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GEOLOGIC HISTORY OF THE DILLON AREA, SOUTHWESTERN MONTANA

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NORTHWEST GEOLOGY

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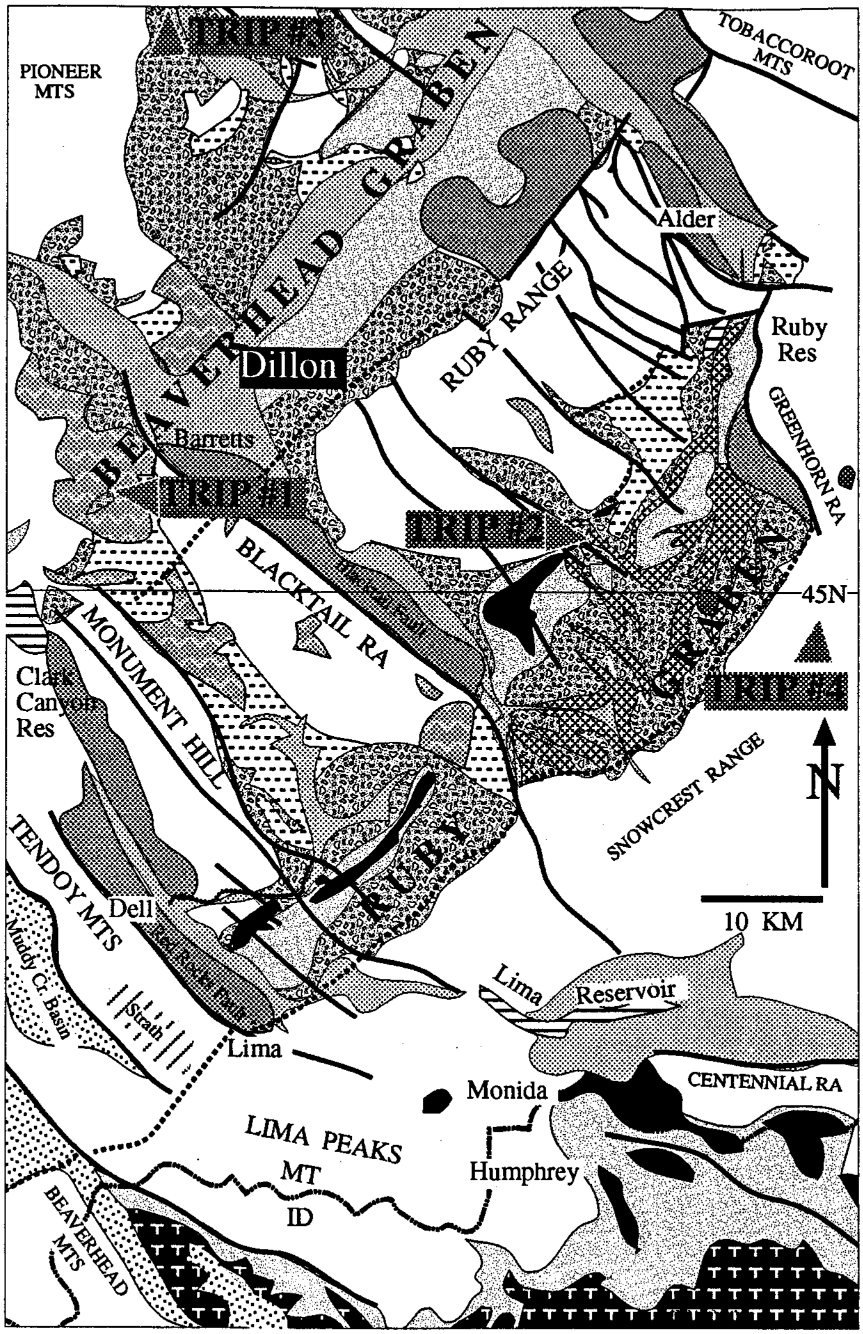

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ZEOLITIC TUFFS IN THE GRASSHOPPER CREEK AREA: FIELD TRIP GUIDE

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INTRODUCTION

The occurrence of clinoptilolite and mordenite in the Cold Springs Volcanics of Cretaceous age near Grasshopper Creek, Beaverhead County, Montana, was first reported by Robert Pearson (1989). The zeolitized area has since been mapped in detail by the authors and samples have been analyzed to quantify the zeolite resource. Personnel from Montana Tech have also done additional sampling and analytical work (Berg, 1993). In February, 1994, a road was constructed into the principal zeolite deposit for bulk testing. Approximately 100 tons of zeolitized tuff was mined from an open pit.

GEOLOGY

The Cold Spring Volcanics comprise a small volcanic field of Cretaceous age that crop out discontinuously over 200 square kilometer area, 10 to 25 km southwest of Dillon, Montana. The volcanic rocks are probably within the Beaverhead Conglomerate and unconformably overlie older Cretaceous sedimentary rocks. They are overlain by pink to red Beaverhead Conglomerate.

The zeolitized sequence of tuffs is from 30 to 100 m thick at the base of the volcanics and consists of graded pyroclistic flows and ash-fall tuffs. In outcrop, the zeolitized tuffs are light colored and flaggy to massive bedded. Their textures range from uniformly fine-grained pumiceous tuff to conglomeratic tuff with 0.5 to 3.0 cm diameter lithic clasts. (Cox and Brenner-Younggren, 1993).

Clinoptilolite and mordenite occur in a variety of tuffaceous lithologies, but not in discrete zeolitic "beds". However, local stratigraphic successions of dominantly zeolitic tuff to opaline tuff suggest a vertical zoning of authigenic minerals. A 5 to 15 m thick sequence of vitric tuff with a gradational lower contact and sharp upper contact is a stratigraphic datum which may have been a permeability control on zeolitization; zeolitization is much more pervasive below the vitric tuff.

FIELD TRIP

The field trip will exit from Interstate 15 at the mouth of Grasshopper Creek and proceed up the creek to the zeolitized tuffs (Figure 1). Most of this trip will be on private property, so we ask that participants please stay on the roads, leave gates as they are found, and stay out of the hay meadows. Four stops are planned: one as we exit Interstate 15, one to discuss the geometry of the tuff basin, a stop to review structures in the Mesozoic rocks and a final stop to examine the zeolitized tuff in detail. Some hiking will be necessary.

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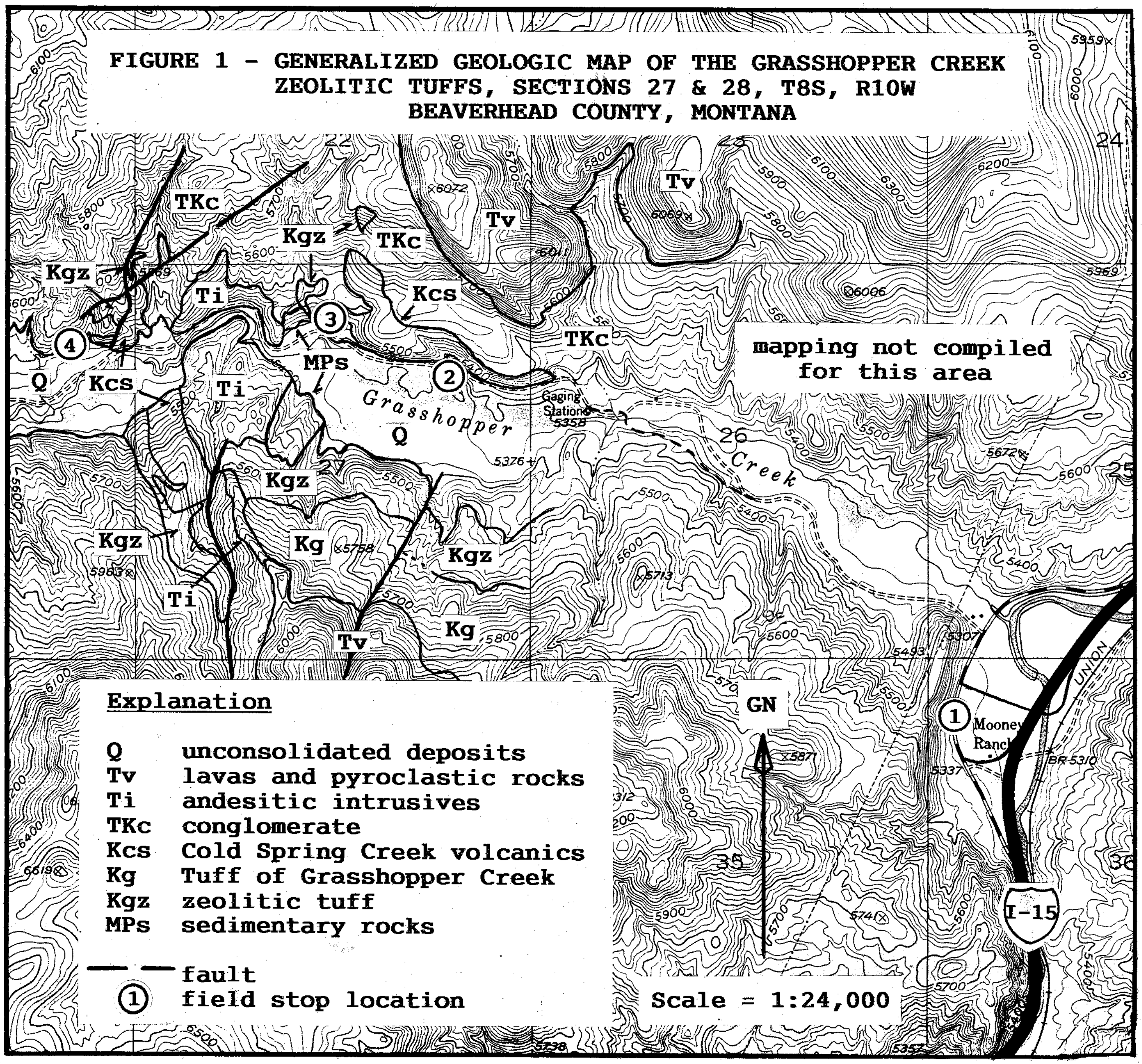
Northwest Geology, v. 25, p. 1-3 , 1995

FIGURE 1 - GENERALIZED GEOLOGIC MAP OF THE GRASSHOPPER CREEK ZEOLITIC TUFFS, SECTIONS 27 & 28, T8S, R10W BEAVERHEAD COUNTY, MONTANA



Explanation

Q	unconsolidated deposits
Tv	lavas and pyroclastic rocks
Ti	andesitic intrusives
TKc	conglomerate
Kcs	Cold Spring Creek volcanics
Kg	Tuff of Grasshopper Creek
Kgz	zeolitic tuff
MPs	sedimentary rocks
— —	fault
①	field stop location

on the Occurrence, Properties and Utilization of Natural Zeolites, F.A. Mumpton, editor.

Cox, B.E., and Brenner-Younggren, E., 1993 Exploration of a Late Cretaceous Zeolitic Tuff, Beaverhead County, Montana, <u>in</u> Mumpton, F.A., ed., Zeolite '93, Program and Abstracts.

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TERTIARY EXTENSIONAL HISTORY OF SOUTHWESTERN MONTANA: FIELD TRIP GUIDE FOR THE SWEETWATER AND UPPER RUBY VALLEYS, MONTANA

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INTRODUCTION

It has long been recognized that late Cenozoic extensional tectonism has played an important role in the development of the topography of southwestern Montana (Pardee, 1950; Scholten et al., 1955; Ruppel, 1982; and Fields et al., 1985). However, the timing of basin formation, the number of extensional events, and the processes responsible for the extension have been more controversial.

Traditionally, most workers have concluded that the existing extensional topography resulted from Basin and Range-style faulting that was initiated during the Paleogene (Reynolds, 1979; Chadwick, 1981; and Fields et al., 1985). More recently, workers have shown that much of the extensional topography was initiated during the Neogene as a result of crustal adjustments along the northern margin of the Yellowstone hotspot track (Anders et al., 1989; Westaway, 1989; Anders and Sleep, 1992; Fritz and Sears, 1993; Sears et al., 1995; Sears, 1995; and Thomas, 1995).

In order to debate these models, a field trip was organized for the 20th annual field conference of the Tobacco Root Geological Society to visit the Sweetwater and Upper Ruby Valleys in southwestern Montana (Fig.1). Structural and sedimentological relationships in this region are critical to understanding the Cenozoic extensional history of southwestern Montana. The focus of the trip will be on the Timber Hill locality, with additional stops to discuss the origin of talc in Archean rocks, Cenozoic carbonates, and Paleogene insect and plant fossils.

CENOZOIC EXTENSION

The origin and timing of Cenozoic extension in southwestern Montana has been a matter of some controversy. The traditional view holds that extensional tectonism started during the Paleogene (i.e., middle Eocene to middle Oligocene time) as a result of Basin and Range province faulting (Reynolds, 1979; Chadwick, 1981; and Fields et al., 1985). According to this model, Cenozoic fluvial and lacustrine deposits in the region (i.e., Renova and Sixmile Creek formations; Fig. 2) were deposited in semi-isolated extensional basins that are still active as the modern extensional basins of southwestern Montana (Reynolds, 1979; Fields et al., 1985; and Hanneman and Wideman, 1991).

A number of variations on this model have recently been proposed. For example, Ruppel (1993) concluded that the basins were largely formed during the Paleogene through extensional collapse of crust over-thickened by Mesozoic compressional deformation. However, he argued that Neogene displacement was primarily strike-slip and oblique-slip due to a combination of lateral extrusion and renewed extensional collapse.

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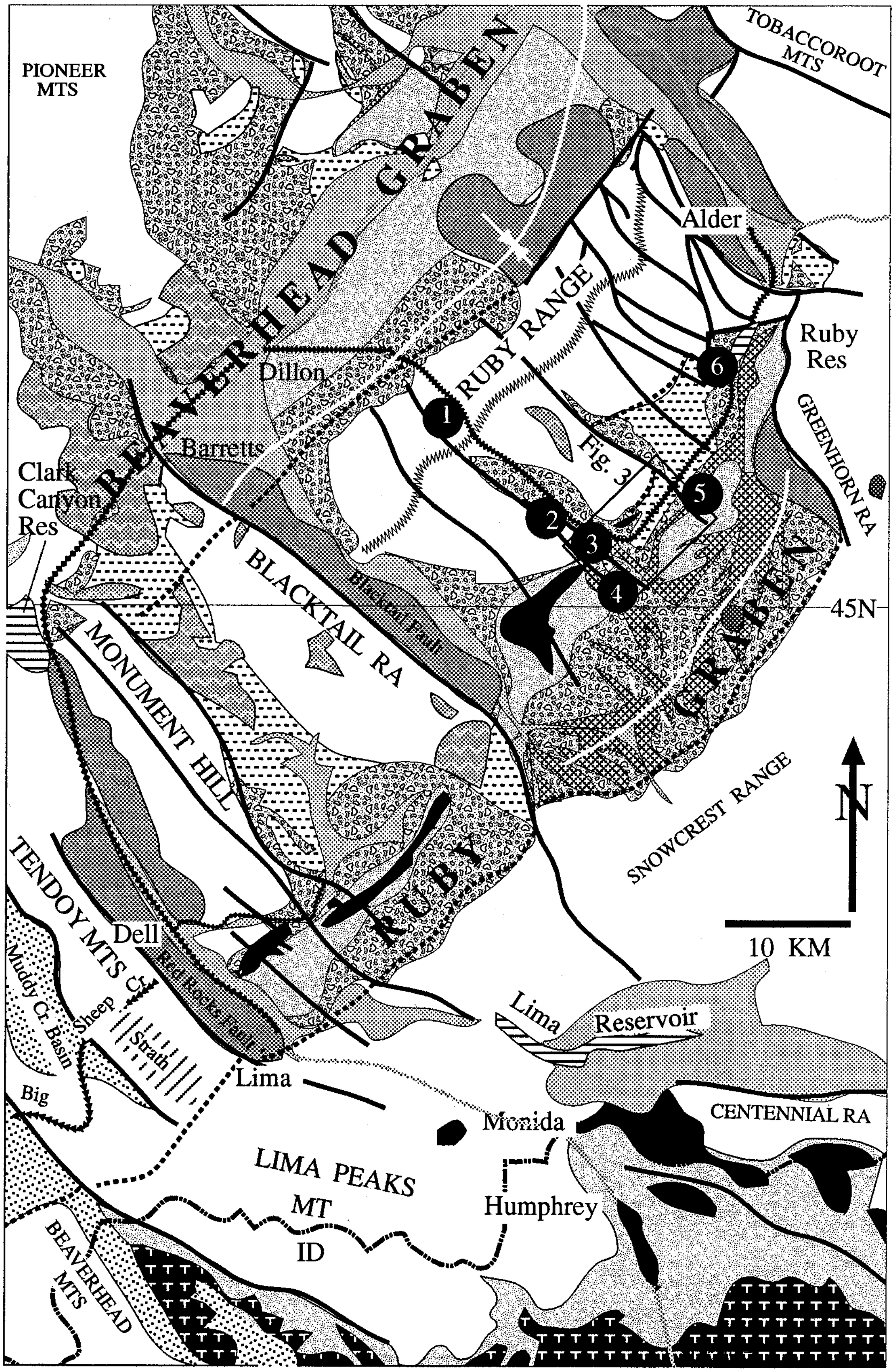


Figure 1. Geologic map of field trip area, showing route and field trip stops (modified from Sears et al., 1995).

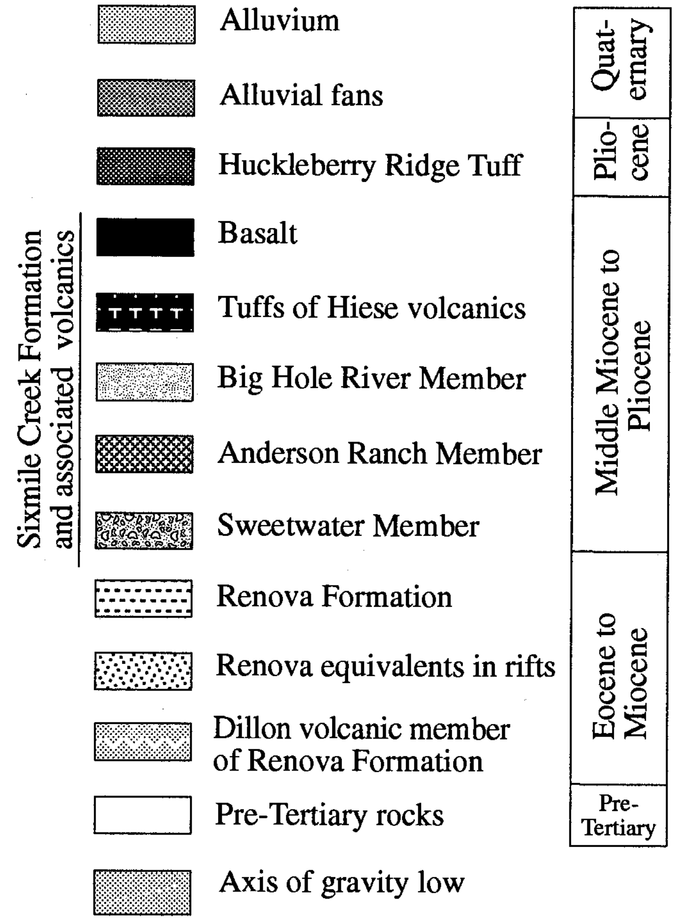


Figure 2. Stratigraphy of the field trip area (Sears et al., 1995).

Similarly, Janecke (1994, 1995) proposed that extensional tectonism in southwestern Montana was initiated during Paleogene time as a result of gravitational collapse of crust over-thickened by Mesozoic compression. However, she argued that the extension was confined to an approximately 100 km wide, north-trending rift zone located west of the eastern boundary of the Sevier fold and thrust belt (Fig. 3). She speculated that sediments derived from uplifts within the rift zone were transported eastward into the tectonically quiescent "Renova basin" (see Fig. 3) by streams that breached the shoulder of the rift. This conclusion is supported by extensive deposits of granitic sandstone within the "Renova basin" that were derived from uplifted blocks within the rift system (Thomas, 1995).

In contrast to previous models, Fritz and Sears (1993) have argued that southwestern Montana is characterized by multiple generations of extensional faults that can be related to different extensional mechanisms. They argued that extensional tectonism began in mid-Miocene time with the opening of northeast-trending grabens associated with the initiation of Basin and Range province faulting in the Great Basin. They concluded that pre-middle Miocene fluvial and lacustrine deposits of the Renova Formation were most likely deposited in broad erosional valleys cut into stable crust, and subsequently preserved in grabens formed during the mid-Miocene extensional event (Fig. 4). Preliminary data from a study of distinctive deposits of Paleogene granitic sandstone support their model, because these regionally correlative deposits occur in basins that have been isolated by post-Paleogene extension (Thomas, 1995; see discussion of stop #5).

By early Barstovian time (~16 Ma based on the age of the oldest vertebrate fauna; Fields et al., 1985), developing grabens captured regional drainages, and filled with debris flows, fluvial gravels and sands, tephras, and volcanic flows of the Sixmile Creek Formation (Fritz and Sears, 1993). The Sixmile Creek deposits are characteristically coarser grained than the Renova deposits, and they overlie the Renova in angular discordance because of pre-middle Miocene extensional tilting (see Fig. 4; Fields et al., 1985; and Sears et al., 1995).

By the end of the Miocene (sometime after 6.0 Ma), the northeast-trending structures were cut by northwest-trending extensional faults attributed to crustal adjustments along the northern margin of the Yellowstone hotspot track (Anders and Sleep, 1992; Anders et al., 1989; Westaway, 1989; Fritz and Sears, 1993; and Sears et al. 1995). In several grabens, the older Miocene stream sytems were diverted into the northwest- trending grabens, and deposits of the Sixmile Creek Formation were uplifted and tilted into the new mountain ranges (Fritz and Sears, 1993; Sears et al., 1995). The northwest- trending faults appear to be recently active, because they generally coincide with a zone of significant historical seismicity in southwestern Montana (Stickney and Bartholomew, 1987).

TIMBER HILL LOCALITY

In order to debate the various models for the Cenozoic extensional history of southwestern Montana, a field trip was organized to visit the Timber Hill locality in the Sweetwater and upper Ruby Valleys east of Dillon, Montana (Fig. 5). This area best illustrates the structural and sedimentological relationships that are critical to understanding the Cenozoic extensional history of southwestern Montana, and should provide an excellent forum for discussion and debate.

