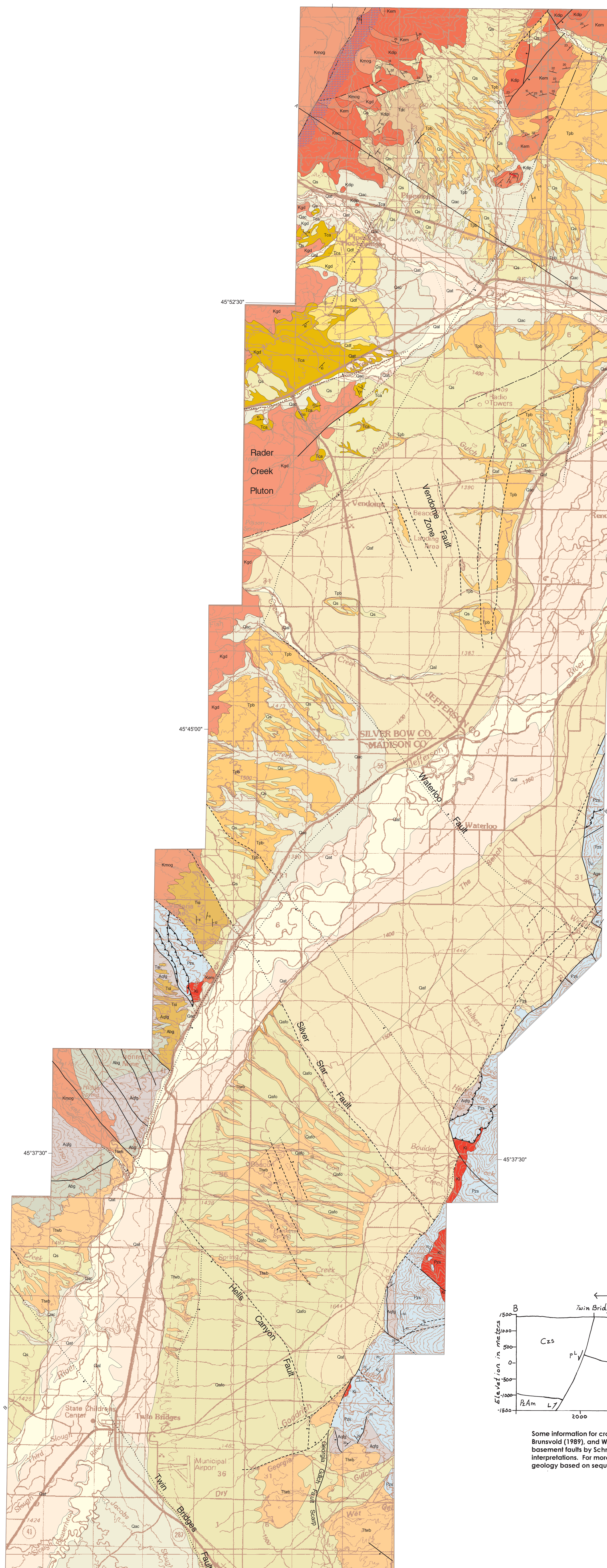
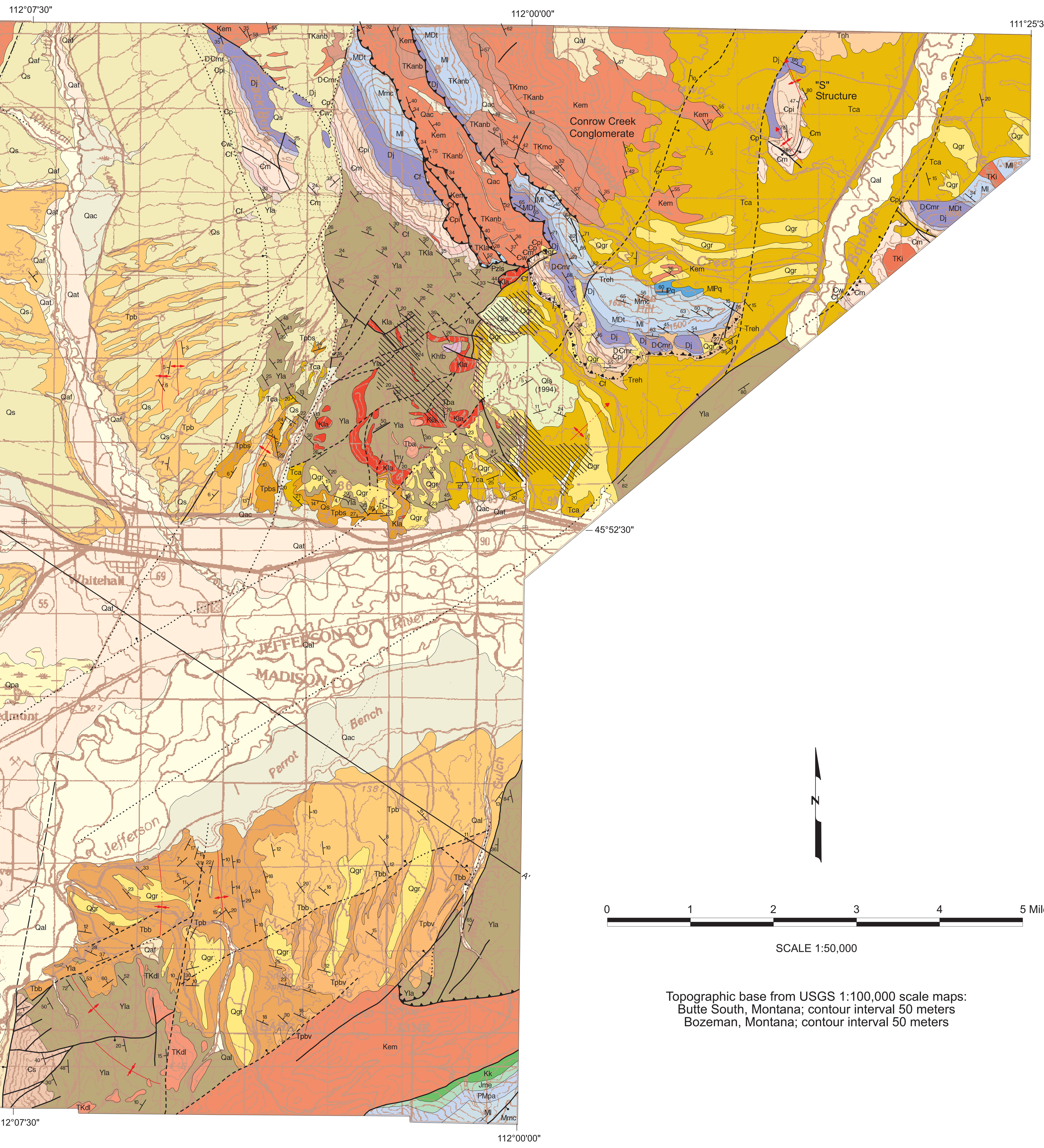
*Current name: Montana Tech of the University of Montana