The Timber Hill locality provides excellent exposures of (1) Archean basement, (2) Eocene volcanics, (3) Renova Formation, (4) Sixmile Creek Formation, and (5) Quaternary alluvial fan and landslide deposits (Fig. 6). The locality is

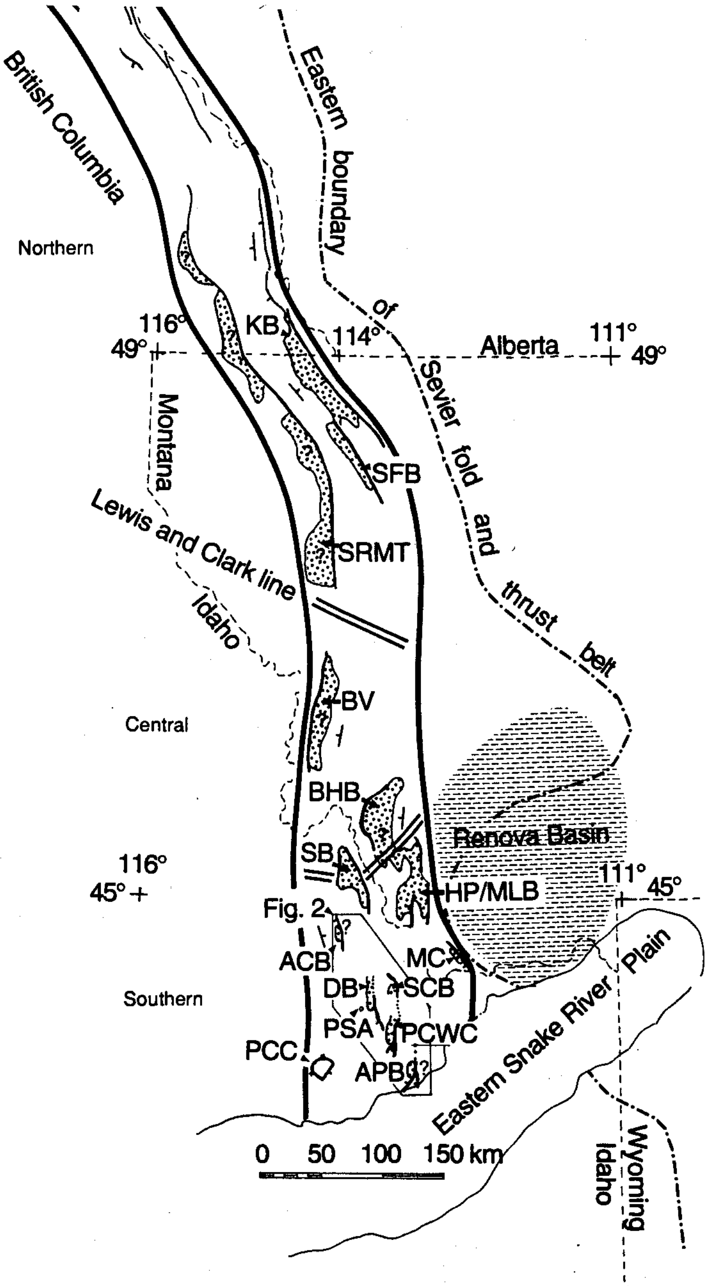
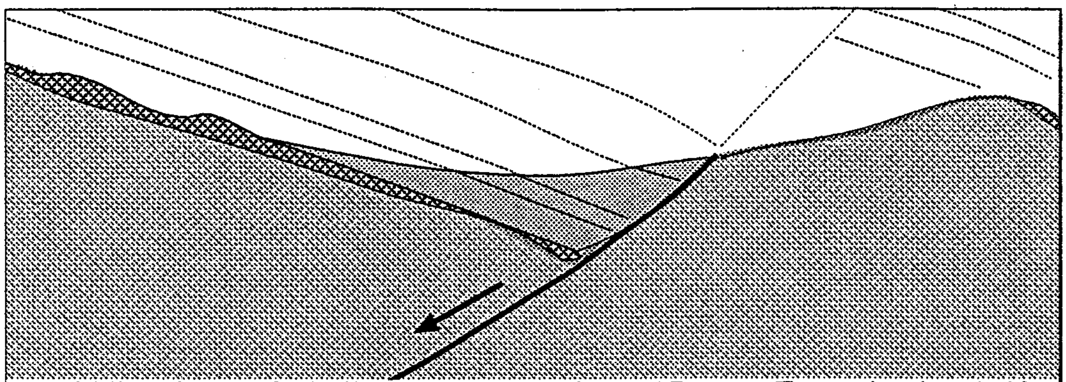
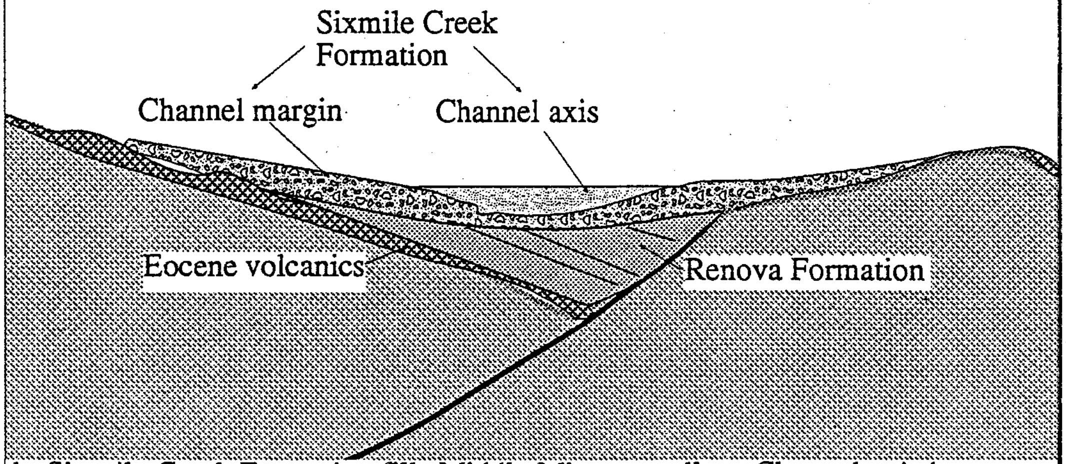


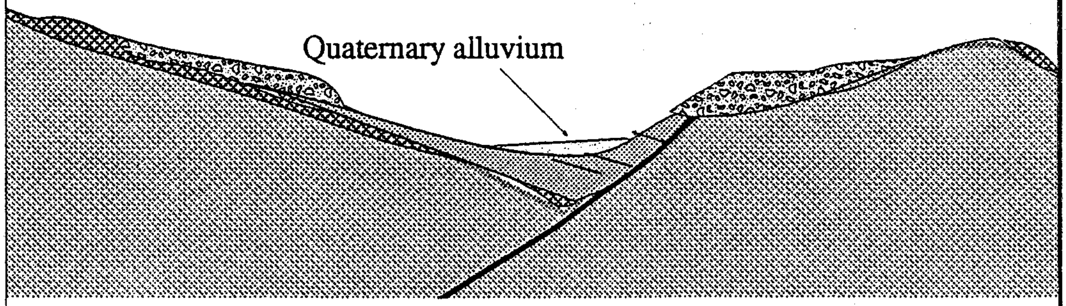
Figure 3. Map showing the location of the Eocene to Oligocene rift zone (north-trending dark lines), and the "Renova basin" in Montana. Stippled areas within the rift represent the position of known and inferred Eocene and Oligocene extensional basins within the rift. (Janecke, 1994).



a. Middle Miocene fault tilts Eocene volcanics and Renova Formation into half-graben. Erosion removes Renova Formation from uplifted areas.



b. Sixmile Creek Formation fills Middle Miocene valley. Channel axis has far-transported stream gravel and tephra. Margins are alluvial fan deposits from neighboring uplifts.



c. Quaternary erosion removes most of channel axis deposits, but channel margin deposits are widely preserved as benches. Tilted Renova Formation exposed.

Figure 4. Model for the development of mid-Miocene grabens in southwestern Montana (based on Beaverhead graben; Sears et al., 1995).

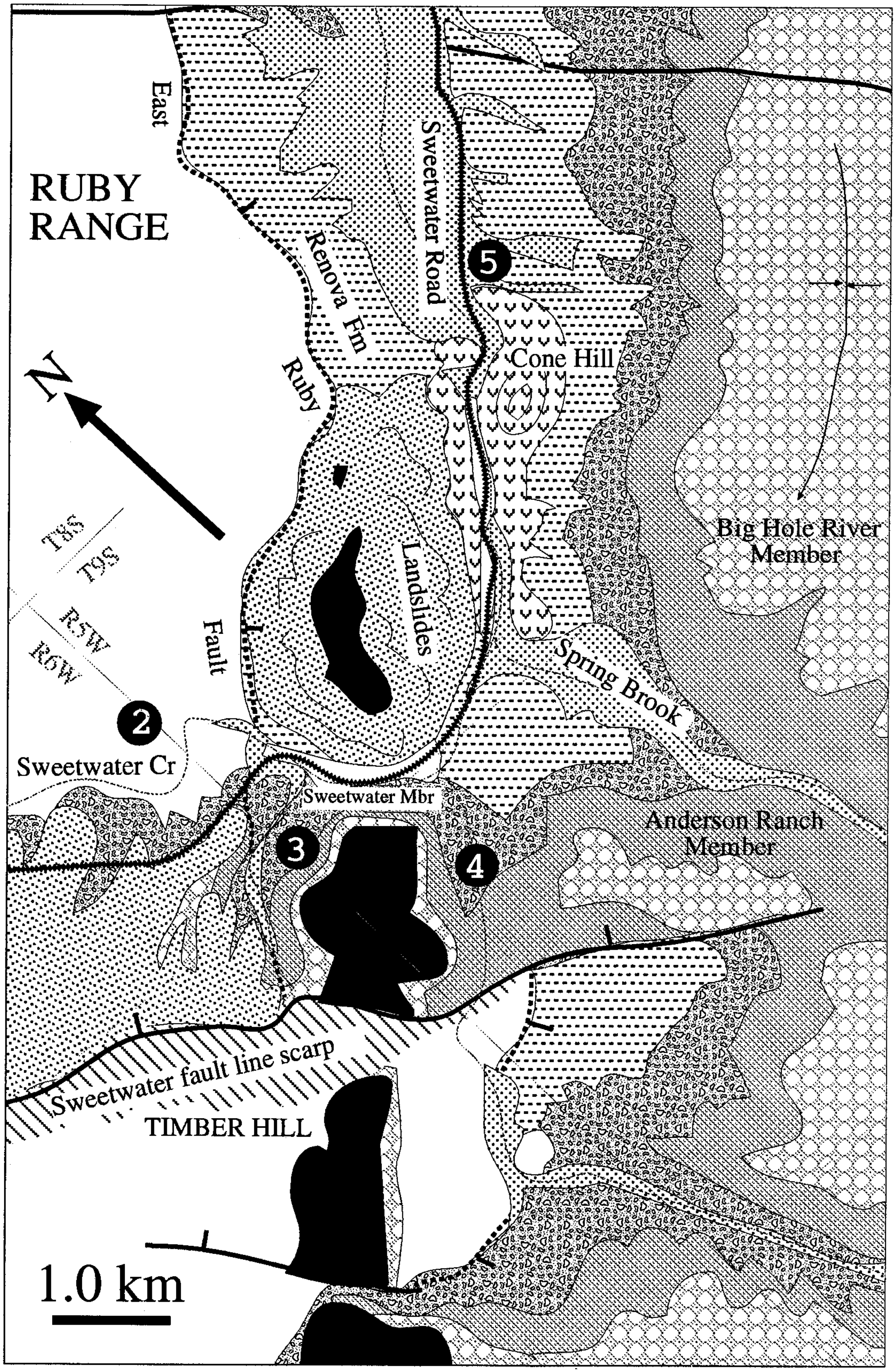


Figure 5. Geologic map of the Timber Hill area, showing field trip stops 2, 3, 4, and 5 (modified from Sears et al., 1995).

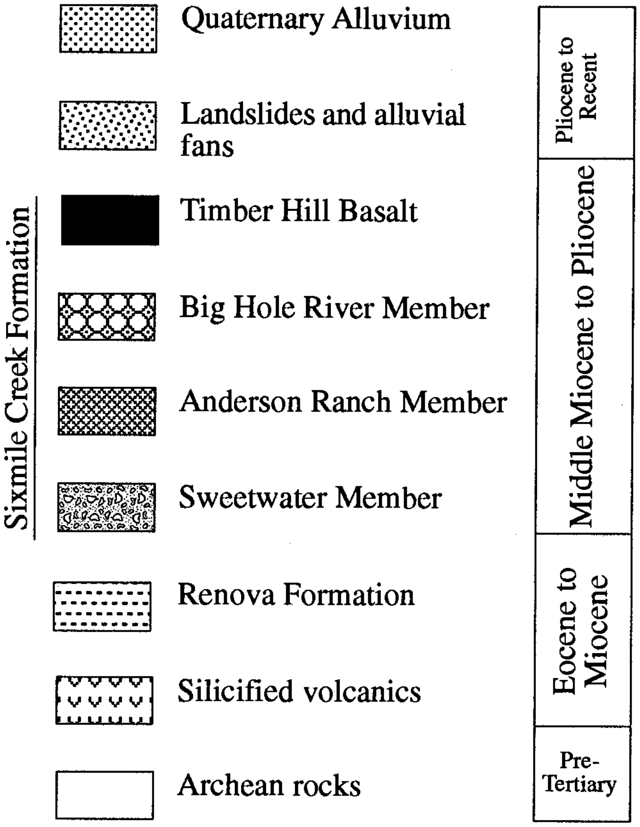


Figure 6. Stratigraphy of the Timber Hill area (Sears et al., 1995).

distinguished by a prominent basalt plateau (i.e.,Timber Hill basalt; see Fig. 5) that serves as an important datum that constrains the timing of extensional faulting associated with the Yellowstone hotspot (Fritz and Sears, 1993).

Tertiary stratigraphy within the Timber Hill area consists of two primary divisions; the Renova Formation (Eocene to early Miocene) and the Sixmile Creek Formation (middle Miocene to late Pliocene). Hanneman and Wideman (1991) proposed that this nomenclature be discarded in favor of subdivisions based on unconformity-bounded sequences. They noted difficulties in recognizing the predominantly fine-grained Renova Formation from the predominantly coarse-grained Sixmile Creek Formation as the primary problem with the traditional nomenclature. At the Timber Hill locality, the lithological differences can be recognized, so the traditional nomenclature is utilized.

RENOVA FORMATION IN THE TIMBER HILL AREA

The Renova Formation in the Timber Hill area consists primarily of light-colored tuffaceous mudstone with minor amounts of conglomerate, sandstone, "paper shale", limestone, marl, and coal (Monroe, 1976). The interpreted environments of deposition include braided streams, meandering streams, deltas, ephemeral alkaline lakes, swamps, caliche soils, and alkaline or hydrothermal springs (Monroe, 1976, 1981; and Ripley, 1995). As previously mentioned, these deposits may have been deposited in a large depositional basin (i.e., "Renova basin") that predates regional extension and basin formation (Thomas, 1995).

Monroe (1976) recognized three mappable units within the Renova Formation in the upper Ruby Valley (listed from oldest to youngest); (1) Climbing Arrow Member, (2) Dunbar Creek Member, and (3) Passamari Member. The Renova Formation in this area has yielded a wealth of fossil plants, insects, microfauna and microflora, and vertebrates that serve as an excellent biostratigraphic framework for the region (Becker, 1960, 1961, 1972, 1973; Monroe, 1976; Fields et al., 1985; and Ripley, 1987, 1995).

SIXMILE CREEK FORMATION IN THE TIMBER HILL AREA

The Sixmile Creek Formation overlies the Renova Formation in angular discordance because of extensional tilting of the Renova Formation during the formation of the Miocene Ruby graben (Fig. 7). Along the margins of the graben, the Sixmile Creek Formation directly overlies pre-Renova units because of erosional removal of the Renova from the uplifted blocks (see Fig. 7; Sears et al., 1995).

The Sixmile Creek Formation represents the sedimentary fill of a valley that formed along the Ruby graben. Fluvial gravels in the axis of the valley were flanked by bajadas that extended into the adjacent ranges (see Fig. 7; Sears et al., 1995). Basin filling appears to have started by late Hemingfordian to early Barstovian time based on vertebrate fossils in the basal deposits of the Sixmile Creek Formation (Monroe, 1976; and Fields et al., 1985).

The Sixmile Creek Formation has been subdivided into three informal members (see Fig. 6; Fritz and Sears, 1993). The basal member consists of matrix-supported breccia, conglomerate, and tuffaceous sandstone of the Sweetwater Creek member. These deposits are interpreted as debris flows derived from blocks uplifted along the margins of the Miocene Ruby graben (Fritz and Sears, 1993). The tuffaceous matrix of these debris flows may have been derived from tuffaceous deposits of the Renova Formation that covered the region prior to mid-Miocene extensional disruption.

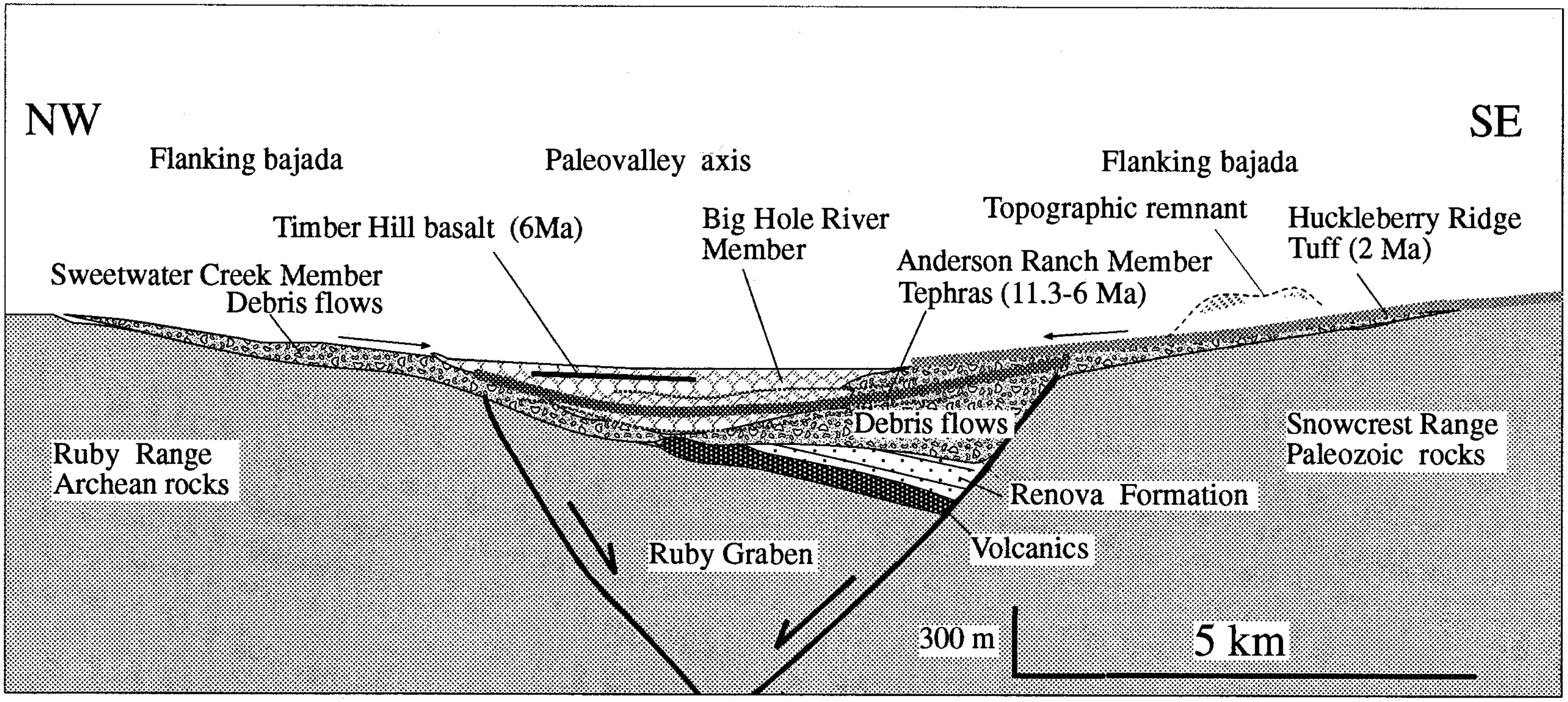


Figure 7. Geologic cross section sketch from the Ruby Range to the Snowcrest Range showing the stratigraphic and structural relationships in the Ruby graben.

Near the axis of the Ruby graben, the debris flows grade into gravels and fluvial tephra deposits of the Anderson Ranch member. The tephra deposits range in age from 11.6 to 6.0 Ma (fission-track ages), and were probably derived from the Picablo and Heise volcanic fields along the Yellowstone hotspot track (Shane and Sears, 1995). The gravels consist of distinctive pebbles and cobbles of Belt Supergroup derived from the Pioneer Mountains, and Swauger quartzite derived from central Idaho. These provenance data prompted Fritz and sears (1993) to conclude that flow in the paleovalley at this time was to the southeast. In addition, they argued that thick deposits of similar quartzite pebbles in Jackson Hole, Wyoming (Love et al., 1972) represents the southern end of a once continuous drainage that was disconnected during the formation of the Heise volcanic field (~6.5 Ma; Fritz and Sears, 1993).

Alternatively, Sears et al. (1995) suggested that the southeast drainage into Jackson Hole may have been disconnected during mid-Miocene time. Sears (1995) argued that the initial outbreak of the Yellowstone hotspot caused the development of a northeast-trending rift system in southwestern Montana that diverted drainages into the northeast-trending grabens. As a result, flow in the paleovalley of the Ruby graben would have been from southwest to northeast during deposition of the Sixmile Creek Formation (see companion paper in this volume by J. Sears).

The upper member of the Sixmile Creek Formation consists of well-rounded gravels and interbedded basalt (i.e., Timber Hill basalt) designated the Big Hole River member. The gravels are concentrated along the axis of the Ruby graben, and grade laterally into debris flow deposits along the flanks of the graben (Sears et al., 1995). As previously mentioned, Fritz and Sears (1993) argued that the gravels were transported to the southeast, and the drainage reversed direction to the northeast during growth of the Heise volcanic field (~6.5 Ma; prior to the eruption of the Timber Hill basalt). However, Sears (1995) now interprets paleoflow to the northeast during deposition of the Sixmile Creek Formation.

The Timber Hill basalt (~6.0 Ma; Kreps et al., 1992), apparently flowed northeastward down the paleovalley as a narrow river of lava. Geochemical studies suggest that the basalt emanated from the Heise volcanic field in the Snake River Plain, approximately 100 km from the northern terminus of the flow (Fritz and Sears, 1993). Because this flow has been cut by numerous norhtwest-trending extensional faults, it serves as a critical datum for the timing of hotspot-related faulting in the region.

LATE CENOZOIC EXTENSION IN THE TIMBER HILL AREA

Sometime after the Timber Hill basalt flow (~6.0 Ma), the Ruby graben was destroyed by northwest-trending extensional faults related to crustal adjustments associated with the formation of the Heise volcanic field (Fritz and Sears, 1993; and Sears et al., 1995). These faults cut the northeast-trending extensional faults that formed the Ruby graben, and offset the Timber Hill basalt with approximately 200 m of vertical throw (see Fig. 6). The resulting half-graben (i.e., Sweetwater graben) captured part of the regional drainage (e.g., Sweetwater Creek), and the Ruby graben deposits were tilted into the southern Ruby Range. Subsequent Quaternary erosion has left the Timber Hill basalt as a classic example of inverted topography.

Much of the tectonic displacement on the northwest-trending faults in the region may have occurred after deposition of the 2.0 Ma Huckleberry Ridge tuff. Distal remnants of the tuff with significant "relief" between outcrops occur as far north as the Ruby Range (Garson et al., 1992). In any case, the northwest-trending faults are apparently the most active faults in the region, because they coincide with documented seismic activity (Stickney and Bartholomew, 1987; Bartholomew, 1989; Doser and Smith, 1989; and Ostenaa and Wood, 1990).

FIELD TRIP ROAD LOG

This field trip was designed to provide the participants with maximum exposure to the Cenozoic extensional history of southwestern Montana with the least amount of driving! The focus of our trip will be on the Timber Hill locality (see Figs. 1, 5, 6, and 7), with additional stops to discuss the origin of talc in Archean rocks, Cenozoic carbonates, and Paleogene insect and plant fossils.

The field trip starts from the south parking lot of the Western Montana College campus in Dillon, Montana. Turn north onto Atlantic Street, and follow the business loop (I-15) to the intersection at Beaverhead County High School. Turn east (right) at the intersection on Thompson Avenue, and proceed four blocks to Oliver Lane. Turn north (left) on Oliver Lane, and proceed to the first intersection. Turn to the east (right) at this intersection, and you are on the Sweetwater Road (County Road 206). The road starts as a paved road, but is an improved two-lane gravel road for most of the trip. Check on weather conditions before proceeding, because the Sweetwater Road is notoriously difficult to drive on when wet. In addition, the road is usually impassible during winter months due to snow.

THE SWEETWATER ROAD

The Sweetwater road trends eastward across the East Bench. This bench is a pediment surface developed on deposits of the Sixmile Creek Formation. A recent roadcut just past the East Bench Canal exposes typical tephra and gravel deposits of the Sixmile Creek Formation. The composition of the gravels, and the imbrication of the pebbles suggests that some of the gravels were transported to the northeast from source areas in central Idaho (Sears et al., 1995). To the southeast (i.e., towards the Ruby Range), the gravels grade into angular gravels derived from the Ruby Range. These data suggest that there was a Miocene drainage divide in the Ruby Range that separated the Beaverhead and Ruby grabens (Sears et al., 1995). The basin margin fault of the Beaverhead graben probably occurs under Sixmile Creek deposits near the turnoff for the Christensen Ranch (see Fig. 1; Sears et al., 1995).

Approximately ten miles east of Dillon, the Sweetwater Road crosses into Archean metamorphic rocks. Talc deposts in these rocks form one of the largest and most important talc districts in the world. The first stop is at the fenced-off talc prospect on the right side of the road.

STOP 1. OVERVIEW OF TALC DEPOSITS IN THE ARCHEAN OF THE RUBY RANGE

Talc is mined from three deposits in Montana, two of which are in the Ruby Range (the Treasure and Beaverhead mines). In addition to these two active mines, there are numerous talc prospects and inactive mines in the Ruby Range. Talc is also mined from one deposit in the Gravelly Range and the associated mineral chlorite is mined from a deposit on the southeast flank of the Highland Mountains. Montana talc is used in paper, paint, plastics, ceramics, rubber and cosmetics.

Talc deposits occur in dolomitic marble in the sequence of Archean metamorphic rocks exposed in southwestern Montana. The inferred time of talc formation is during the Proterozoic when hydrothermal fluids introduced SiO_2 and Mg^{2+} to replace dolomite by talc (Anderson et al., 1990). Although most talc formed by the replacement of dolomite, talc also replaced tremolite, magnesite, serpentine and phlogopite. Rarely, textures suggest direct precipitation of talc from hydrothermal solutions in open space. Chlorite associated with talc deposits has formed where Al-bearing rocks were subjected to Mg-bearing hydrothermal fluids. Brady and others (1991) suggested that deep circulation of water (possibly sea water) during Belt rifting may have been resonsible for the formation of these talc deposits.

Continue to the southeast over Sweetwater Pass and into the Sweetwater Valley. This valley is a late Cenozoic, northwest-trending extensional basin that has preserved a wedge of Sixmile Creek gravels that were deposited into the Miocene Ruby graben. The Sweetwater fault is clearly visible as a prominent scarp on the southwest side of the road. Approximately 10 miles southeast of Sweetwater Pass, the road descends to several ranch buildings along Sweetwater Creek. Stop at an overview point at the top of the hill.

STOP 2. OVERVIEW OF THE TIMBER HILL AREA

This vantage point provides a spectacular view into the heart of the northeast-trending paleovalley that occupied the Miocene Ruby graben (see Figs. 5, 6, and 7). The vantage point is on the northwest margin of the graben, where basin-margin deposits of the Sixmile Creek Formation drape the basement rocks. These deposits include hydrothermal carbonates (located down slope of the vantage point) that may have emanated from springs along the basin margin fault of the Ruby graben (see companion paper in this volume by A. Ripley for a discussion of Tertiary carbonates in southwestern Montana).

Directly to the southeast are flat-topped mesas of Timber Hill basalt (elevation 6600 to 6400 feet). The basalt can be traced to the south, where it occurs at the top of a forested knob known as Timber Hill (elevation 7100 feet). The change in elevation marks approximately where the Sweetwater Fault offset the 6.0 Ma Timber Hill basalt. The fault is a nowthwest-trending normal fault with approximately 200 meters of vertical throw. The fault is down-to-the-northeast, and the basalt is tilted gently to the southwest (see Fig. 5). Similar faults cut the Timber Hill basalt flow along much of its course to the south (Hurlow, 1995). This datum illustrates that the northwest-trending topography north of the Snake River Plain must be younger than 6.0 Ma.

With the formation of the Sweetwater graben, a new stream drainage developed along the northwest-trending axis of the graben (i.e., Sweetwater Creek). The drainage cut across the paleovalley deposits of the Ruby graben, and superimposed itself on the Timber Hill basalt. Subsequent Quaternary erosion has left the Timber Hill basalt flow as inverted topography. The resulting steep slopes have apparently been susceptible to mass wasting (e.g., notice the large landslide on the northeast wall of the "Sweetwater notch").

Continue down slope to a turnout just beyond the ranch buildings and park the vehicles. Walk southwest to the cliff exposures of the Sixmile Creek Formation. Access is through private property belonging to Mr. John C. Anderson of the Ruby Dell Ranch in Alder, Montana. Please obtain written permission before entering the property. Very large bulls are known to lounge in the grassy access area along Sweetwater Creek, so please be vigilant!

STOP 3. NORTHWEST MARGIN OF THE MIOCENE RUBY GRABEN

Excellent exposures of all three members of the Sixmile Creek Formation occur in cliff exposures at this stop (see Fig. 5). At the base of the cliff, debris-flow deposits of the Sweetwater member contain angular clasts of Eocene volcanics and

Archean metamorphic rocks derived from uplifted blocks along the northwest margin of the Ruby graben. The hydrothermal carbonate deposit that drapes basement rocks at stop #2 is interbedded with the Sweetwater member at this locality.

The Anderson Ranch member consists of a number of fluvial tephra deposits, but unlike outcrops near the axis of the paleovalley, the interbedded units tend to be locally-derived debris flows. The top of the cliff is a capped by roundstone gravels of the Big Hole River member. As with most other localities, the gravels contain distinctive pebbles derived from sources up to 100 km to the southwest in central Idaho. Although the gravels occur below and above the Timber Hill basalt at a number of localities, the basalt overlies a number of different lithologies within the region. Sears et al. (1995) interpret this as evidence for activity on the Sweetwater fault prior to the eruption of the Timber Hill basalt, because older deposits were removed from uptilted areas.

Continue through the canyon cut by Sweetwater Creek to the road into the Spring Brook drainage. Take a right onto the dirt road, cross Sweetwater Creek, and go to the first fork in the road. Take the right fork (the road less traveled) and proceed through two gates into the Virginia Springs drainage. Drive up the drainage and park below the distinctive outcrops of white-colored tephra in the cliff to the east.

STOP 4. AXIS OF THE MIOCENE RUBY GRABEN

Deposits of the Sixmile Creek Formation at this locality are more characteristic of the axis of the Miocene paleovalley. The Sweetwater Creek member is not well exposed at this stop, but in the region it consists of relatively fine-grained debris flow deposits interbedded with stream gravels.

The Anderson Ranch member consists of spectacular beds of tephra that appear to be fluvially deposited. Fritz and Sears (1993) interpreted one of the tephras as an ash-flow tuff ("tuff of Spring Brook") with an associated ground-surge deposit. The tephra deposits are interlayered with siltstone, sandstone, and conglomerate at this locality, but no debris flow deposits were recognized. The tephra deposits thicken to the south, and are interpreted to have been derived from eruptions of calderas of the Picabo and Heise volcanic fields along the Snake River Plain (Shane and Sears, 1995). Fission-track dates on glass shards from tephras throughout the region show an age range of 11.6 to 6.0 Ma (Shane and Sears, 1995). The tephra probably blanketed the drainage basin, and subsequently washed into the axis of the paleovalley. The amount of tephra apparently swamped the system, because the deposits consist almost entirely of glass shards (Sears et al., 1995). Preliminary paleocurrent measurements on the tephras show that flow direction reversed during the initial inundation of tephra, and recovered through time as the tephra was reworked (Thomas, unpublished data).

A thick section of the Big Hole River member occurs at this locality. The pebbles and cobbles are relatively large, and consist of the same distinctive lithologies found at other localities that suggest a source in central Idaho.

Go back to the Sweetwater Road, and continue to the northeast. The road passes through Archean metamorphic rocks that are overlain by silicified volcanics, and tuffaceous mudstones of the Renova Formation. Stop at the first outcrops on the east side of the road as you enter the broader Ruby basin.

STOP 5. PALEOGENE SANDSTONE DEPOSITS

Outcrops of Paleogene sandstone within the Renova Formation at this locality may represent the distal part of a large fluvial system that predates significant extension in southwestern Montana (Thomas, 1995). Provenance and paleocurrent data show that the sands were probably derived from a two-mica granitic source in the Idaho Batholith, and distributed eastward by fluvial processes (Fig. 8; Thomas, 1995). This conclusion is supported by grain size analyses that show a decrease in grain size to the east (Fig. 9), and point-count data that show an eastward increase in the relative percentage of quartz (Fig. 10). In addition, individual deposits of granitic sandstone thin to the east (Thomas, 1995).

Since these regionally correlative deposits are presently isolated by basin and range topography, the topography must post-date deposition of the sand. Limited age control brackets deposition between 27 and 40 Ma, suggesting that minimal topography existed in the region during deposition of most of the Paleogene Renova Formation. This model is compatible with the initiation of extensional tectonism during middle-Miocene time as proposed by Fritz and Sears (1993), and Sears (1995). In addition, this model supports Janecke's (1994, 1995) placement of an Eocene to Oligocene rift system in western Montana, because uplifted blocks within the rift were probably the source of the Paleogene granitic sands.

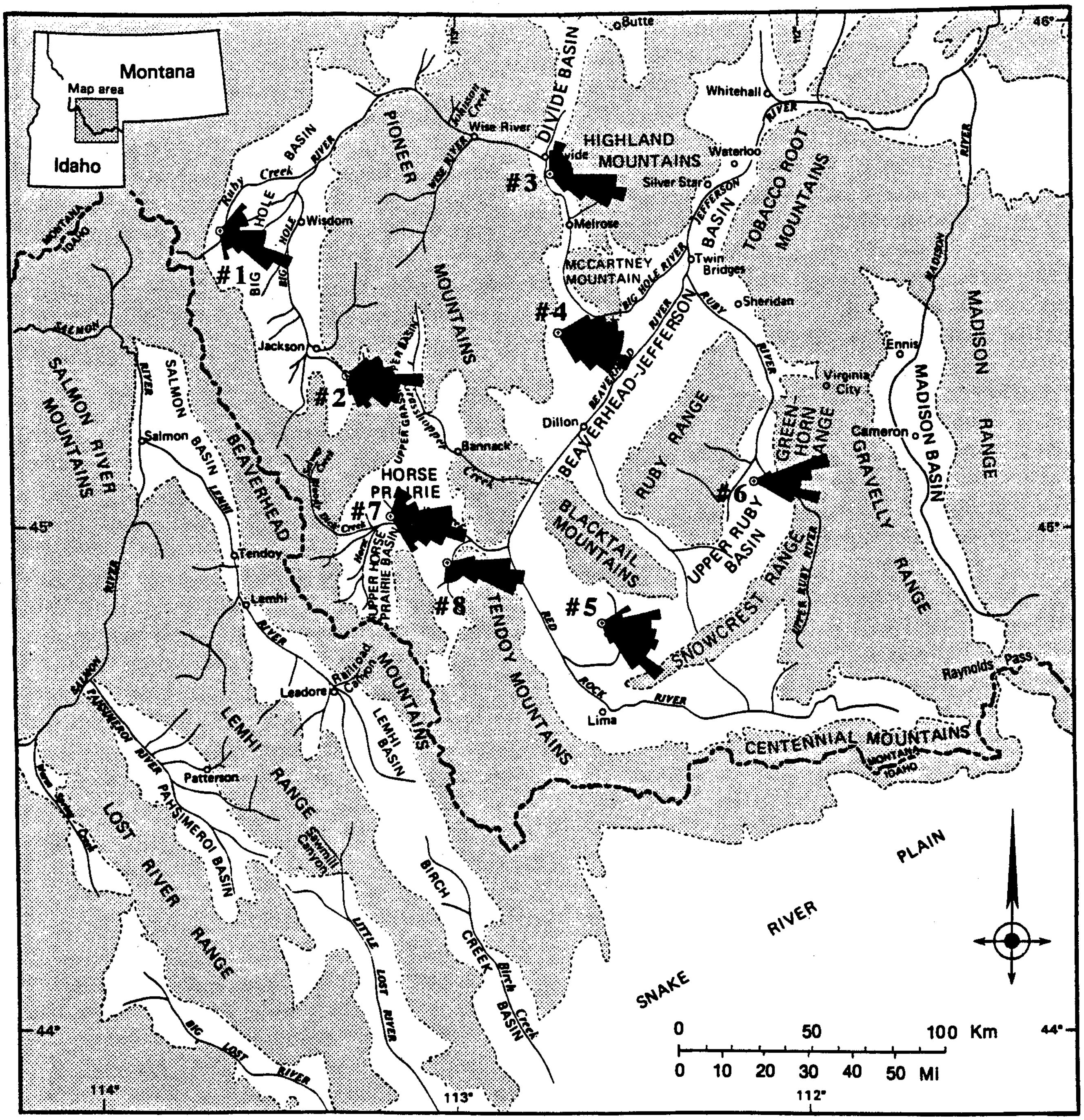
Continue to the northeast on the Sweetwater Road towards Ruby Reservoir. The road changes to the Ruby Road just past the bridge across the Ruby River. The upper Ruby Valley in this region consists of well-exposed deposits of both the Renova and Sixmile Creek Formations (Monroe, 1976). A very subtle angular unconformity is visible between these units on the northwest side of the valley. Take a left on a dirt road approximately 0.5 miles south of the reservoir. Cross over the Ruby River, and continue towards the ranch house to the northwest. The road to the quarry is a vague dirt road just before the ranch house. Take a left on this road and follow it to the visible pits in the Renova Formation. The pits occur south of Peterson Creek in Fossil Basin. This locality is on private land, so please ask permission at the ranch house before entering the property.

STOP 6. BECKER QUARRY

The Becker quarry is well known (at least in Paleontological circles!) for its world-class insect and plant fossils. The fossils occur as impressions and carbon films on very fine-grained, lacustrine shales ("paper shales") within the Renova Formation. Becker (1961) assigned a late Oligocene age to the deposit, and placed it in the Passamari Member of the Renova Formation. The "Paper Shale Flora" contains well preserved leaves, flowers, stems, and seeds of over 100 plant species. Species of fir, spruce, pine, dawn redwood, maple, birch, hackberry, beech, ash, Oregon grape, poplar, rose, elm, ginkgo, and keaki tree dominate the flora. Becker (1961) recognized several paleoecological floral communities, including lake, marsh, riparian, woodland, slope, and desert scrub. He concluded that the climate was warmer, and the elevation was lower than that of the Ruby Valley today.

The locality is also known for a quality insect assemblage. Species of bees, bumblebees, mosquitoes, earwigs, grasshoppers, crickets, beetles, caddis-fly larval cases, crane flies, robber flies, dragon flies, alder flies, wasps, and ants comprise the fauna. In addition, fish and bird remains have been found in the "Paper Shale Flora" (Becker, 1961).

Return to the Ruby Road and continue north to Alder, Montana. Take a left onto State Highway 287, and continue to Twin Bridges, Montana.



#1 - **Big Hole Basin**
#2 - **Upper Big Hole Basin**
#3 - **Divide Basin**
#4 - **Beaverhead Basin**
#5 - **Sage Creek Basin**
#6 - **Upper Ruby Basin**
#7 - **Upper Horse Prairie Basin**
#8 - **Medicine Lodge Basin**

Figure 8. Map showing paleocurrent rose diagrams for the Paleogene sandstone deposits (Thomas, 1995).

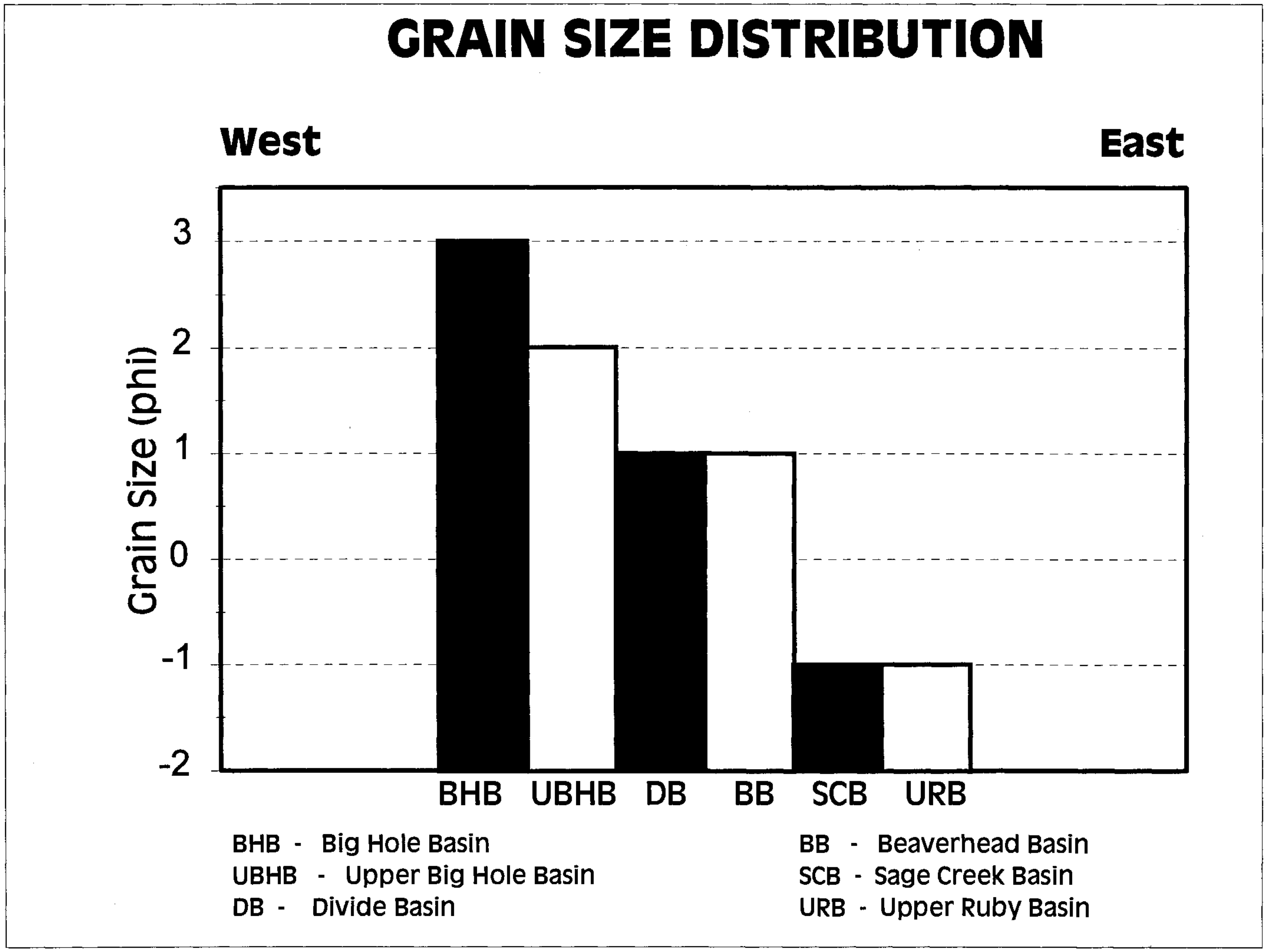


Figure 9. Grain size distribution data for the granitic sandstone deposits. See Figure 8 for a map showing the locations of the data points (Thomas, 1995).

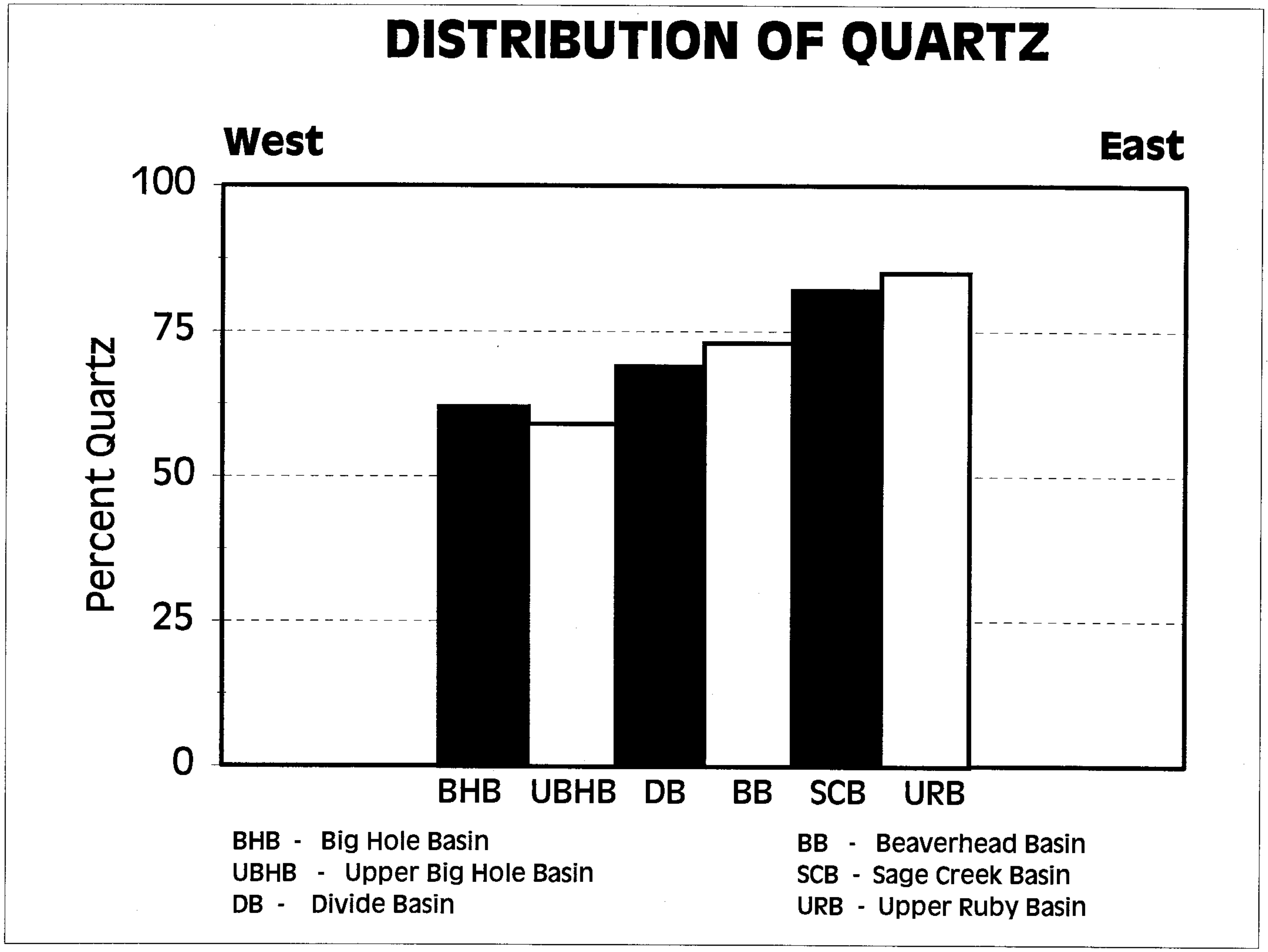


Figure 10. Relative percentage of quartz for the granitic sandstone deposits. See Figure 8 for a map showing the locations of the data points (Thomas, 1995).

Turn left onto State Highway 41, and continue back to Western Montana College to complete the loop trip.

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COMPRESSIONAL TECTONICS OF THE SOAP GULCH AREA, SW MONTANA: FIELD TRIP GUIDE

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INTRODUCTION

In the Soap Gulch-Camp Creek area, four Precambrian faults influenced the compressional structures developed during the Laramide Orogeny. The four faults (NE McCartney Mountain Fault, SW Rochester Fault, unnamed fault, and Camp Creek Fault) are shown in Figure 1. The Paleozoic sequence between McCartney Mountain and Soap Gulch strikes northwest and dips southwest. The earliest compressional failures occurred along the northwest-trending Precambrian faults. The hanging walls on their northeast sides rose. As compression intensified, southwest-dipping thrusts repeated the Meagher and the Pilgrim. As compression continued, thrusts telescoped younger over older beds. At the northwest end of the block, the Paleozoic sequence collided obliquely with a block of Precambrian schist rising north and east of the Camp Creek Fault. The Soap Gulch Thrust formed along this collision zone, probably occupying both the Camp Creek Fault and the unnamed fault. The Paleozoic sequence slid northeastward under the schist along this fault, crumpling the fault surface itself as the schist rode southwestward.

ACCESS

The field trip area is indicated on the map (Figure 2). Access to the area is by somewhat improved dirt roads eastward from Melrose up Camp Creek and eastward up Soap Gulch from the interstate frontage road a few miles north of Melrose. Other unimproved trails lead from these main roads to give some access to the area in other than hunting season when they are closed. Much of the area is accessible only on foot.

Northwest Geology, v. 25, p. 27-32, 1995

DISCUSSION

The area looks deceptively simple from the air. The beds strike nothwest and mostly dip about 25 degrees to the southwest. However, the faults form a complex sequence. With some overlap, the Precambrian faults failed first during the Laramide compression, followed by faults that repeated the beds, followed by faults that telescoped the sequence, thrusting younger beds over older rocks. Where the faults cut up or down across the beds they are much easier to locate than where they parallel the beds. Some individual faults change from reverse faults that repeat beds to bedding plane faults to younger-over-older faults as they are traced along strike or up dip. In addition, some of the faults clearly show irregular surfaces on which the rocks brecciated as they slid (Figure 3). Some faults are folded, and although I have been conditioned to think of folding and faulting as distinct episodes, I believe the Soap Gulch Thrust shows evidence that folding and thrusting occurred together, or at least in an interwoven sequence(Figure 4). In all probability the Soap Gulch Thrust is a blind thrust developed at the collision zone between crustal blocks bounded by Precambrian faults that were reactivated by the Laramide compression. The crustal blocks consist of a Paleozoic sequence sliding northeastward under a rising block of Precambrian schist that overrode it to the southwest. Because of this collision, the Paleozoic sequence shows back-sequence thrusting, wherein younger higher thrusts cover older lower thrusts, and many of the thrusts telescope younger over older beds.

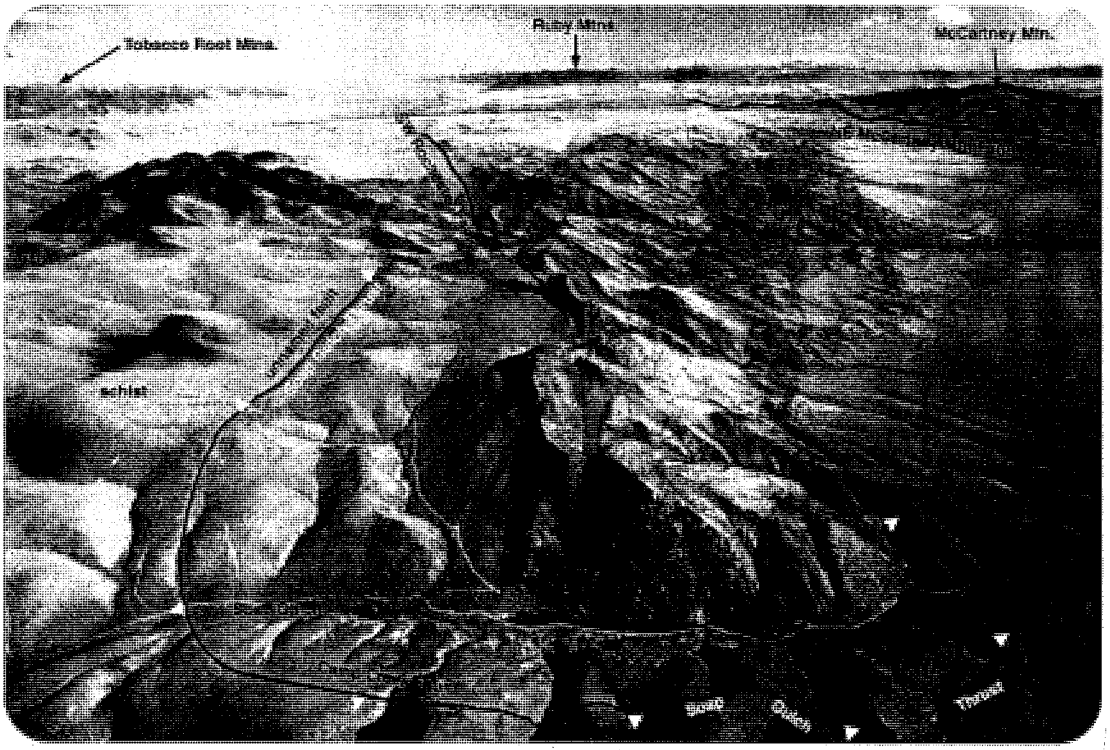

Figure 1. View looking southeast at the Precambrian faults that influenced the compressional structures formed during the Laramide Orogeny in the Camp Creek-Soap Gulch area.