0 1 2 3 4 5 Miles

SCALE 1:50,000

Topographic base from USGS 1:100,000 scale maps:
Butte South, Montana; contour interval 50 meters
Bozeman, Montana; contour interval 50 meters

MAP UNITS

Qal	Alluvium of modern channels and flood plains
Qls	Landslide deposit
Qpa	Paludal deposit
Qac	Alluvium-colluvium
Qat	Alluvium of alluvial terrace deposit
Qs	Sediment, undivided
Qaf	Alluvial fan deposit
Qdf	Debris flow deposit
Qgr	Gravel
Qafo	Alluvial fan deposit, older
Tpb	Parrot Bench map unit, informal
Tpbs	Shale breccia of Parrot Bench map unit
Tpbv	Volcanic fanglomerate of Parrot Bench map unit
Tsi	Silver Star map unit, informal
Ttwb	Twin Bridges map unit, informal
Treh	Red Hill map unit, informal
Tnh	Negro Hollow map unit, informal
Tdc	Dunbar Creek Member of Renova Formation
Tbb	Bone Basin Member of Renova Formation
Tca	Climbing Arrow Member of Renova Formation
Tba	Basalt
TKi	Intrusive rocks, undivided
TKanb	Andesite and basalt
TKdl	Dacite and latite
TKmo	Monzonite and/or quartz monzonite
TKl	Latite
TKla	Lamprophyre
Ki	Intrusive rocks, undivided
Khtb	Hydrothermal breccia
Kla	Latite
Kdip	Diorite porphyry
Kem	Elkhorn Mountains Volcanics
Kmog	Monzogranite of Boulder Batholith
Kgd	Granodiorite of Boulder Batholith
Kk	Kootenai Formation
Jme	Morrison Formation and Ellis Group, undivided
Pzls	Paleozoic limestone
Pzs	Sedimentary rocks, undivided
PMpa	Phosphoria, Quadrant, and Amsden Formations
IPq	Quadrant Formation
MIPa	Amsden Formation
Mmc	Mission Canyon Limestone
Ml	Lodgepole Limestone
MDt	Three Forks Formation
Dj	Jefferson Formation
D€mr	Maywood and Red Lion Formations, undivided
€pi	Pilgrim Limestone
€p	Park Shale
€m	Meagher Limestone
€w	Wolsey Shale
€f	Flathead Formation
€s	Sedimentary rocks, undivided
Yla	LaHood Formation
Abg	Biotite gneiss
Ags	Gneiss and schist
Aqfg	Quartzofeldspathic gneiss

MAP SYMBOLS

Contact between geologic units–Dashed where approximately located; dotted where concealed

Linear Feature–Possibly controlled by fracture or fault

Fault–Dashed where inferred, dotted where inferred fault is concealed. Bar and ball on downthrown side where relative displacement known

Fault, thrust–Dotted where concealed; teeth on upper plate

32 **Strike and dip of beddding**–Number indicates angle of dip in degrees

75 **Strike and dip of foliation**–Number indicates angle of dip in degrees

Syncline–Showing trace of axial plane and direction of plunge; dotted where concealed. Plunge arrow omitted where not plunging or plunge direction unknown

Anticline–Showing trace of axial plane and direction of plunge; dotted where concealed. Plunge arrow omitted where not plunging or plunge direction unknown

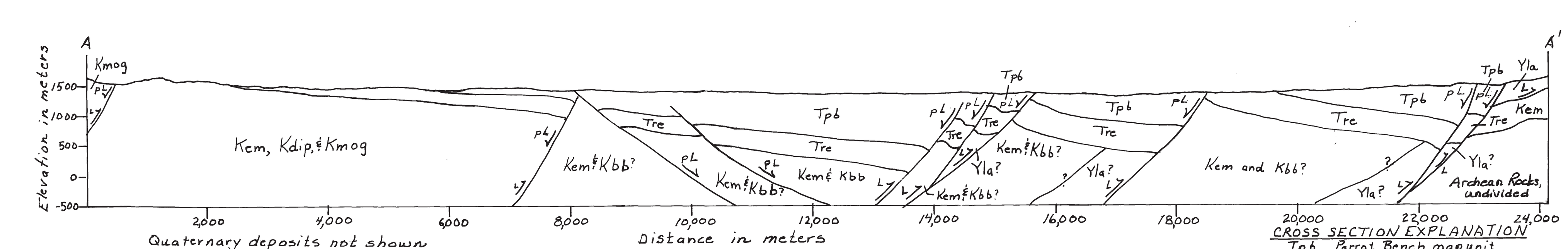
Zone of tectonic brecciation. Tectonic breccia also interpreted, but not shown in Red Hill map unit