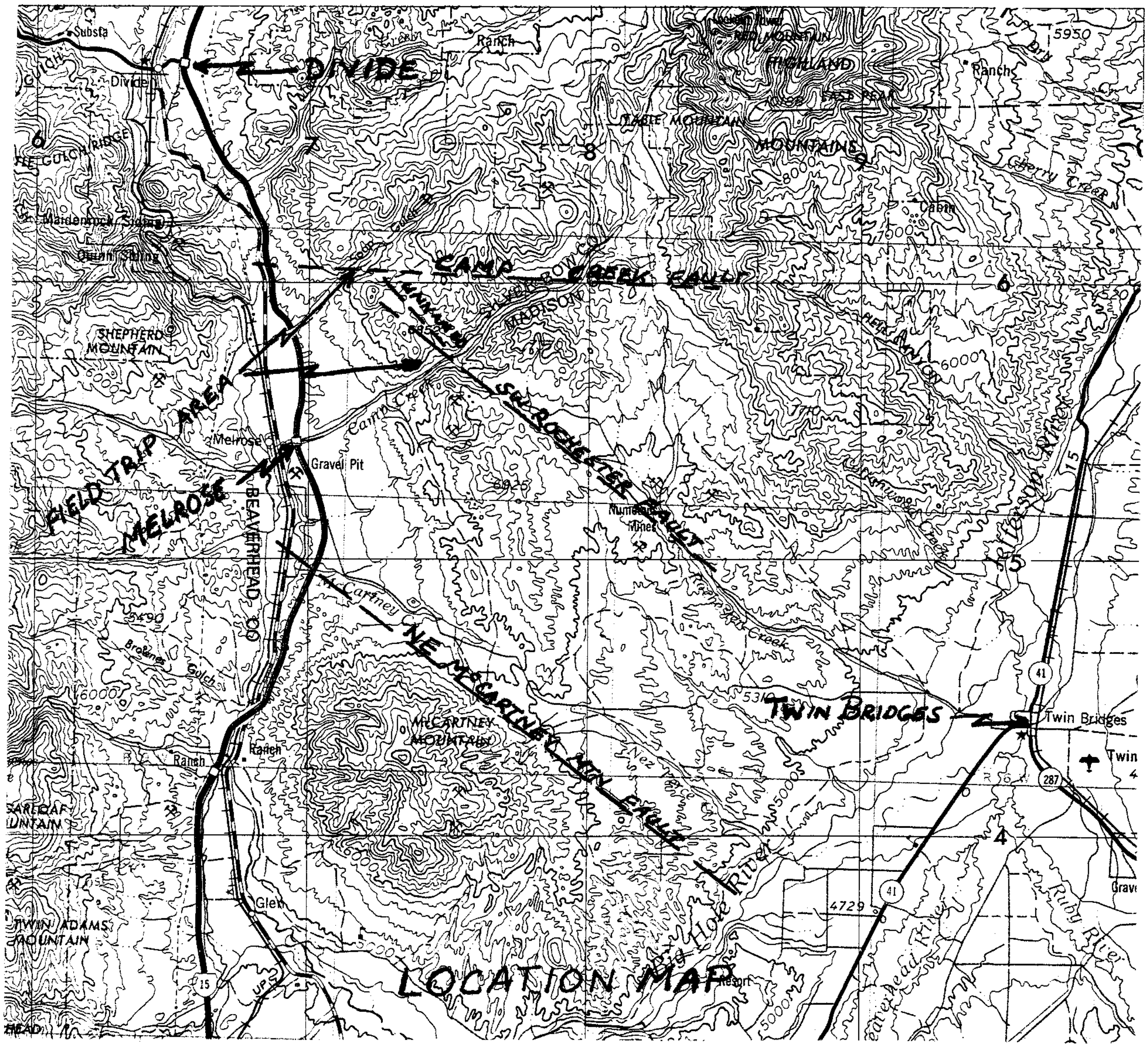

Figure 2. Index map showing the location of the field trip areas.

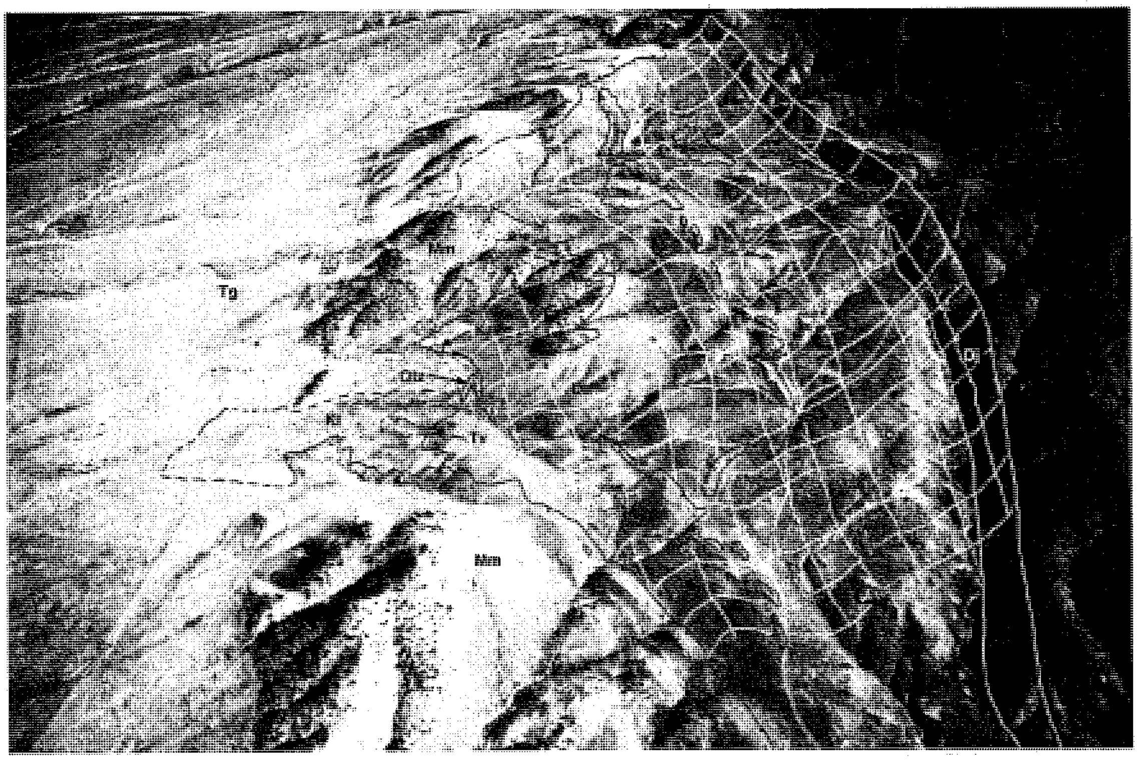

Figure 3. View looking northward at an area between Camp Creek and Soap Gulch where the Madison limestone was thrust across the Three Forks Shale. Unless otherwise indicated, the enclosed outcrops are erosional remnants (klippen) of Madison Limestone. The white grid is an attempt to show the irregular fault surface by projecting the fault's dip and by connecting the klippen.

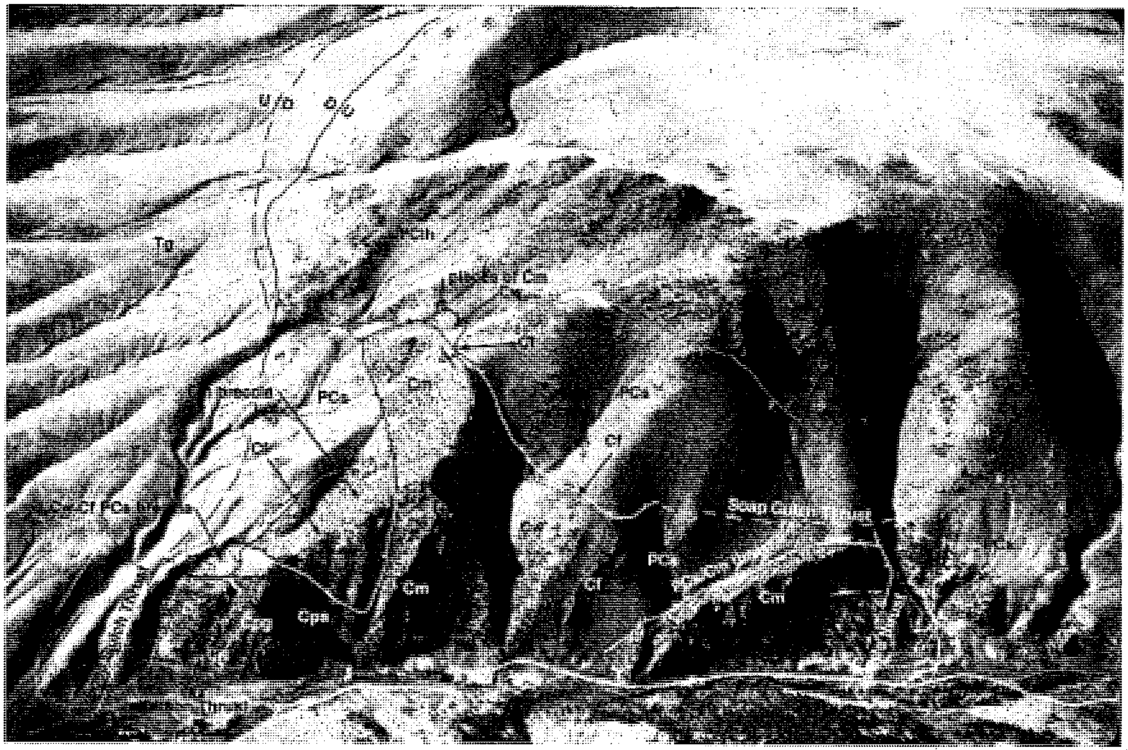

Figure 4. View looking northward across Soap Gulch at the Soap Gulch Thrust. PCs = Precambrian schist, PClh = Precambrian Lahood, Cf = Cambrian Flathead Sandstone, Cw = Cambrian Wolsey Shale, Cm = Cambrian Meagher Dolomite, Cpa = Cambrian Park Shale, Cpg = Cambrian Pilgrim Dolomite, Crl = Cambrian Red Lion Formation, Dj = Devonian Jefferson Dolomite, Tg = Tertiary gravel. As the Precambrian schist rode southwest over the Flathead, Wolsey, and Meagher, it overturned them. The thrust carried the torn-off Meagher southwestward as the fault surface buckled into a tight syncline, smashing the Meagher into a breccia. The tight fold immobilized that part of the fault and the Flathead, Wolsey, and schist slid over the Meagher breccia, forming a breccia of their own. The schist continued to override the Flathead-Wolsey-Schist breccia on the folded fault surface.

For more detailed information about these faults, please see the separate field guide, "A Pictorial Guide to the Faults of the Camp Creek-Soap Gulch Area, Southwestern Montana".

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I owe much to discussions I have had with M.J. (Jerry) Bartholomew, Christopher J. (Chris) Schmidt, J.M. (Mike) O'Neill, and Willard E. (Will) Cox about this area. I am especially indebted to Chris for the concept of northwest-trending Precambrian faults reactivated during the Laramide Orogeny. This concept has been a key to understanding these thrusts. I owe my concept of the folded Soap Gulch Thrust to Jerry. During a feild visit when I was thinking in terms of intersecting thrusts, he suggested that it could be a folded thrust. Mike and Chris do not agree with this interpretation of a single folded thrust, preferring the concept of intersecting thrusts. Will early recognized that the Madison was thrust over the Three Forks, and Mike has mapped the area for the USGS. Alvin M. Hanson measured the Cambrian section at Camp Creek.

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THE GEOLOGIC SETTING OF PREHISTORIC LITHIC PROCUREMENT SITES IN THE GRAVELLY RANGE OF SOUTHWEST MONTANA: FIELD TRIP GUIDE

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INTRODUCTION

The southern part of the Gravelly Range contains several primary lithic sources exploited by prehistoric Indians for chipped-stone tools. Along the crest of the Gravelly Range there are major campsites containing abundant debris and formal tools composed of chert, silicified quartzite, and obsidian. Primary and secondary deposits of Jurassic Morrison Formation cherts appear to be the most important lithic source. A northeast-trending high angle-angle fault controlled the intrusion of Miocene basaltic plugs which hydrothermally altered these chert-bearing formations. Potential economic development of gypsum deposits associated with the hydrothermal alteration has led the Beaverhead National Forest to conduct an archeological survey and excavation to determine the prehistoric significance of these archeological sites in the southern Gravelly Range.

SETTING

The Gravelly Range is elevated grassland between 6,000 and 10,000 ft. Black Butte is the dominant topographic feature of the range with the Snowcrest Range to the west and the Madison Range to the east. The Gravellys are physiographically different from either the Snowcrest or the Madison Range. The Gravellys are lobe-shaped with elevated grasslands and the Madison and Snowcrest are triangular and rugged.

Standard Creek is one of the major prehistoric access routes into the Gravelly Range. The headwaters of Standard Creek is at Black Butte, the geographic center of the range. Prehistoric access to the Gravellys was from the Madison, Centennial, and Ruby Valleys. Prehistoric peoples traveled into the vicinity of Black Butte to replenish took-kits, hunt for meat, and collect vegetal foods. The unique geology of the Monument Ridge area allowed direct procurement (Leudke, 1976) of lithic material for chipped-stone tools (Munger and O'Neill, 1995).

GEOLOGY

The Gravelly Range is a large fault-block with margins on the western side of the Snowcrest and along the west side of the Madison Valley (Figure 1). The range is rising at 2mm per year and crumbling on the southeast side into the tributaries of the Madison River (O'Neill 1995). As an example of the major slumping on the southeastern margin of the range (while the center quickly rises), note that the Huckleberry Ridge Tuff is located at 9,600 ft., 8,000 ft., and at 6,500 ft. in the section (Figure 2).

The entire section above the meta-sedimentary rocks is dipping to the west at 25 degrees. The pertinent formations are the Jurassic Morrison, the Triassic Woodside and Dinwoody, and the Permian Shedhorn. These formations were hydrothermally altered by intrusive Miocene basaltic plugs. A northeast trending high angle fault controlled intrusion of the Miocene basalt plugs and localized the alteration of Morrison Formation chert and silicified sandstone (Figure 3).

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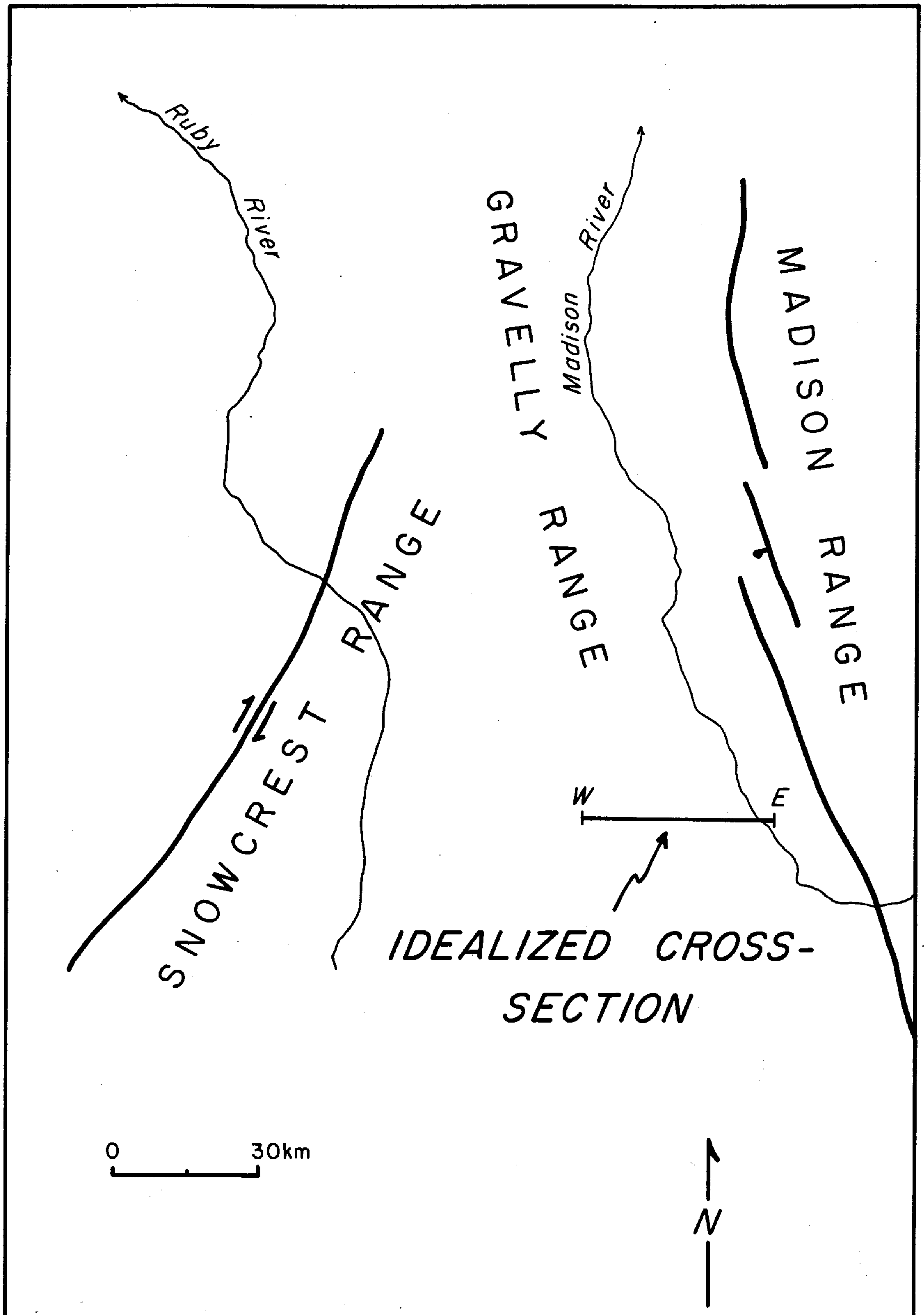
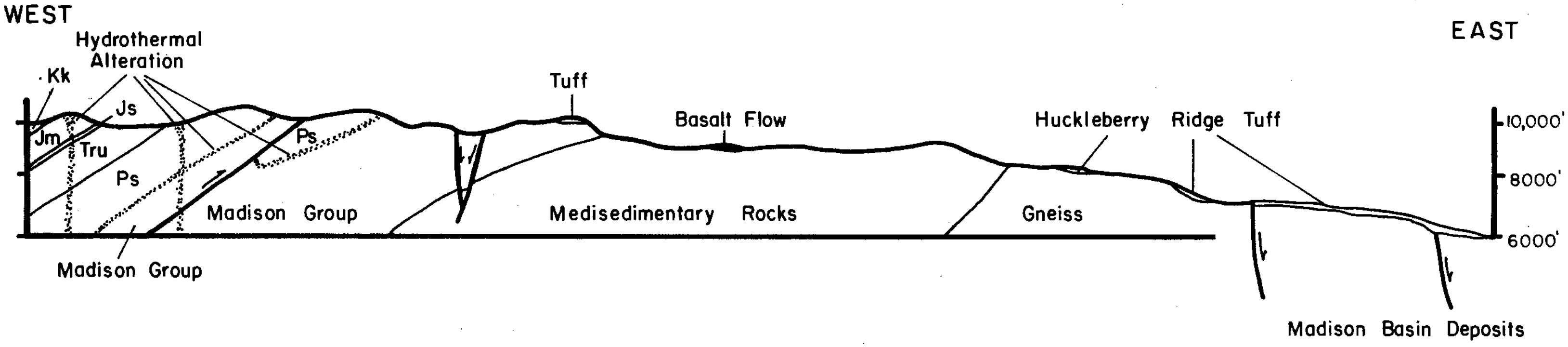


Figure 1. Field trip locality map.



Qls	Quaternary Landslide
Tg	Tertiary Gravels
Kk	Cretaceous Kootenai
Jm	Jurassic Morrison
Js	Jurassic Swift
Tru	Triassic Undifferentiated (Trw: Woodside, Trd: Dinwoody)
Ps	Permian Shedhorn
IPmg	Pennsylvanian Quadrant

(Note: Explanation of rock symbols are for figures 2 & 3)

Figure 2. Cross-section between Horse Creek and Standard Creek.

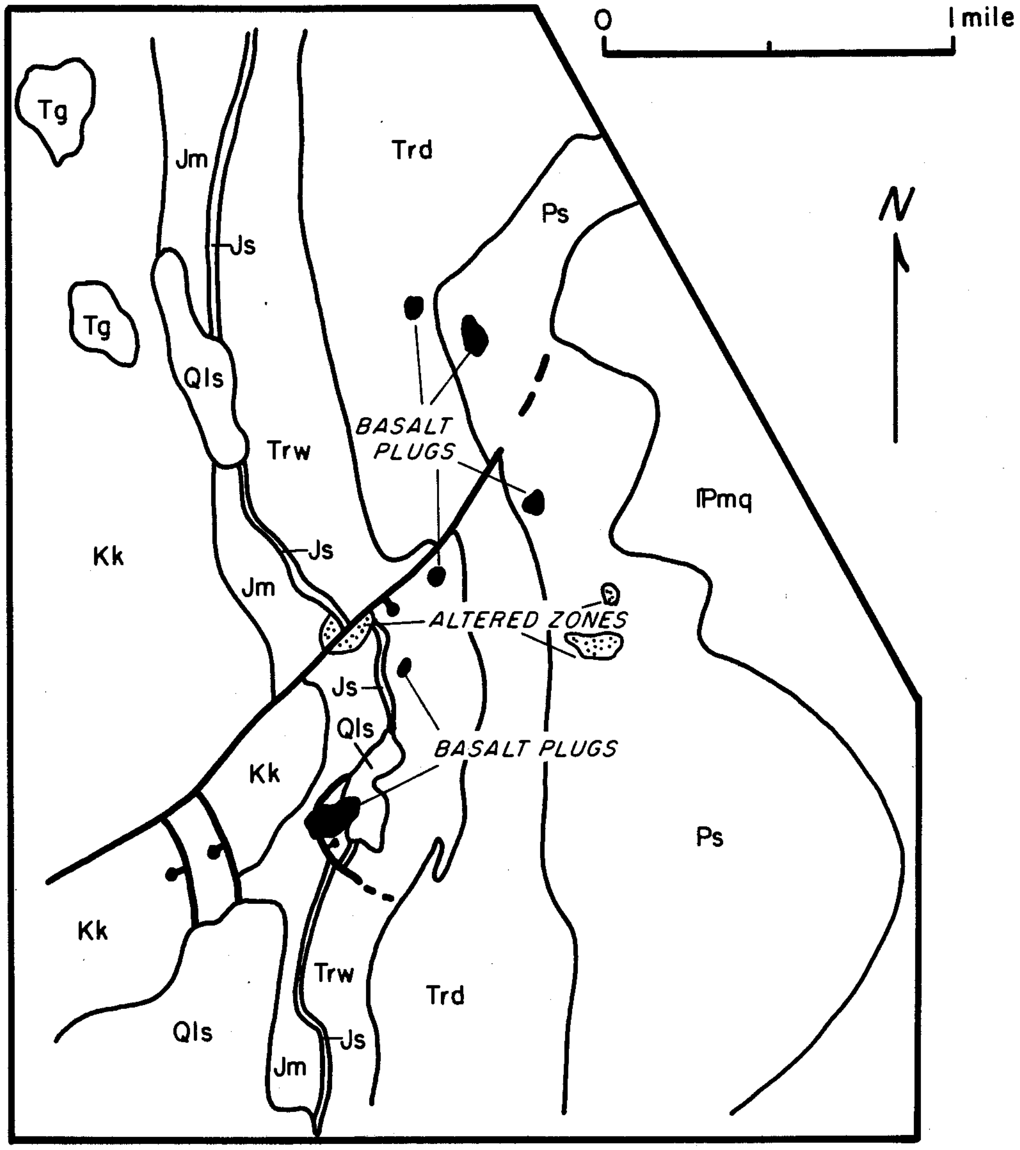


Figure 3. Generalized ~~geologic map~~ of Monument Ridge
(see Fig. 2 for key to map symbols).

High quality Morrison cherts were directly procured by prehistoric peoples from the contact of the Morrison and Swift Formations (Munger and O'Neill, 1995). At Monument Ridge, the contact of the Swift and Morrison formations shows a distinct gully that allowed prehistoric peoples to directly procure chert in a primary context (Francis, 1986). Altered zones in the Shedhorn were also used as sources of chipped-stone material. The Kootenai, Morrison, and Swift Formations form cliffs, ledges, and steep slopes. The Woodside and Dinwoody Formations erode to flat surfaces. The majority of prehistoric campsites are located in the Dinwoody and Woodside Formations.

The intrusion of Miocene basalt plugs produced, not only hydrothermally altered cherts, but also baked claystone favored by the prehistoric peoples at Monument Ridge. Exposures of tuffaceous sediments and baked claystone are visible from Monument Ridge. Huckleberry Ridge Tuff obsidian is located within 2 kilometers of Monument Ridge. This obsidian, though of marginal quality, was also used for chipped-stone tools.

ARCHEOLOGICAL INVESTIGATIONS

Archeological investigations have been conducted for three years by the Beaverhead Naitonal Forest at Monument Ridge. Excavations have yielded evidence of prehistoric camps focused on the procurement of chipped-stone material. Excavations have primarily focused on the Woodside Formation. Geologic mapping has shown that clusters of rocks in the excavation units were probably made by humans. The rocks in the excavation were from the Dinwoody Formation located at least 10 meters down section. Excavation and survey at Monument Ridge was sponsored by the Forest Service's Passport in Time program and all labor was donated. Passport in Time is a National Volunteer Program focused on heritage resources. The Gravelly Range in the vicinity of Monument Ridge is ideally suited for a broad-spectrum adaptation to the mountains by prehistoric peoples (Bender and Wright 1988, Munger 1993). Prehistoric use of the Gravellys can be understood with a "collector model" (Binford 1980) of hunter-gatherer organization, probably beginning in the Middle Plains Archaic 3000 BC (Frison 1978). With a base camp in the Madison Valley of extended family members (see Aaberg 1993) smaller groups would enter the mountain high-country in mid to late summer to collect vegetal foods, hunt, and to directly procure sources for chipped-stone tools (Figure 4).

SUMMARY

Geologic context is key to understanding the archeology of the mountains. Geologic mapping refines archeological site-location prediction models, and accurate, technical descriptions of source materials allow archeologists in the Northern Rocky Mountains to speak a common language (Miller, 1991). Mountains are "supermarkets" to prehistoric peoples for materialistic and spiritual needs. The unique geologic setting of the Gravelly Range provides an important framework for understanding prehistoric use of the mountains.

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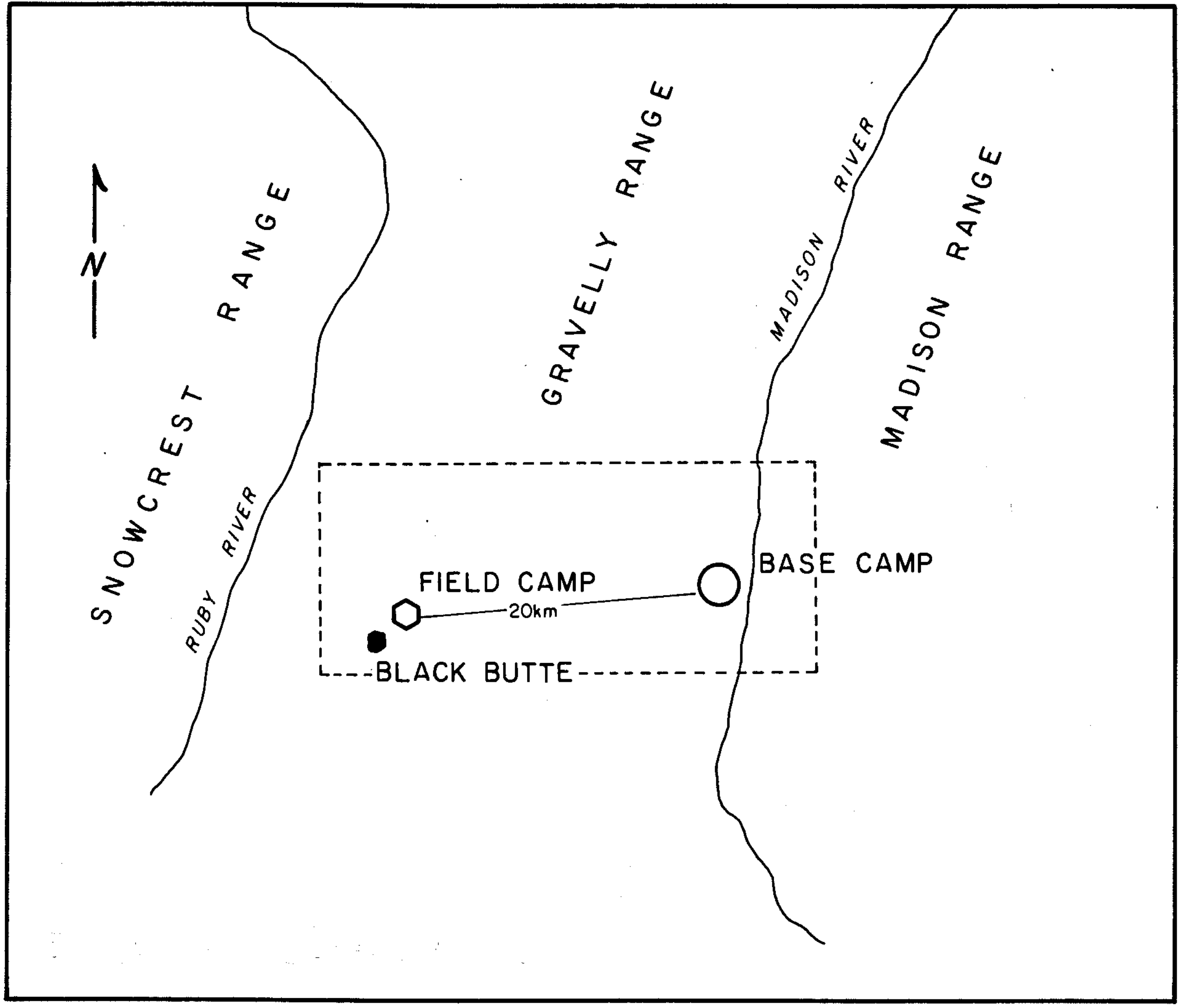

Figure 4. Archeological investigation strategy.

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RIPARIAN MANAGEMENT ON THE BEAVERHEAD NATIONAL FOREST, SOUTHWESTERN MONTANA

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INTRODUCTION

Riparian environments hold the key to life in the otherwise arid West. Yet, historic human uses have had significant detrimental effects on many streams. Not surprisingly, rehabilitating riparian areas has become a leading issue faced by the Forest Service, Bureau of Land Management, and concerned individuals and interest groups.

Livestock grazing is one of the many historic uses that has affected riparian areas. As a result, professionals in range, fisheries, soil science, and hydrology from the Beaverhead National Forest and the BLM's Butte District developed "riparian guidelines" to better manage riparian areas and livestock. The guidelines have become a new, useful tool for solving problems on grazing allotments.

THE PROBLEM

So, why all the concern about streams and stream banks? As stated, water holds the key to life in the west. Riparian areas, when they function correctly, store water and release it slowly throughout the year.

Our guidelines (already field tested in the Upper Ruby allotment) help us measure three basic things about a stream:

- •Can the stream reach its flood plain?
- •Can the stream store water in its banks?
- •Does the correct riparian vegetation grow along the banks?

Functioning streams can rise out of their channels during floods, dissipating the flood energy over a wide area. When riparian systems don't work correctly, flood waters remain in the channel causing serious erosion. This leads to more sediment in the stream, affecting fish spawning gravels, general stream channel stability, and water quality downstream.

A functioning riparian area in some "stream types" has a narrow, deep stream channel and overhanging vegetation. In the channel, cool water (shaded by vegetation and by deep water), nurtures trout and the water table remains high. If the banks are broken down by any activity, such as trampling by cattle hooves, the channel widens and becomes shallower. The shallower water gets warmer, gravels get covered by silt, insect life declines, and a lot of riparian values are affected.

More importantly, the stream banks lose their natural "sponge" quality. As stream banks get sheared and laid back by excessive trampling, the water table drops. Why? A deep and narrow stream has lots of surface area where soil in the stream banks contacts water. When banks get sheared off, they drop back at a much lower angle and so there's very little soil and water contact. Without this contact, riparian soil pores don't get refilled with water.

The water table drops to the depth where the stream can still contact the soil. This, in turn, reduces water storage and late-season stream flow. It also means dry-land species like sagebrush move in and replace water loving species like willow, because the willow's roots can no longer reach ground water.

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SOLUTIONS

The original damage to the stream may have occurred as long ago as the turn of the 20th century. But often, grazing practices since then have kept streams from recovering. Only by giving stream banks a long-term opportunity to heal over decades will we restore them.

Keeping livestock out of stream bottoms takes a lot of work. Riders moving cattle away from riparian areas, to "upland" sites where they'll stay, has given the best results. Additional water at upland sites, fencing, and salting can help keep cattle from moving back down into the stream bottoms. Each situation in each allotment, on different reaches of each stream, will prove different. However, the overall need remains the same: to restore functioning riparian areas while continuing livestock grazing.

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MIDDLE MIOCENE RIFT SYSTEM IN SW MONTANA: IMPLICATIONS FOR THE INITIAL OUTBREAK OF THE YELLOWSTONE HOTSPOT

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DISCUSSION

A northeast-trending rift system cross-cut southwestern Montana about 17 Ma ago, during the initial outbreak of the Yellowstone hotspot (Sears et al, 1995). The rift system is radial to the outbreak point of the hotspot, which has been located by Pierce and Morgan (1992) in southeastern Oregon. It is part of a set of middle Miocene extensional features that radiates from the outbreak point across a >1500-km diameter region of western North America (Figure 1). Other Miocene tectonic features that are radial to the outbreak point include the central Nevada rift or Oregon-Nevada lineament (Stewart et al., 1975; Pierce and Morgan, 1992), Brothers fault zone (Hooper and Conrey, 1989), Portland Hills-Clackamas River tectonic zone (Beeson et al., 1989), Monument and Joseph dike swarms (Tolan et al, 1989), and possibly the collapsed Granite Mountains of Wyoming (Love, 1970) and Brown's Park graben of Utah (Hansen, 1969).

The southwest Montana rift system consists of several en echelon half-grabens that contain tilted remnants of pre-hotspot volcanic and sedimentary rocks of the Renova Formation, overlain with angular unconformity by units of the Sixmile Creek Formation that were deposited in the grabens during and after initial outbreak of the hotspot. The grabens link northward into the Lewis and Clark line. Throughout the rift system, and along the Lewis and Clark line, faults are onlapped by Sixmile Creek Formation with an average basal age of 16.5-17 Ma (cf. Fields et al., 1985). The Lewis and Clark line is an older structure that was reactivated during the middle Miocene (Harrison et al., 1974; Rasmussen, 1973). It is concentric to the hotspot outbreak point, and trends into eastern Washington, where it is onlapped by Columbia River flood basalts as old as the 15.6-16.5 Ma Grand Ronde Basalt (Tolan et al., 1989).

The southwest Montana rift system likely resulted from lithospheric stretching on a broad dome that was centered on the outbreak point of the Yellowstone hotspot. The grabens split in a radial fashion on the flank of the dome. Rivers were diverted into the grabens and flowed off the dome, transporting clasts from southwest to northeast down the axes of the grabens (Sears et al., 1995).

Detailed biostratigraphic studies in 18 graben segments in southwest Montana narrow the hiatus represented by the unconformity to between 20 and 17 Ma ago (Fields et al., 1985). This may indicate that doming and radial extension preceded the outbreak of the hotspot by as much as 3 Ma. However, the youngest parts of the Renova Formation may have been eroded or buried, so the time gap could be much shorter.

The middle Miocene rift system is cross-cut by northwest-trending, late Cenozoic faults in a seismically active, 150-km wide band on the northern border of the Yellowstone hotspot track, associated with lithospheric adjustments to the hotspot track (Pierce and Morgan, 1992, Ruppel,1993; Anders et al., 1989, Anders and Sleep, 1992; Fritz and Sears, 1993).

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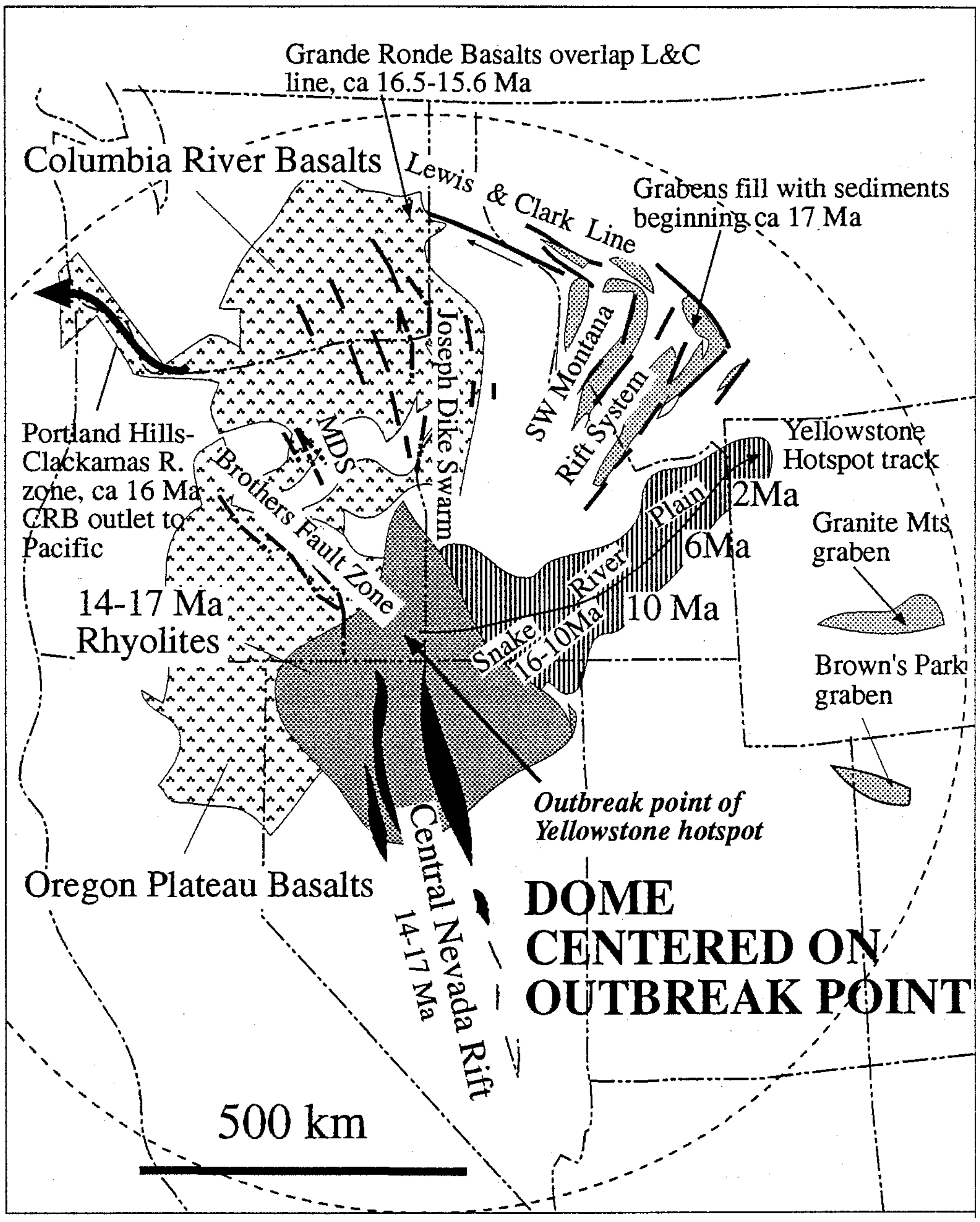

Figure 1. Middle Miocene tectonic features that are radial to the initial outbreak point of the Yellowstone hotspot. Path of hotspot along Snake River Plain is also shown. Modified from Pierce and Morgan (1992), with annotations derived from works cited in the text. MDS = Monument dike swarm.

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TERTIARY CARBONATES IN THE UPPER RUBY AND JEFFERSON RIVER VALLEYS, MONTANA

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ABSTRACT

Tertiary carbonate deposits in western Montana have long been interpreted as lacustrine limestones. Examination of the textural, mineral, floral, faunal, and chemical aspects of Tertiary carbonates in the upper Ruby and Jefferson River Valleys suggests their depositional environments were quite diverse. The interpreted depositional environments include: ephemeral alkaline lakes and ponds; alkaline or hydrothermal springs; and caliche soils.

Facies relationships between the upper Ruby Valley carbonates and their related sediments were determined by measuring three stratigraphic sections. The mineral, floral, faunal, and chemical components of the carbonate samples and their related sediments in the upper Ruby and Jefferson River Valleys were determined by x-ray diffraction, x-ray fluorescence, petrographic and SEM analyses to interpret the physical, chemical, biological and climatic factors controlling carbonate deposition during Tertiary time. Sedimentary, vertebrate fossil, and mineralogical evidence in the upper Ruby and Jefferson River Valleys in western Montana indicate the prevailing climate during carbonate deposition in the Renova Formation was arid to semi-arid.

INTRODUCTION

Terrestrial deposits in western Montana's Tertiary basins (Fig. 1) contain a minor carbonate component, the origin of which has been attributed to lacustrine sedimentation (Kuenzi, 1966; Rasmussen 1969, 1977; Kuenzi and Fields, 1971; Monroe, 1976; Axelrod, 1984) and hot spring deposition (Monroe, 1976). Although most investigators generally agree that the majority of carbonates in western Montana's Tertiary basins were deposited in lacustrine systems, none have considered the environmental factors controlling carbonate precipitation. This study focuses on the mineral, floral, faunal, and chemical components of Tertiary carbonates and their related sediments, as well as their vertical and lateral facies relations, to interpret the physical, chemical, biological and climatic factors controlling carbonate deposition . Carbonate deposits discussed herein are exposed in the upper Ruby and Jefferson River Valleys (Fig. 1).

The primary depositional environments for lacustrine carbonates include saline lakes and playa flats in arid regions, and brackish and freshwater lakes in humid regions (Kelts and Hsü, 1978). Carbonate sediments may be composed of allocthonous grains, biologically produced tests, or inorganically precipitated crystals. The bulk of lacustrine carbonates consists of inorganic calcite. Precipitation of inorganic calcite may be biologically or chemically induced and is largely controlled by environmental factors (Kelts and Hsü, 1978).

METHODS

One-hundred-thirty-three samples of Tertiary carbonates and their related sediments were collected from eleven localities in the upper Ruby and Jefferson River Valleys (Ripley, 1987). Three stratigraphic sections were measured in the upper Ruby Valley to develop a stratigraphic framework for sampling. Samples were collected at every

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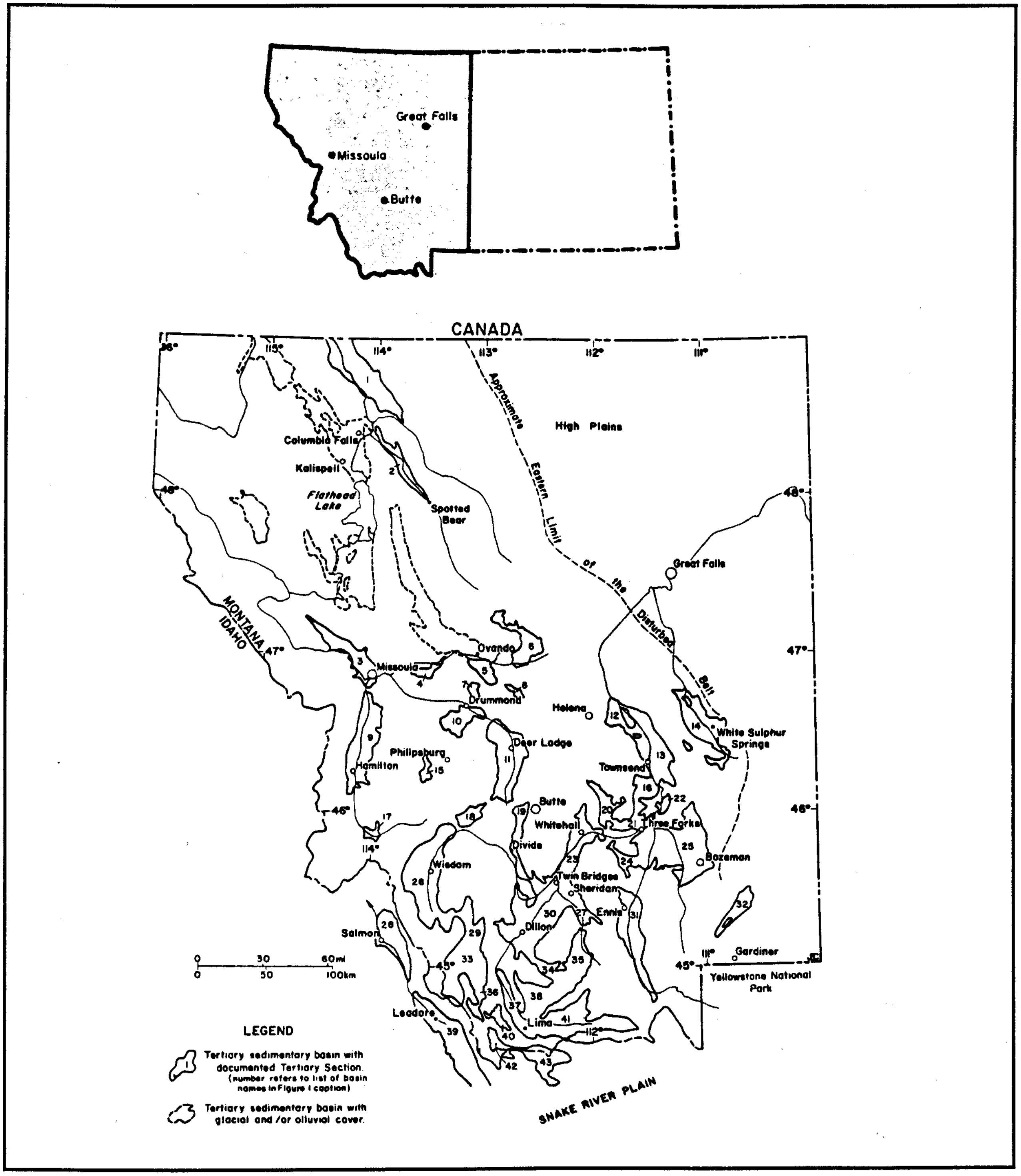

Figure 1. Index map of intermontane basins in western Montana and eastern Idaho (Fields et al., 1985). Basin names: 1. Kishenehn; 2. South Fork-Flathead; 3. Missoula; 4. Potomac; 5. Blackfoot; 6. Lincoln; 7. Douglas Creek; 8. Avon-Nevada Creek; 9. Bitterroot; 10. Flint Creek; 11. Deer Lodge; 12. Helena; 13. Townsend; 14. Smith River; 15. Philipsburg; 16. Toston; 17. East Fork-Bitterroot; 18. French Gulch; 19. Divide; 20. North Boulder; 21. Three Forks; 22. Clarkston; 23. Jefferson River; 24. Norris; 25. Madison-Gallatin; 26. Big Hole; 27. lower Ruby River; 28. Salmon; 29. Grasshopper; 30. Beaverhead; 31. upper Madison; 32. upper Yellowstone (Paradise); 33. Horse Prairie; 34. Blacktail Deer; 35. upper Ruby River; 36. Medicine Lodge; 37. Red Rock River; 38. Sage Creek; 39. Lemhi; 40. Muddy Creek; 41. Centennial; 42. Nicholia; and 43. Lake Hollow.

major lithologic horizon. Where stratigraphic data could not be obtained carbonate samples were collected as available in outcrop.

Clay mineral content of forty-four samples was determined by x-ray diffraction. The samples were crushed using a ceramic mortar and pestle and then disaggregated in deionized water using an ultrasonic probe. Na-metaphosphate was added as a dispersant. The less than 0.5 micron fraction was separated for analysis by centrifugation. Glycol-solvated, oriented samples were analyzed using a Philips Norelco x-ray diffractometer with CuKá radiation and a graphite crystal monochrometer. X-ray patterns were run with the x-ray tube operated at 30 Kv and 30 Ma. Randomly oriented bulk powder samples were additionally analyzed by x-ray diffraction. To determine the presence of attapulgite, six samples with intense dolomite peaks at 2.89Å were treated with 1 N Na-acetate (pH=5.0) for carbonate removal (Jackson, 1969) and then the glycol-solvated, oriented slides were analyzed by x-ray diffraction.

Sixteen carbonate and shale samples were chosen for bulk chemical analysis of silicon, aluminum, titanium, iron, manganese, calcium, magnesium, potassium, sodium, and phosphorous. Dr Peter R. Hooper, of Washington State University, conducted the analysis by x-ray fluorescence with matrix corrections. Results were normalized on a volatile-free basis with total iron expressed as FeO. Analytical precision using x-ray florescence is: SiO_2 0.55%, Al_2O_3 0.31%, Fe_2O_3 0.35%, MgO 0.15%, K_20 0.03%, CaO 0.22%, Na_2O% 0.16.

Mineral, floral, and faunal contents of the carbonate samples were determined with a Zeiss petrographic scope and a Zeiss Novascan 30 scanning electron microscope. Ninety two thin sections cut from fifty-four samples were studied under the petrographic scope.

Folk's (1959) carbonate classification was used to describe carbonate rock types. In some cases, because of the clastic content, Folk's classification was not adequate and a modified classification was necessary for description.