Zone of shearing

Golden Sunlight Mine, Inc., pit

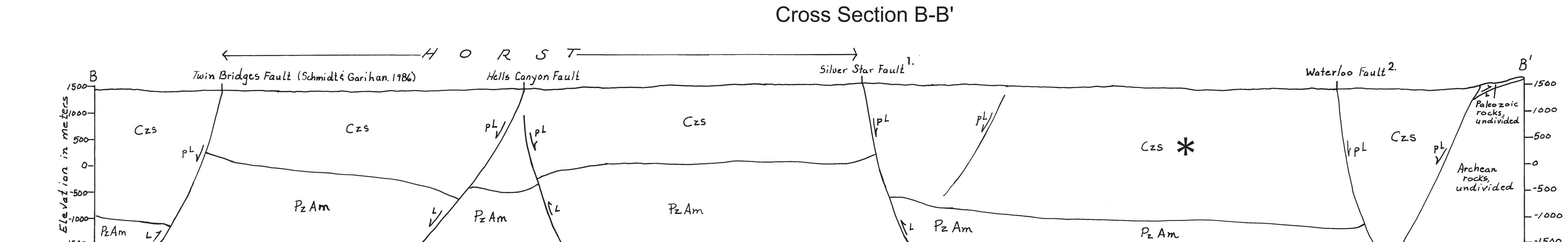
Golden Sunlight Mine, Inc., mine dump

Cross Section A-A'



Some information for cross section A-A' was taken from Burfiend (1966), particularly his cross section I-I', and from Hanna and others (1993).

Cross Section B-B'



Some information for cross section B-B' was taken from Hanna and others (1993), Brunsvold (1989), and Wigger (1985). Models for Cenozoic reactivation of basement faults by Schmidt and Garihan (1986) were used for Cenozoic fault interpretations. For more detailed information about Cenozoic subsurface geology based on sequence stratigraphy, see Hanneman and Wideman (1991).

1. Silver Star Fault as used by Schmidt and Garihan (1986). The western basin-bounding fault has also been called the Silver Star Fault (Ruppel, 1993). The Silver Star Fault of the present report has also been called the Cherry northwest-striking Cherry Creek basement fault of the eastern Tobacco Root Mountains.

2. The Waterloo Fault has also been called the Bismark Fault (Hanneman and Wideman, 1991).

* The Cenozoic deposits are shown as *undivided* on the cross section because older Tertiary units are not exposed in this part of the valley, so it is not possible to determine Tertiary unit thicknesses from outcrop. Depth to the basement (Paleozoic? and Archean rocks, undivided) was taken in part from Hanna and others (1993), Brunsvold (1989), and Wigger (1985).

Using seismic data not available for the present report, Hanneman and Wideman (1991) interpreted five sequence stratigraphic units (Sequence 1 through 5) in the Cenozoic deposits in the subsurface of this part of the Jefferson Valley. Based on gravity and seismic data also not available for the present report, Rasmussen and Fields (1983, 1985) interpreted three lithostratigraphic units in the Cenozoic deposits in the subsurface as follows: a lower set with consistent lateral seismic character (possibly equivalent to the Renova Formation), a middle set that unconformably overlies the lower set (equivalent to the Sixmile Creek Formation), and an upper set composed of west-dipping Quaternary deposits.

Maps may be obtained from
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Partial support has been provided by the STATEMAP component of the National Cooperative Geologic Mapping Program of the U.S.Geological Survey under Contract Number 03HQAG0090.

GIS production: Ken Sandau and Paul Thale, MBMG. Map layout: Susan Smith, MBMG.

Montana Bureau of Mines and Geology
Open File 505

Geologic Map of the Cenozoic Deposits of the Upper Jefferson Valley Southwest Montana

Compiled and mapped by Susan M. Vuke, Walter W. Coppinger, and Bruce E. Cox

2004