UPPER RUBY VALLEY

Dorr and Wheeler (1964) first described the fossil content and stratigraphy of Tertiary Bozeman Group sediments in the upper Ruby Valley. They recognized two unconformably bounded, lithologically distinct formations: the Passamari Formation and overlying "Madison Valley equivalent". Kuenzi and Fields (1971) revised Bozeman Group nomenclature following the rules of the American Commission of Stratigraphic Nomenclature (1961, p. 649, article 4b) to standardize nomenclature of Tertiary deposits in western Montana based on their geographic and temporal proximity, lithologic similarity and homotaxial stratigraphic positions. In accordance with Kuenzi and Fields' (1971) proposed classification, Becker (1973) and Monroe (1976) revised Dorr and Wheeler's stratigraphy of the upper Ruby Valley. The Passamari Formation was relegated to a member of the Renova Formation and the Madison Valley equivalent was established as the Sixmile Creek Formation. Plant and vertebrate fossils in the upper Ruby Valley suggest age ranges of Early Oligocene (Chadronian) to Early Miocene (latest Arikareean - earliest Hemingfordian) for the Renova Formation, and Late Miocene (Barstovian to Hemphillian) for the Sixmile Creek Formation (Monroe, 1976).

Monroe (1976) recognized three mappable members in the Sixmile Creek Formation and three in the Renova Formation in the upper Ruby Valley. The members present in the Renova Formation are similarly recognized in other Tertiary basins and are assigned the formal stratigraphic names Climbing Arrow Member (Robinson, 1963), Dunbar Creek Member

(Robinson, 1963), and Passamari Member (Petkewich, 1972). Members of the overlying Sixmile Creek Formation occur only in the upper Ruby Valley and are assigned the informal stratigraphic names metamorphic fanglomerate member, feldspathic sandstone member, and quartzite pebble conglomerate member. Limestone units occur in all of the Bozeman Group members in the upper Ruby Valley, but significant deposits (>1.0% of the total member) exist only in the Dunbar Creek and Passamari Members of the Renova Formation. Monroe (1976) interpreted the Dunbar Creek limestones as travertine deposits and the Passamari limestones as lake marls.

SEDIMENTARY FEATURES

Three stratigraphic sections were measured in the upper Ruby Valley (Ripley, 1987). The sections were chosen because they represent different facies within the Passamari Member, they are well exposed, and contain varying amounts of carbonate. Monroe (1976) originally measured and described the Sweetwater Creek (SCRV), Caldwell Springs (CSRV), and Campbell Place (CPRV) Sections. They were remeasured for this study, concentrating on the stratigraphic relationship between the carbonate and clastic sediments and on the sedimentary structures which they contain, to determine the environment and processes of deposition.

The Sweetwater Creek Section, measured one mile west of Conley Ranch from the SE¼ sec. 22 to the NW¼, SE¼ sec 21, T.8S., R.5W., contains 118 meters of the Passamari Member. The section does not contain the base of the Passamari Member. The Passamari Member consists of 66% paper shale, 19% siltstone, 5% mudstone, 5% limestone, 4% sandstone, and less than 1% tuff in the Sweetwater Creek Section. Interbedded flat-laminated paper shales and silts dominate the upper 63 meters, whereas the lower 55 meters are dominated by repeated cycles of ripple- and trough-cross-stratified siltstone, flat-laminated paper shale, crenulated biolithite, and massive intradismicrite. The repeated sedimentary packages of the lower 55 meters vary somewhat, but in general consist of basal trough-cross-stratified tuffaceous silts and sands which interbed with flat-laminated paper shales and are overlain by laminated biolithites. Each sedimentary package is capped by intradismicrite containing calcite psuedomorphs of gypsum (Fig. 2). Some of the basal silts contain ash shards (Fig. 3 and 4). Thin gypsum layers (0.5-4.0 cm thick) run parallel to and across bedding in silty shale units 23, 24, and 38 (Ripley, 1987). Occasional mudcracks of uncertain origin occur in the paper shales and collapse breccias occur in the intradismicrites (Fig. 5). Diamond shaped crystal molds occur near the tops of all the intradismicrite units; in some of these units the original crystals have been replaced by sparry calcite (Fig. 6). Planed oscillation ripples occur on bedding surfaces of coarse (0.05-2.0 cm diameter) trough-cross-stratified pebble-sands in Unit 37 (Ripley, 1987).

The Caldwell Springs Section, located in the west center of sec 13, T.8S., R.5W., represents a coarser facies of the Passamari Member than does the Sweetwater Creek Section.

Neither the base nor the top of the Passamari Member is exposed in the Caldwell Springs Section. Fine sands and silts compose up to 72% of the total 41 meters, while paper shales compose 38% of the section. A variety of sedimentary structures is present throughout the section, including planar laminations (0.1-2.0 cm thick), channel scours (3.0-10.0 cm high, 10.0-5.0 cm wide), load structures, flame structures, and mud diapirs (1.0-2.0 m high). Lenticular beds of coarse, rip-up clast sands repeatedly occur in the section. The pebble sized rip-up clasts (0.5-4.0 cm diameter) are composed of calcareous silts and clay. Occasional

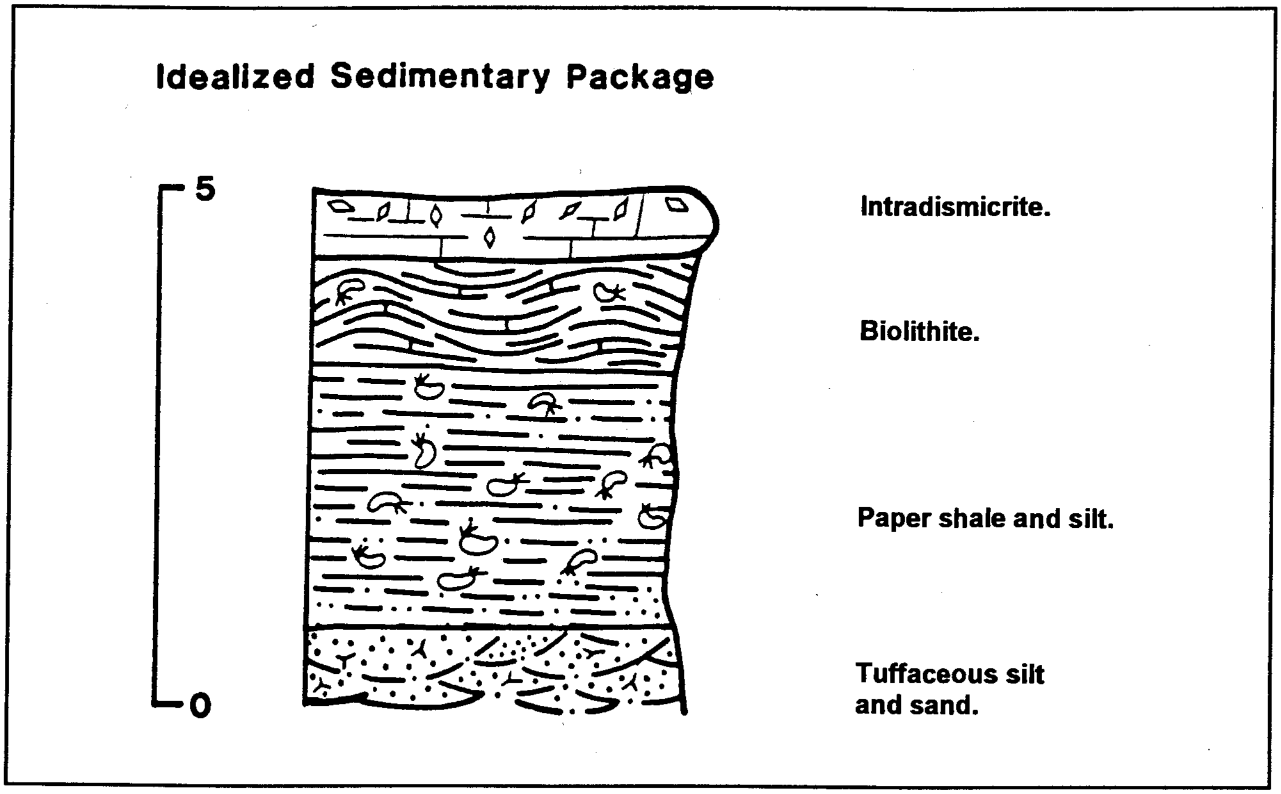

Figure 2. Repeated sedimentary package in the Sweetwater Creek Section. Scale in meters.

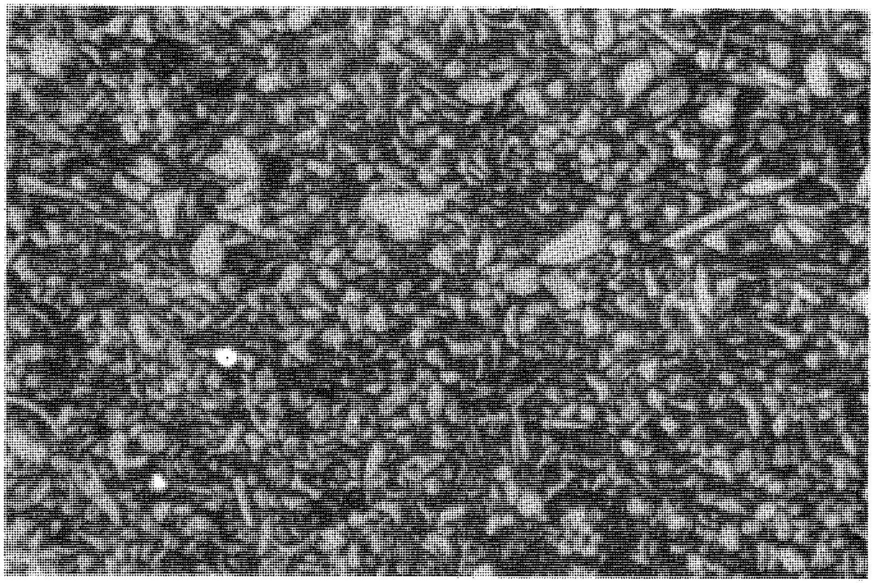

Figure 3. Photomicrograph of tuffaceous silty sand (SCRV-23), x10, plane light.

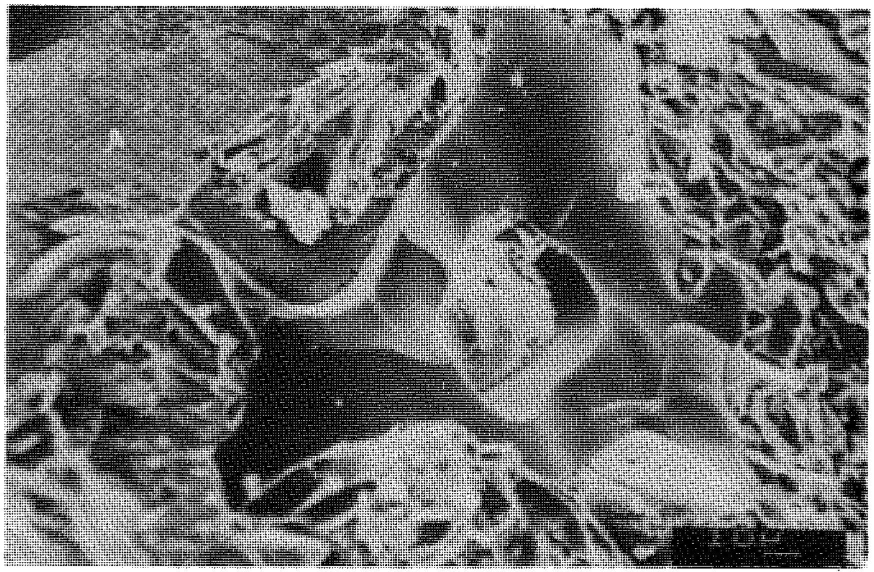

Figure. 4. SEM photograph of volcanic glass shard (SCRV-23), x1K.

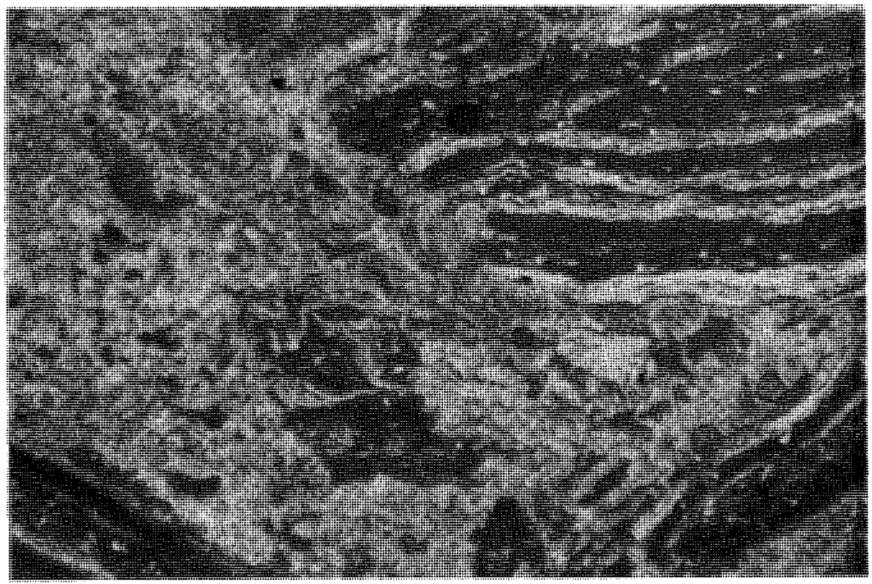

Figure. 5 Photomicrograph of brecciated micrite (SCRV-19), x10, plane light.

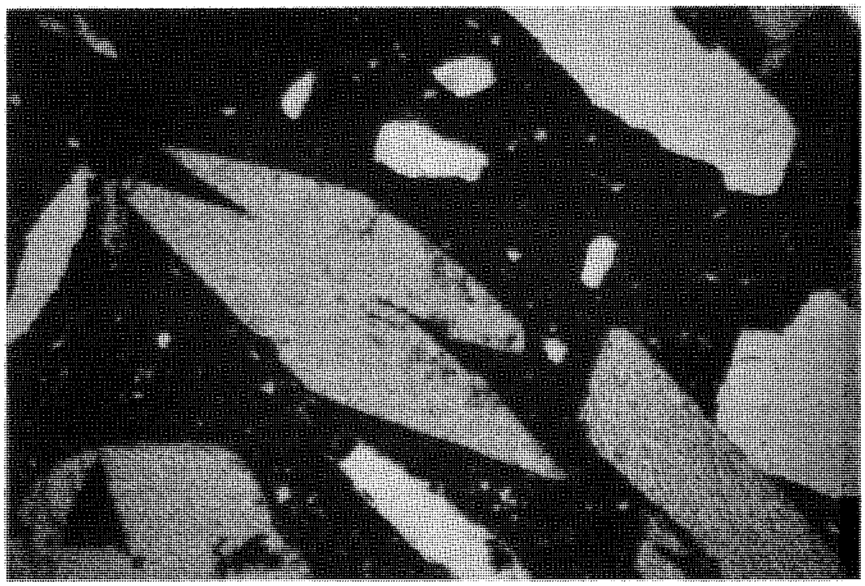

Figure 6. Photomicrograph of calcite psuedomorphs after gypsum (SCRV-19), x10, plane light.

mudcracks and gypsum layers (1.0-2.0 cm thick) occur in the calcareous paper shales.

The Campbell Place Section, in the NW¼, SW¼, sec. 11, T.8S., R.5W., represents the coarsest facies of the Passamari Member in the upper Ruby Valley. The section measures 32 meters and contains neither the base nor the top of the Passamari Member. Poorly sorted sands make up 90% of the section while conglomerates comprise 10%. Paper shale is not present in the Campbell Place Section. Isolated cobble to boulder sized, basalt clasts commonly occur "floating" in a matrix of massive sands. Poorly developed conglomeratic channel lenses (5.0-10.0 cm high, 1.0-2.0 m wide) also occur in the massive sands. Four lenticular beds (0.5-1.0 m thick) of cobble conglomerates alternate with the poorly sorted sand units. Well developed channel scours (10.0-50.0 cm high, 3.0-10.0 m wide) cut into the sands. Conglomeratic beds low in the section are matrix supported, whereas those higher in the section are clast supported.

Massive carbonate deposits occur in the upper Ruby Valley near the present basin margins (Fig. 2). These deposits include: the Warm Springs carbonates (WSRV) located in secs. 12 and 13, T.7S., R.5W., and secs 7, 8, 17, and 18, T.7S., R.4W.; Table Mountain carbonates (TMRV) in secs. 3, 4, and 10, T.8S., R.5W.; Hot Springs carbonates (HSRV) in sec 16, T.8S., R.5W.; and Timber Hill carbonates (THRV) in sec. 7, T.9S., R.5W. The carbonates do not interbed extensively with clastic deposits and in some cases they occur in isolated patches. Monroe (1976) interpreted the deposits as calcareous tufa and travertine resulting from hot spring activity. Internal structures are not apparent in field exposures or hand samples, however petrographic analysis reveals algal laminations and abundant ostracod shells (Fig. 7 through 9). All of the travertine biosparites and biolithites have been neomorphosed.

MINERAL CONTENT

The mineral content of Renova deposits in the upper Ruby Valley was determined by x-ray and petrographic analyses. The most common mineral assemblage in the upper Ruby Valley consists of smectite, calcite, rhyolitic glass (Monroe, 1976), quartz, and feldspar. The silt- to sand-sized quartz and feldspar grains and glass shards are all allogenic, whereas calcite occurs as an endogenic precipitate. Allochthonous Paleozoic and Mesozoic carbonate clasts do not occur in any of the upper Ruby Valley deposits.

Dolomite, gypsum, halite, illite, and attapulgite are present in some horizons. The most common occurrence of these minerals is in the lower 80 meters of the Sweetwater Creek Section . Halite and illite also occur in the Caldwell Springs Section. Attapulgite was tentatively indentified based on a 10.5 Å d-spacing reflection in two x-ray diffraction patterns from the Sweetwater Creek Section (SCRV-8 and SCRV-15). Although a (110) d-spacing 10.5 is not definitive, it is suggestive of attapulgite. Attapulgite is a magnesium silicate mineral that is stable in alkaline environments (Carroll, 1970).

The dominant mineral assemblage of the Warm Springs, Hot Springs, Table Mountain, and Timber Hill carbonates consists of smectite and calcite. Chalcedony is present in these carbonates as a secondary mineral. Glass shards and quartz and feldspar grains occur in a few of the Table Mountain and Timber Hill samples.

CHEMICAL CONTENT

Chemical content of 12 samples from the upper Ruby Valley was determined by x-ray fluorescence (Table 1). The samples chosen for analysis include calcareous paper shales (SCRV-33 and SCRV-40), silty micrites (SCRV-16 and SCRV-27), micrites (SCRV-20, SCRV-21, SCRV-26, SCRV-30, and SCRV-32) and sparites

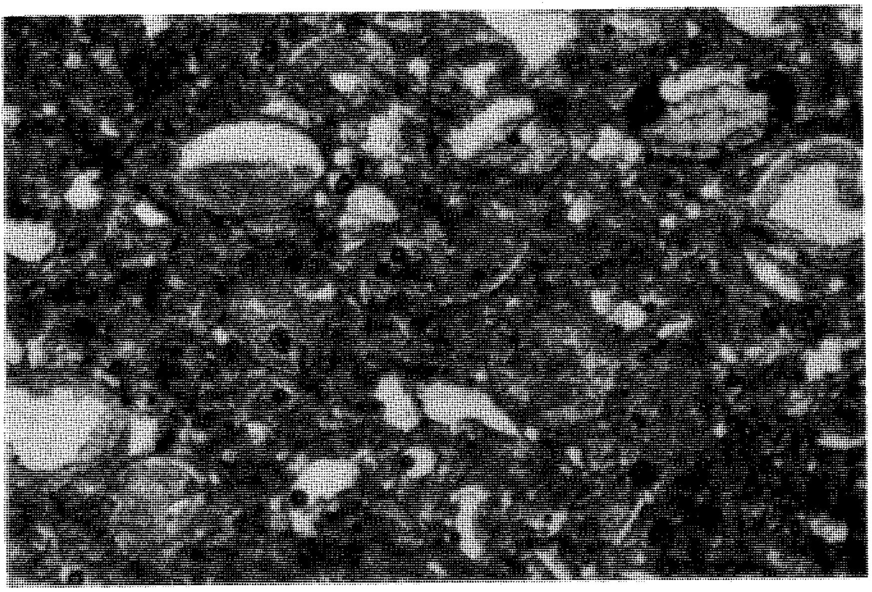

Figure 7. Photomicrograph of ostracod biosparite (THRV-14), x10, plane light. Note geopetal structure and neomorphic spar.

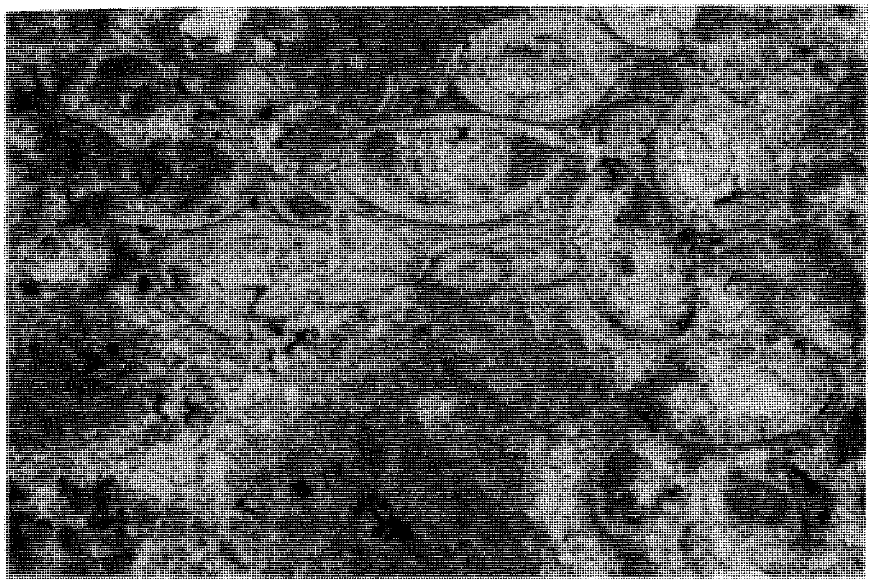

Figure 8. Photomicrograph of ostracod biosparite (HSRV-1), x10, plane light. Note neomorphic spar.

RUBY VALLEY CHEMICAL DATA

Sample		SiO_2	Al_2O_3	TiO_2	Fe0	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
Calcareous Paper Shale	SCRV-33	37.43	8.48	0.471	3.30	0.288	45.16	1.77	1.57	1.23	0.287
	SCRV-40	35.88	6.80	0.354	2.53	0.979	50.73	1.45	1.32	0.35	0.289
Silty Micrite	SCRV-16	38.73	8.15	0.446	1.70	0.246	46.36	1.47	1.59	1.17	0.157
	SCRV-27	36.84	7.77	0.375	2.22	0.244	49.12	1.35	1.91	0.76	0.185
Micrite	SCRV-20	16.66	3.18	0.180	1.59	0.282	49.95	27.72	0.61	0.27	0.219
	SCRV-21	17.86	3.03	0.180	1.04	0.244	72.98	3.71	0.64	0.09	0.219
	SCRV-26	13.31	2.71	0.211	1.19	0.390	80.25	1.23	0.55	0.07	0.111
	SCRV-30	12.26	1.72	0.12	0.46	0.27	83.86	0.87	0.32	0.00	0.12
	SCRV-32	7.32	1.11	0.12	0.34	0.09	57.32	32.84	0.20	0.42	0.26
Sparite	THRV-13	2.04	0.29	0.06	0.00	0.16	97.01	0.38	0.00	0.00	0.08
	TMRV-2	20.57	3.95	0.25	1.32	0.04	70.16	2.24	0.98	0.37	0.1
	WSRV-3	3.12	0.57	0.07	0.00	0	94.67	1.49	0.07	0.00	0.03

Table 1. Chemical data from the upper Ruby Valley listed in weight percent.

(THRV-13, TMRV-2, and WSRV-3). Results of chemical analyses are listed in Table 1.

Paper shales and silty micrites contain the highest percentage of silicon and aluminum in the upper Ruby Valley samples. Aluminum and silicon oxide values are interpreted to represent the clay mineral assemblage. Titanium, magnesium, iron, and potassium all increase with increasing silicon and are interpreted to occur with the clay fraction. The sparites (THRV-13, and WSRV-3) contain the lowest percentage of silica which is consistent with the clastic content of these samples.

Norm calculations were conducted to semiquantitatively describe the mineral content of the twelve upper Ruby Valley samples (Table 2). Before proceeding with the calculations several assumptions were made: 1. all the magnesium was used to make dolomite; 2. all the remaining calcium was used to make calcite; 3. all the aluminum was used to make smectite; 4. all octahedral cations in the smectite are aluminum; and 5. all the sodium was used to make halite. Total normative percentages exceeded one hundred by approximately 20 percent probably because the clay characterization was oversimplified and gypsum was not included in the calculation. Using this approach the highest clay content was determined at 33 percent (SCRV-33) and the lowest was less than 1 percent (THRV-3). Calcite contributions range from15 to 126 percent. Halite never exceeds 1 percent and silica (allogenic glass and quartz) never exceeds 19 percent of the total mineral assemblage. The normative calculations give only a rough estimation of the mineral content of the samples analyzed, but corroborate petrographic analysis.

FOSSIL CONTENT

Floral and faunal studies conducted in the upper Ruby Valley focus primarily on the macrofossil content. Becker (1960, 1961, 1972, 1973) recognized four Tertiary floras in the valley only one of which, the Paper Shale flora, he placed in the Passamari Member. The Paper Shale flora (Late Oligocene) occurs south of Peterson Creek in Fossil Basin (secs. 23, 24, 25, 26, T.7S., R.5W.) and contains well preserved plant leaves, flowers, stems, and seeds, as well as insect and fish (Teleostei, cf. Amia) remains. Species of fir (Abies), spruce (Picea), pine (Pinus), dawn redwood (Metasequoia), maple (Acer), birch (Betula), hackberry (Celtis), beech (Fagus), ash (Fraxinus), Oregon grape (Mahonia), poplar (Populus), rose (Rosa), elm (Ulmus), and keaki tree (Zelkova) genera contribute to the flora. The Paper Shale flora has not been documentedelsewhere in the Passamari Member; therefore, its stratigraphic relationship to measured sections is questionable.

Monroe (1976) recognized five faunas in the upper Ruby Valley only one of which, the Belmont Park fauna, occurs in the Passamari member. The Belmont Park fauna (latest Arikareean - earliest Hemingfordian) includes ancestral beavers (Palaeocastor), rabbits (Palaeolagus), horses (Parahippus, Anchitherium), tragulids (Nannotragulus, cf. hypertragulid), deer (Blastomeryx), camels (Oxydactylus), and oreodonts (Ticholeptus, Phenacocoelus, Merychyus).

Microfossils present in the Passamari Member include ostracods (Fig. 10 and 11) and diatoms (Fig 12 through 19). Van Nieuwenhuise (1986) cited the presence of three species of benthonic foraminifera (Elphidium) in a limited horizon (Monroe, 1976, Unit 28) of the Sweetwater Creek Section. Monroe's Unit 28 tentatively correlates with Ripley's (1987) Unit 34 based on lithologic descriptions, but no evidence of a foram horizon was found.

Ostracod molds and impressions are abundant in the Sweetwater Creek and Caldwell Springs paper shales. They also occur in some of the

RUBY VALLEY MINERAL PERCENTAGES

Sample		Calcite	Dolomite	Clay	Free Silica	Halite
Calcareous Paper Shale	SCRV-33	63.90	6.82	33.05	17.2	1.00
	SCRV-40	72.90	5.53	26.45	18.72	0.29
Silty Micrite	SCRV-16	67.80	5.72	32.58	6.06	0.90
	SCRV-27	72.00	5.35	30.69	17.62	0.58
Micrite	SCRV-20	16.80	94.76	1.13	7.87	0.18
	SCRV-21	96.70	13.46	11.33	9.35	0.06
	SCRV-26	107.36	4.24	1.21	8.98	0.06
	SCRV-30	115.30	3.13	6.14	6.95	0.00
	SCRV-32	15.30	110.98	3.78	3.77	0.29
Sparite	THRV-13	126.00	1.29	0.94	1.11	0.00
	TMRV-2	96.00	8.30	14.64	10.26	0.29
	WSRV-3	122.00	4.98	1.89	0.02	0.00

Table 2. Results of norm calculations listed in percent.

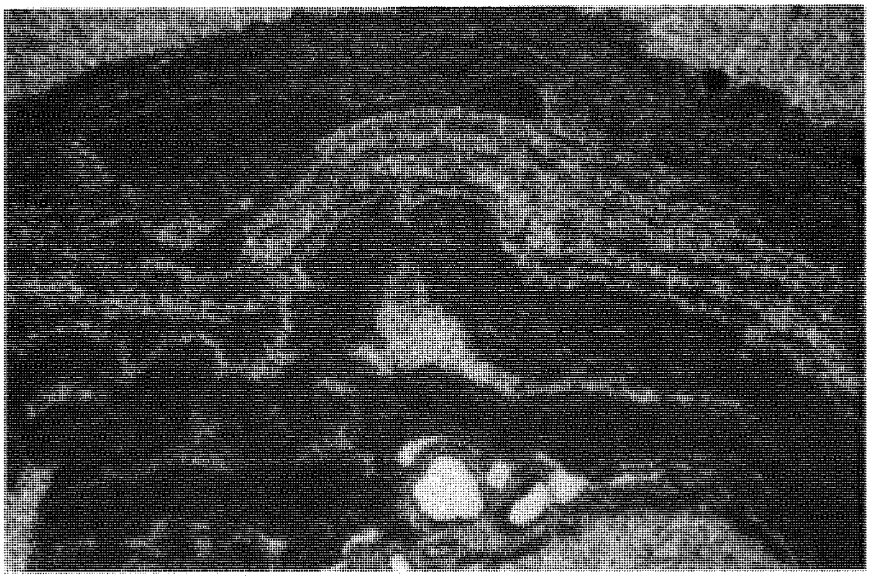

Figure 9. Photomicrograph of algal laminations in spring deposit (TMRV-4), x10, plane light.

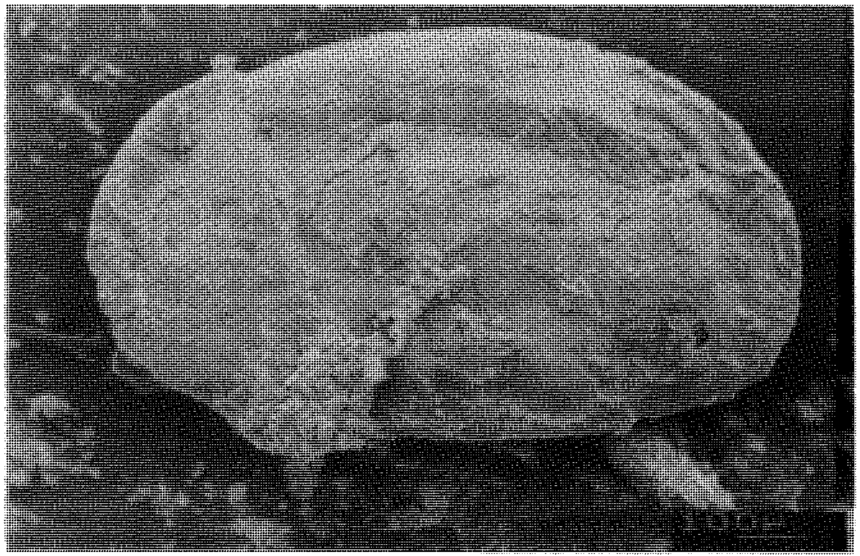

Figure 10. SEM photograph of ostracod (SCRV-31), x50.

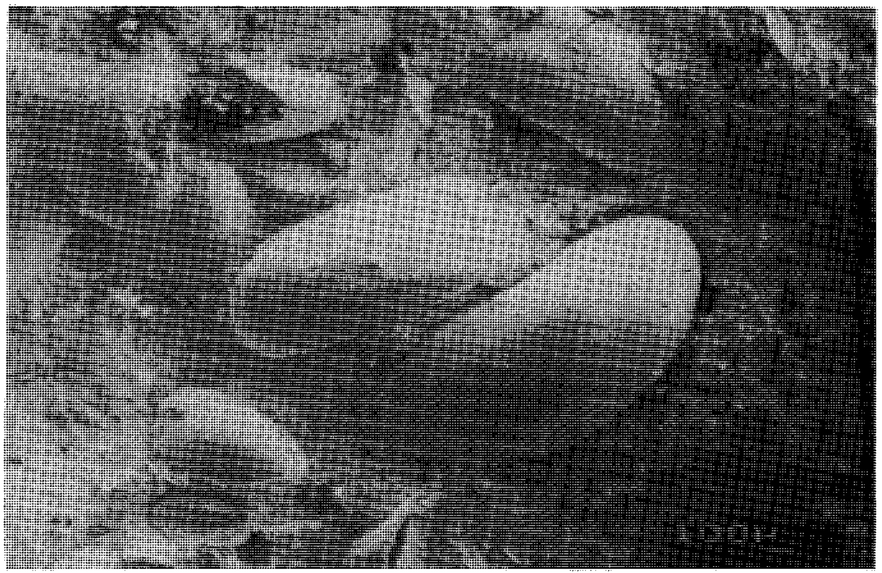

Figure 11. SEM photograph of ostracods (SCRV-32), x50.

Figure 12. SEM photograph of the diatom Melosira (SCRV-32), x5K.

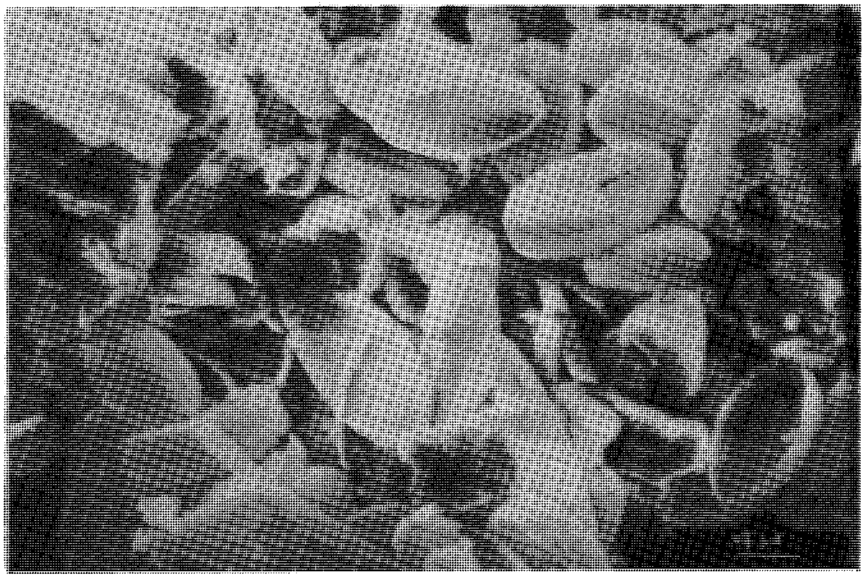

Figure 13. SEM photograph of the diatom ? Navicula (SCRV-32), x2.5K.

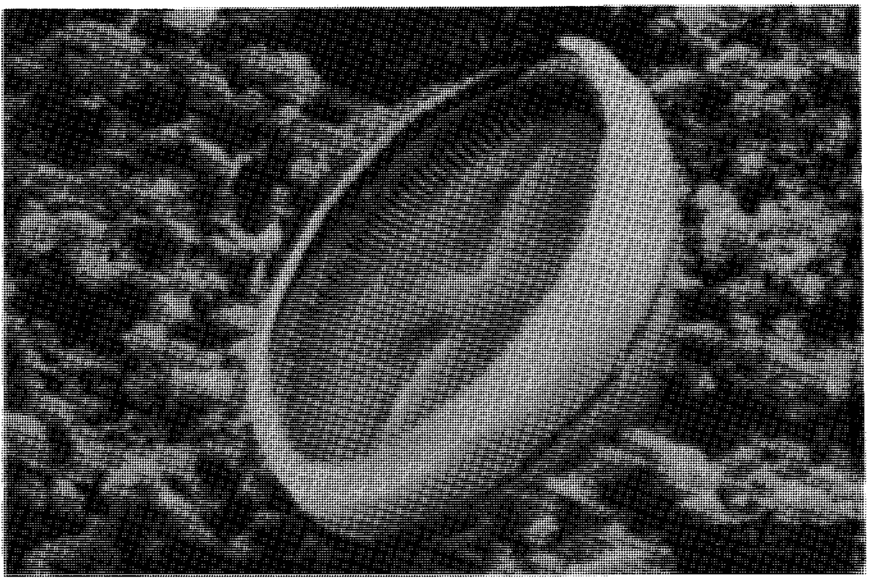

Figure 14. SEM photograph of the diatom ? Mastogloia (SCRV-32), x2.5K.

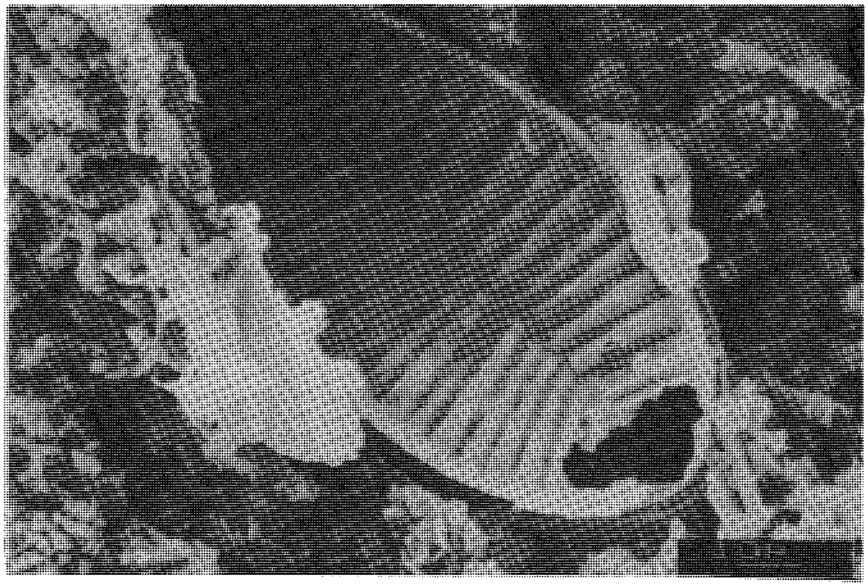

Figure 15. SEM photograph of the diatom ? Surirella (SCRV-32), x1K.

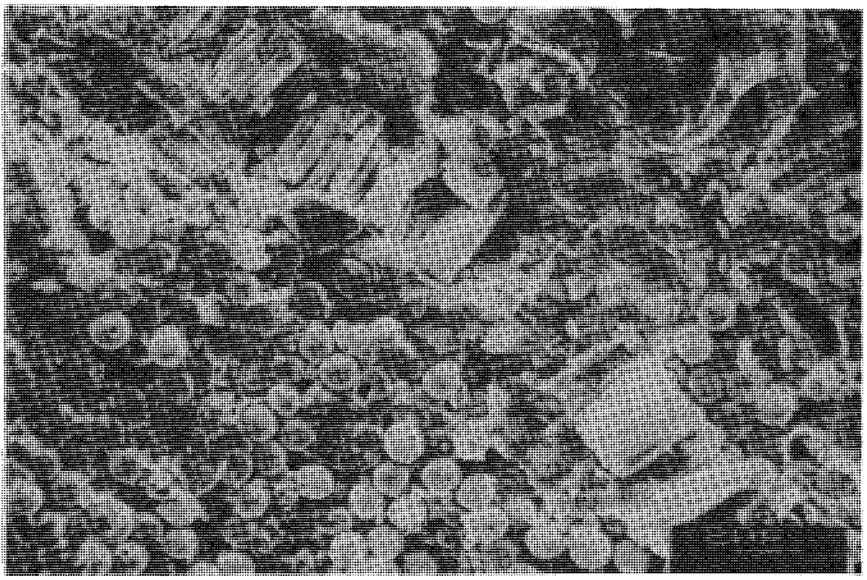

Figure 16. SEM photograph of diatom colony and coccoid green algae (SCRV-40), x500.

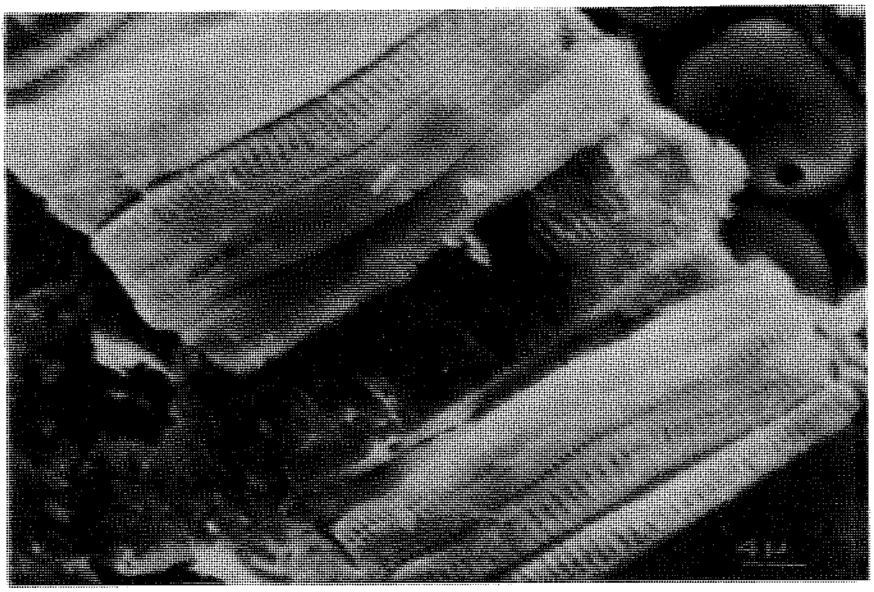

Figure 17. Close up of photograph of diatom colony (SCRV-40), x2.5K.

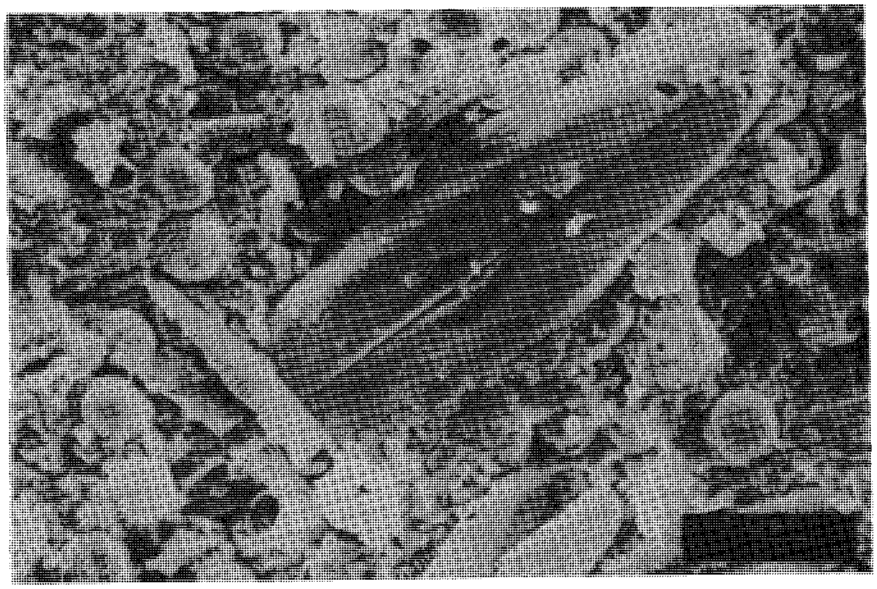

Figure 18. SEM photograph of the diatom Navicula and coccoid green algae (SCRV-40), x1K.

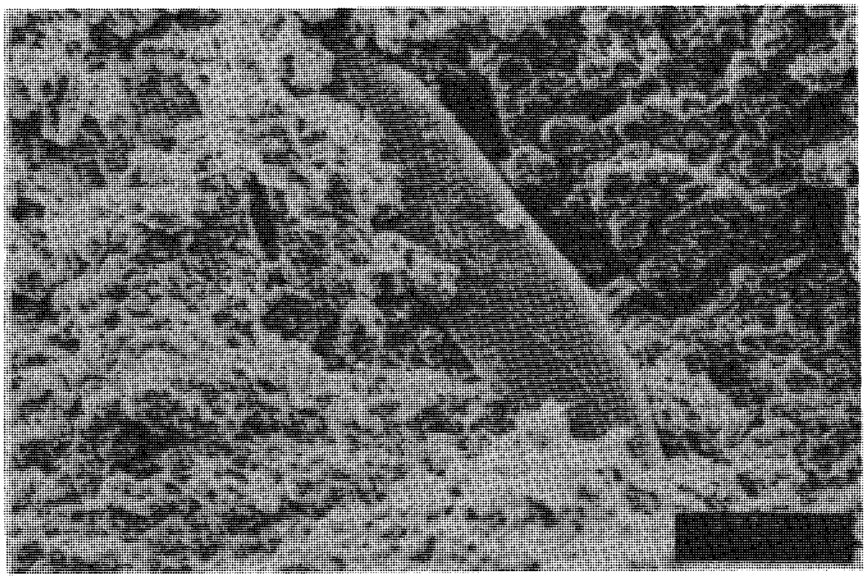

Figure 19. SEM photograph of the diatom Navicula (SCRV-32), x1K.

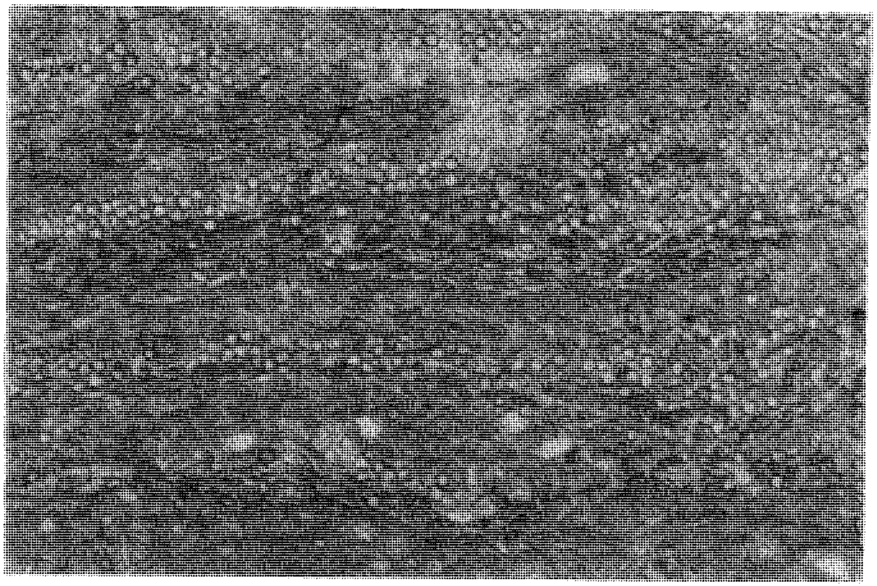

Figure 20. Photomicrograph of coccoid green algae (SCRV-30), x10, plane light.

Sweetwater Creek biolithites and intradismicrites, but are not as numerous in these rock types. Ostracod identification is difficult due to poor preservation. Dorr and Wheeler (1964, p. 302) identified some of the ostracods as Candona. Ostracods in the Warm Spring, Table Mountain, Hot Spring, and Timber Hill travertine deposits are recognized only in thin section (Fig. 7 and 8).

Coccoid green algae occur throughout the Sweetwater Creek Section. The algal spheres (Fig. 16, 18, and 20), similar to Chlorellopsis coloniata from the Green River Formation (Bradley, 1929), dominate the biolithites and occur scattered throughout the intradismicrites. Chlorellopsis coloniata is an extinct unicellular green algae similar to the modern genus Chlorella. Coccoid green algae in the Sweetwater Creek carbonates differ from Chlorellopsis coloniata in size and growth habit. Individual spheres of Chlorellopsis coloniata range in diameter from 110-140 microns, and form algal heads 0.7-1.7 meters high and 0.6-0.7 meters in diameter, whereas algal spheres from the Sweetwater Creek section range from 8-10 microns in diameter and form laminated mats 5.0-10.0 centimeters thick. The Sweetwater Creek algae are probably not the same species as Chlorellopsis coloniata, but they may belong to the same genus.

Numerous and varied forms of diatoms occur in the Sweetwater Creek shales, biolithites, and intradismicrites. The genera present include Navicula, ? Surirella, ? Melosira, and ? Mastogloia (Fig. 12 through 19). Monroe (1981) cited the presence of a 0.3 meter thick diatomite bed in the Passamari lacustrine facies. A pure diatomite bed was not found in the Sweetwater Creek Section, but many of the units are diatomaceous.

INTERPRETATION

The Sweetwater Creek, Caldwell Springs, and Campbell Place Sections each display different textural fabrics, sedimentary structures, mineral assemblages, and fossil assemblages. Monroe (1976, 1981) interpreted these three sections respectively as lacustrine, deltaic, and alluvial fan facies of the Passamari Member. Monroe (1976, 1981) suggested the Sweetwater Creek limestones precipitated in a shallow perennial lake (Lake Passamari) which occupied a closed basin. Reexamination of the Sweetwater Creek Section leads to a slightly different interpretation of the lacustrine environment. The presence of desiccation cracks, collapse breccias, halite, attapulgite, pseudomorphs of calcite after gypsum, and a flora and fauna restricted to ostracods and algae suggest the carbonates were precipitated in an ephemeral lacustrine environment. This interpretation is supported by the repeated sedimentary packages of silts, paper shales, biolithites, and intradismicrites which are interpreted to record recurrent flooding and desiccation of ancient Lake Passamari. Repeated sheetflow and mudflow deposits in the Caldwell Springs and Campbell Place sections support this interpretation.

Monroe (1976) interpreted the Tertiary carbonates at the Warm Springs, Table Mountain, and Hot Springs localities as travertine deposits resulting from hot spring activity. The Timber Hill carbonate deposits of this report can also be included in this category. This is a reasonable interpretation given the mineral, faunal, and textural aspects of these deposits. Travertine deposits are commonly associated with perennial and ephemeral lacustrine environments in arid regions (Hardie, et al., 1978; Smoot, 1978; Esteban and Klappa, 1983).

Trona is a common evaporite mineral in the Wilkens Peak Member of the Eocene Green River Formation in Utah (Eugster and Hardie, 1975; Smoot, 1978) and in modern Lake Magadi in Africa (Eugster and Hardie, 1975), but is absent in the Passamari Member of the Renova Formation in western Montana. The absence of trona ($NaHCO_3$ Na_2CO_3 H_2O) in the evaporitemineral assemblage indicates Lake Passamari waters either never became concentrated enough to precipitate trona or that they were slightly depleted in bicarbonate relative to calcium. Bicarbonate is less soluble in alkaline environments (Eugster and Hardie, 1978), and any free bicarbonate probably reacted with calcium to precipitate calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). A 25-fold brine concentration is required after precipitation of gypsum ($CaSO_4$) for halite to precipitate and an additional 250-fold brine concentration is needed for trona to precipitate (Eugster and Hardie, 1978). The absence of trona in the Passamari Member indicates either the evaporative brine in ancient Lake Passamari never reached a 250-fold increase after gypsum precipitation or that the system was highly alkaline and depleted with respect to bicarbonate.

Pebble and cobble compositions in coarse-grained facies of the Campbell Place and Caldwell Springs sections indicate metamorphic basement and basalt were the primary source rocks for Passamari deposits. Exposed bedrock surrounding the upper Ruby Valley today consists of Precambrian Cherry Creek Group gneiss, schist, marble, and quartzite (Monroe, 1976). Precambrian Belt rocks are not present in the region. Solutes necessary for precipitation of calcite, dolomite, halite, and gypsum could have been supplied from chemical weathering of the carbonate and silicate minerals present in the gneiss, schists, marble, and basalt (Eugster and Hardie, 1978).

Illite in the lacustrine and deltaic facies may be detrital, but its association with gypsum, halite, and dolomite in the Sweetwater Creek and Caldwell Springs Sections and exclusion from other sections implies a genetic relationship. Jones and Weir (1983) described the chemical transformation of smectite to illite in a modern alkaline, lacustrine environment in Oregon. Eberl et al. (1986) suggest the smectite to illite transformation may result from frequent periods of wetting and drying and from chemical reaction in high pH environments.

The fossil assemblage in the upper Ruby Valley Passamari facies further supports an ephemeral alkaline lacustrine interpretation. Ostracods dominate the fossil assemblage, occurring primarily in the laminated paper shales. The paper shales are interpreted as quiet water deposits laid down after flooding events. Ostracod abundance declines in the biolithites and intradismicrites. Forester (1983, 1986) states ostracod occurrence is determined by dissolved anion concentrations, and that ostracod species are anion-specific. Without knowing whatostracod species are present in the Passamari Member it is impossible to determine what specific anion limited their occurrence to the paper shales, but evidence of their decline in the biolithites and intradismicrites suggests chemical conditions in the lake were changing.

Pulmonate gastropods are terrestrial snails that live in freshwater environments. The complete absence of land snails in the upper Ruby Valley deposits suggests the lake and spring waters were too alkaline, or in the case of the springs, too warm.

The abundance of algae in the Sweetwater Creek biolithites may indicate that initial carbonate precipitation was enhanced by biological extraction of carbon dioxide. As evaporation continued, biological activity declined, as indicated in the declining flora and fauna of the intradismicrites, and calcite precipitated chemically.

Two carbonate depositional environments are interpreted in the upper Ruby Valley. They are an ephemeral, alkaline, saline lake represented by the Sweetwater Creek, Caldwell Spring and Campbell Place localities; and alkaline or hydrothermal springs represented by the Warm Spring, Table Mountain, Hot Spring, and Timber Hill localities. The processes resulting in carbonate deposition include direct precipitation from loss of carbon dioxide in spring waters and evaporative concentration of solutes in alkaline lakes. Biological activity may have induced carbonate precipitation in the upper Ruby Valley by extracting carbon dioxide from the water column.

JEFFERSON VALLEY

Tertiary sediments in the Jefferson Valley range from late Eocene to late Miocene based on vertebrate fossil data (Kuenzi, 1966). Kuenzi (1966) first described the stratigraphy in the Jefferson Valley recognizing two units: the basal Renova Formation and the overlying Parrot Bench Formation. In 1971, Kuenzi and Fields revised Tertiary nomenclature in the Jefferson Valley to standardize similar stratigraphic units. In doing so they formalized the Renova Formation and designated Kuenzi's (1966) Parrot Bench Formation as a member of the Sixmile Creek Formation. The type section for the Renova Formation (Kuenzi, 1966) is approximately 1.25 miles southeast of Renova, along the east bank of the Jefferson River from the NW¼, NW¼, sec. 33, T.1N., R.4W. to the NW¼, NW¼, sec. 28, T.1N., R.4W. The top of the Renova Formation is not exposed at the type locality (Jefferson River Section) and all rock typesincluded in the formation are not present. Kuenzi (1966) measured three principal sections to include the Pipestone Springs Member, Easter Lily Member, and top of the Bone Basin Member in the Renova Formation.

The type section for the Bone Basin Member is the same as the type Renova section. The Lower Parrot Bench Section (secs. 23, 26, 27, T.1N., R.4W.) is a principal section of the Renova Formation which includes the upper contact between the Bone Basin Member and overlying Sixmile Creek Formation. The Bone Basin Member is the only member of the Renova Formation in the Jefferson Valley that contains significant limestone. Kuenzi (1966) interpreted the Bone Basin carbonates as chemical precipitates deposited in shallow lakes and ponds on a low lying flood plain.

The Jefferson River and Lower Parrot Bench Sections were not remeasured for this study. Stratigraphic data was obtained from Kuenzi (1966) and field checked. All of the carbonate samples from the Jefferson Valley used in this study were obtained from the Bone Basin Member in Bone Basin at the north east corner of the Tobacco Root Mountains.

SEDIMENTARY FEATURES

Kuenzi (1966) suggested a probable thickness for the Bone Basin Member of greater than 296 meters based on the cumulative thickness of the Jefferson River and Lower Parrot Bench sections. The composite sections consist of 31% limestone and marl, 25% mudstone, 19% sandstone, and 17% siltstone. Limestone beds occur throughout the member. Some of the limestone units contain an abundant invertebrate fauna and are very calcareous (>60% CaO), whereas other carbonate units are strongly silicified (>30% SiO_2) and contain a sparse ostracod fauna and abundant root casts.

Most of the silicified limestone units show transitional lower boundaries with underlying tuffaceous silts and sands, and display sharp upper bounding surfaces. Silicified and calcified root casts (Fig. 21) commonly occur near the tops

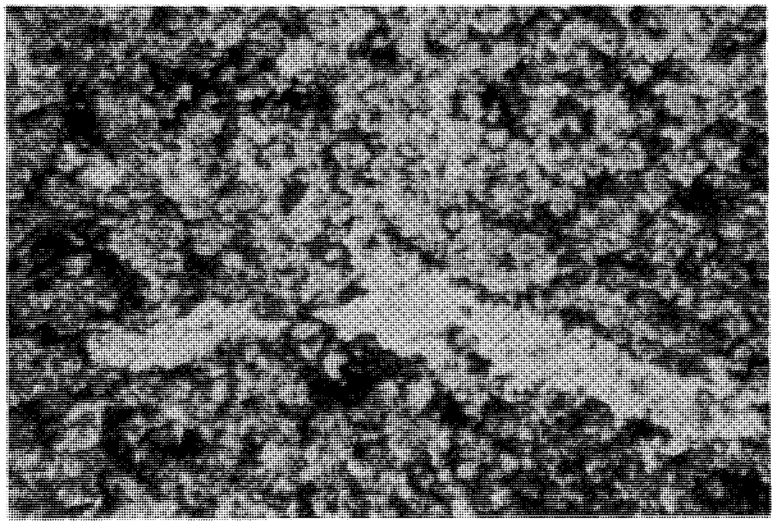

Figure 21. Photomicrograph of silicified root cast (PBJV-7), x10, crossed nicols.

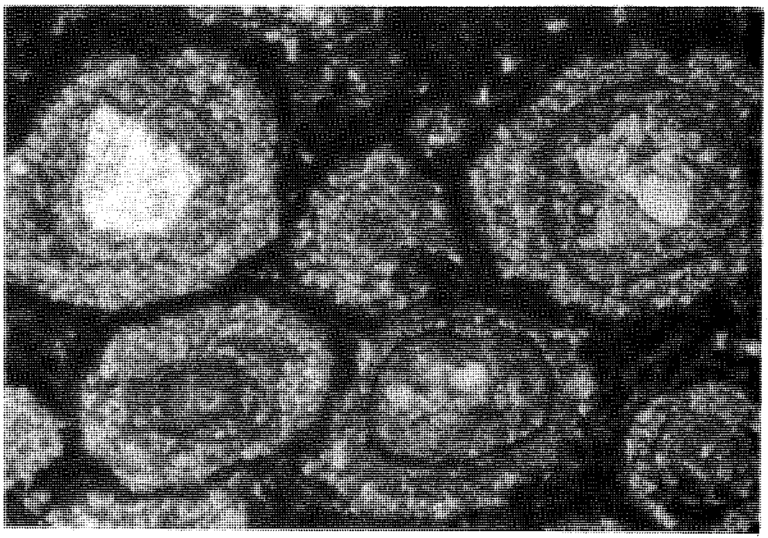

Figure 22. Photomicrograph of "ooids" (PBJV-7), x10, plane light.

of these units. The ashy-sand to silicified limestone units range from 0.5-5.0 meters thick. The original micrite in these units has been replaced by chalcedony, chert, and opal giving the "limestones" a porcelain-like quality. They are aphanitic, hard, break with a conchoidal fracture, and display a dull luster. Petrographic analysis of one of the limestones (PBJV-7) reveals interlocking irregularly shaped "ooids" ofmicrite cemented with chalcedony (Fig. 22). The term "ooid" is used to describe these grains primarily because of their shape and size; it is not meant to imply a genetic origin.

Clastic sediments in the Bone Basin Member are predominantly fine-grained, tuffaceous sands and silts. Most of the clastic units are massive, however Kuenzi (1966) notes trough cross-stratification in some sandstone units. The sands exhibit poor to moderate textural and compositional maturity. The Bone Basin Member in the Jefferson Valley is slightly more tuffaceous than the Passamari Member in the upper Ruby Valley.

MINERAL CONTENT

The most common mineral assemblage in Bone Basin consists of smectite, calcite, glass, quartz, chalcedony, opal, and feldspar. Evaporite minerals, illite, and dolomite are completely lacking. Glass shards, quartz, and feldspar occur as allogenic grains; calcite occurs as an endogenic precipitate; and chalcedony and opal occur as authigenic cements.

CHEMICAL CONTENT

Four samples from the Jefferson Valley were analyzed to determine their chemical content (Table 3). The samples chosen for analysis include one micrite (DGJV-7) and three silicified micrites (PBJV-5, PBJV-7, and PBJV-12). Silicon and calcium oxide values content are inversely related in the Jefferson Valley carbonates. Aluminum, titanium, magnesium, manganese and potassium oxide weightpercentages are fairly constant in these samples indicating the clay content is fairly uniform. The decrease in silica relative to calcium is probably the result of secondary silica replacing calcite.

Dolomite and halite minerals were not detected in any of the x-ray diffraction patterns or thin sections of the Jefferson Valley samples and were not included in the norm calculations. Norm calculations were overestimated by nearly 20 percent for the Jefferson Valley samples (Table 4). Calcite content ranges from 63 (PBJV-12) to 100 (DGJV-7) percent, clay content ranges from 5 (DGJV-7) to 17 (PBJV-5) percent, and free silica content ranges from 19 (DGJV-7) to 45 (PBJV-12) percent. High aluminum, iron, titanium, and magnesium values for PBJV-5 correlate with its higher clay content. Abnormally high iron and manganese oxide percentages in PBJV-7 are probably a result of stronger oxide staining in this sample. PBJV-7 is the only sample from the Jefferson Valley with a brown coloration, everything else is a creamy tan color.

FOSSIL CONTENT

Kuenzi (1966) first collected and described the invertebrate and vertebrate fossil content of the Bone Basin Member. Invertebrate fossils occur in a few of the limestone and marl units and include ostracods, gastropods and pelecypods. Pelecypods occur only in one limestone unit which also contains an abundant gastropod fauna (Kuenzi, 1966). Ostracod shells are present in most of the calcareous limestone units, but are sparse in the silicified limestones.

JEFFERSON VALLEY CHEMICAL DATA											
Sample		SiO_2	Al_2O_3	TiO_2	Fe0	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
Micrite	DGJV-7	21.14	1.42	0.13	0.58	0.164	75.28	0.99	0.20	0.00	0.096
Silicified Micrite	PBJV-5	32.44	4.45	0.21	1.23	0.186	58.97	1.06	1.09	0.29	0.053
	PBJV-7	40.45	1.37	0.11	1.00	1.300	54.36	1.00	0.23	0.00	0.182
	PBJV-12	55.50	1.39	0.11	0.38	0.298	41.20	0.80	0.18	0.00	0.100

Table 3. Chemical data for the Jefferson Valley listed in weight percent.

JEFFERSON VALLEY MINERAL PERCENTAGES				
Sample		Calcite	Clay	Free Silica
Micrite	DGJV-7	100.0	5.0	19.0
Silicified Micrite	PBJV-5	85.0	17.0	19.5
	PBJV-7	79.0	5.2	31.7
	PBJV-12	63.0	5.7	45.0

Table 4. Results of norm calculations listed in percent.

Vertebrate fossils are not numerous in the Bone Basin Member. The assemblage collected by Kuenzi (1966) includes ancestral rabbits (Palaeolagus), camels (?Poebrotherium), horses (Mesohippus), rhinoceros (? Caenopus or Trigonias), tragulids (Leptomeryx), mustelids (cf. Daphoencyon), oreodonts (Merycoidon), titantotheres (? Brontothere), and anthracotheres(? Anthracothere). The vertebrate assemblage implies an early Oligocene (Chadronian) age for the Bone Basin Member which is older than the Passamari Member in the upper Ruby Valley.

INTERPRETATION

Kuenzi (1966) and Axelrod (1984) interpreted the Bone Basin Member carbonates as representing deposition in shallow lakes and ponds on a low lying floodplain. This interpretation is adequate for the carbonate units that contain an abundant invertebrate fossil assemblage and high calcite content, but it fails to account for the irregularly shaped "ooids" and massive clastic units (0.7-12.0 m thick) which become increasingly more lithified toward their tops and are capped by silicified, rhizolithic carbonates.

Axelrod (1984, p. 39) interpreted the "ooids" in the Parrot Bench Section as ooliths which formed by "agitation in extensive lake margin flats". The nature of the "ooids"— their irregular sizes and shapes, their lack of radial fibrous textures, and the lack of associated sedimentary structures indicative of wave action—does not support such an interpretation.

The textures present in the Bone Basin Member's silicified carbonates are indicative of caliche. Most of the world's massive caliche deposits occur in Tertiary, fluvial sands and gravels (Reeves, 1976) and typically are silica cemented and display increasing lithification toward the tops of units, concretionary glaebules, massive bedding, and rhizolithic mats (Reeves, 1976). Esteban and Klappa (1983) believe rhizoliths (root casts) are reliable indicators of subaerial exposure.

A few of the limestones in Bone Basin, Jefferson Valley are interpreted to have precipitated in shallow ponds. The occurrence of trough-cross-stratified sands lower in the Jefferson River Section suggests that the ponds formed on or adjacent to a fluvial flood plain. The shallow ponds supported a limited invertebrate fauna and never became saline enough to precipitate evaporite minerals. Caliche development on fluvial flood plains in arid environments is common (Reeves, 1976).

The Bone Basin Member of the Renova Formation is exposed only in Bone Basin in the Jefferson Valley. Whether these deposits were associated with a much larger lacustrine system can not be determined from the section.

CARBONATE DEPOSITION

Tertiary carbonates in western Montana display a variety of textural and compositional features indicating deposition in diverse environments. Textural features include algal laminations, evaporite mineral molds, collapse breccias, neomorphic spar, root casts, glaebules, and patchy silica replacement. Compositional variation includes the presence or absence of evaporite minerals, fossils, silica cements, and magnesium and potassium clay minerals. The interpreted Tertiary environments resulting in carbonate deposition include: ephemeral alkaline lakes and ponds, alkaline or hydrothermal springs, and caliche soils. Evidence of similar Tertiary environments is not restricted to western Montana. Lacustrine and hydrothermal carbonates occur in the Eocene Green River Formation in Utah and Wyoming (Bradley, 1929; Eugster and Hardie, 1975; Surdam and Wolfbauer, 1975; Smoot, 1978, 1983); and lacustrine and pedogenic carbonates occur in the Late Arikareen Harrison Formation in Nebraska and Wyoming (Hunt, 1985).

The bulk of Tertiary carbonate deposits in western Montana are endogenic. No allogenic Paleozoic or Mesozoic carbonate clasts were found in any of the basins. The carbonates are interpreted to have precipitated from organic and inorganic processes. Organically produced carbonate tests make up only a fraction of Tertiary carbonate deposits. The interpreted processes resulting in inorganic precipitation of carbonate minerals include evaporative concentration of solutes, biological extraction of carbon dioxide from the water column, and a physical release of carbon dioxide from the water column.

The Green River and Harrison Formations represent deposition influenced by arid (Smoot, 1978) to semi-arid (Hunt, 1985) climatic conditions. Thompson et al. (1982) suggested the climate in western Montana during deposition of the Renova Formation was also arid to semi-arid. Vertebrate fossil data, sedimentary data, and mineral data in Tertiary deposits in the upper Ruby and Jefferson Valleys support an arid to semi-arid climatic interpretation.

Cursorial, grazing animals dominate Tertiary vertebrate fossil assemblages in the upper Ruby and Jefferson Valleys. Related modern forms of horses, camels, deer, and tragulids generally live on grassy steppes and plains characterized by arid to semi-arid climates. Fields etal. (1985) stated the trend in mammalian faunas through Renova time was toward adaptations suited for aridity.

Sedimentary structures present in the Renova Formation support an arid to semi-arid climatic interpretation. Trough-cross-stratified beds are the most common sedimentary feature and are interpreted to represent braided stream channels. Braided stream channels form when sediment load is high and bank resistance is low (Reineck and Singh, 1980, p. 260). Braided streams are common in arid climates because vegetation is sparse and not capable of stabilizing stream banks and soil horizons. Massive bedding, evident in the Campbell Place Section, also indicates that sediment load was high. Sediments in the Campbell Place Section are interpreted to represent mudflow deposits.

Inorganic calcite contributes to the bulk of Tertiary carbonate deposits in western Montana. Kelts and Hsü (1978) state inorganic carbonate may precipitate in alkaline and saline lakes in arid regions or in fresh to brackish water lakes in humid regions. The alkaline nature of Tertiary carbonate environments in western Montana is reflected by their mineral content and implies that the climate was influenced by arid to semi-arid conditions.

CONCLUSIONS

Tertiary carbonate deposits in western Montana have long been interpreted as lacustrine limestones (Kuenzi, 1966; Monroe, 1976, 1981; Axelrod, 1984). Reexamination of the textural, mineral, floral, faunal, and chemical aspects of Tertiary carbonates in the upper Ruby and Jefferson Valleys suggests their depositional processes and environments were quite diverse. Three carbonate depositional processes are interpreted to have operated in these basins. The first process operative in the upper Ruby and Jefferson Valleys involved deposition due to evaporative concentration of solutes in shallow ephemeral saline lakes, ponds, marshes and caliche soils which lead to supersaturation and precipitation of carbonate minerals. The second process involved biological extraction of carbon dioxide from the water column leading to precipitation of carbonate minerals. The last process occurred in the upper Ruby Valley alkaline or hydrothermal spring environments from the physical release of carbon dioxide.

Timing of deposition in each of these basins varies, but the carbonates all developed sometime during deposition of the Renova Formation (20 to 42 Ma). Sedimentary data, vertebrate fossil data, and mineral data indicate the prevailing Renova climate was arid to semi-arid.

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GEOLOGICAL CURIOSITIES OF SOUTHWESTERN MONTANA

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ABSTRACT

Southwest Montana contains numerous geological curiosities, and many geologic mysteries remain to be solved. For example, a meteorite impact site has been identified in southern Beaverhead County, although the age and dimensions of the disturbance are poorly known. The location of Lewis and Clark's Beaverhead rock could possibly be south of Dillon, MT, rather than at the official site between Dillon and Twin Bridges. Many workers have assumed that diamictons (poorly sorted gravels) and exotic blocks (boulders deposited far from outcrops) were transported by glaciers, although a non-glacial origin seems likely because the deposits predate knkown glacial advances. In the Ruby Range near Sweetwater Pass, almandine garnets as large as grapefruit occur in Archean amphibolite schist. Gold nuggets as large as 178 ounces may, in part, date from a period of semitropical climatic conditions in Miocene time, when gold particles were effectively released from host rocks. The 2.5 million ounces of gold in Alder Gulch-Virginia City gold placers could have been derived from the source rocks containing near the crustal abundance of gold (1-10 ppb Au) if weathering and erosin of these source rocks has continued since the Miocene. Ringing Rocks, near Butte, chim when struck because a weathered rind raises the resonant frequency of the monzonite boulders. Reigonal drainage development is poorly knonw, although it appears that parts of some rivers, including Grasshopper Creek, have reversed course. The study of rock glaciers could provide information on climatic variations since the end of the Pleistocence.

INTRODUCTION

Southwest Montana is known for exceptional geology, and contains a number of geological attractions that are so unique and unusual that they deserve to be called "curiosities". A meteorite impact site, huge crystals, gold nuggets, fabulously rich gold placers, rivers that have reversed course, and rocks that ring like bells are unexpected phenomena that are the icing on the cake in a land of great geology. Geologists have always known about these scattered wonders, although some of these attractions should also be of interest to the general public.

The present paper is a summary of a few of the many geological curiosities in southwest Montana. The purpose of this paper is to promote enjoyment of our geologic treasures by all citizens, to stimulate research interest in solving some geologic mysteries, and to suggest that some geologic sites are special enough to warrant protection (even from hammer-wielding geologists!). I learned about most of these sites through oral communication with other geologists, rather than from literature sources. Surely there are many other uniquely interesting sites that should be added to this list.

BEAVERHEAD IMPACT STRUCTURE

There is little doubt that a meteorite struck southwestern Montana, southwest of Dillon, in the far distant past. Shattered rock, commonly forming small cone-shaped structures (shatter cones), occurs in billion-year old quartzite throughout an area greater than 70 mi^2 in southern Beaverhead County (Hargraves and other, 1990;

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Fiske and Hargraves, 1991). Intensely broken rock and shatter cones occur in other parts of the world in circular structures interpreted as meteorite impact craters, which strongly suggests that southwest Montana was struck by a large meteorite. The structure is so old that nothing is left of a circularcrater, although the distribution of shocked rocks suggests that the crater was possibly larger than 60 mi in diameter (Hargraves and others, 1990).

The age of impact is loosely bracketed between the 1.4 billion year age of Belt quartzite units that have been shattered, and the 350 million year (Ma) age of unshattered limestone which overlies the quartzite in some areas. Additional information is needed to better constrain the time of impact. A road log tour of the impact site is given in Hargraves (1993).

BEAVERHEAD ROCK CONTROVERSY

The true location of Lewis and Clark's famous Beaverhead rock is uncertain (this is less a geological curiosity than a historical one, but presents an interesting challenge for some detective work). The "Beaver's Head", now named "Beaverhead Rock", is a landmark that was recognized by Sacajawea, a Shoshone woman who accompanied the Lewis and Clark expedition as they crossed western Montana during the summer of 1805 on their way to the Pacific Ocean. On Thursday, August 8, 1805, Meriwether Lewis recorded the following observations in his journal (DeVoto, 1953):

> "the Indian woman recognized the point of a high plain to our right which she informed us was not very distant from the summer retreat of her nation on a river beyond the mountains which runs to the west. This hill she says her nation calls the beaver's head from a conceived re[se]mblance of it's figure to the head of that animal."

In the area near Dillon, Montana, there are two possible candidates for this important historical landmark. The rock officially known as Beaverhead Rock (namesake for the Beaverhead River, Beaverhead County, Beaverhead National Forest, etc.) is a mass of gray Mission Canyon Limestone located along the Beaverhead River between Dillon and Twin Bridges. However, this well-known outcrop resembles the whole beaver, not just the head. In contrast, a rounded mass of gray rhyolite (dated at about 48 Ma by radioactive decay) located southwest of Dillon, on the west side of the highway near Barretts, resembles only a beaver's head. The rock near Dillon also makes a better landmark for a trail running west to Idaho because it marks the mouth of the canyon that runs south, and which the expedition followed to reach Lemhi Pass by way of Grant, MT. Therefore, there are good reasons why the rock near Dillon may, indeed, be the famous rock. However, navigational data from Lewis and Clark's journals suggests that the official designation of Beaverhead Rock is correct. On Aug. 7, 1805, the party camped on "the forks of the Jefferson River", meaning the confluence of the Big Hole and Ruby Creek, near the site of present Twin Bridges. The official Beaverhead Rock would have come into view within 5 mi on the next day out, and this is when Sacajawea identified the landmark. In contrast, the rock near Dillon is about 36 mi from Twin Bridges, more than one day's walk for the party, and may not have been visible for several days.

DIAMICTONS AND EXOTIC BLOCKS

Poorly sorted, unconsolidated, matrix-supported boulder deposits (diamictons) occur throughout the Rocky Mountains, as do boulders deposited at some distance from their original outcrops, known as "exotic blocks". In most cases it is difficult to establish how these rocks were transported to their site of deposition. However, careful efforts should be made to interpret their meaning, because these deposits provide an important record of geologic history. Alden (1953) describes many diamictons and exotic blocks scattered throughout southwest Montana, and the Gravelly Range is named for deposits of problematic boulders that crown the ridge. Diamictons have also been mapped in the Anaconda Range (Poulter, 1956; Wallace and other, 1992), and along Grasshopper Creek between Polaris and Elkhorn in the Pioneer Mountains (Pearson and Zen, 1985). In addition, a sequence of diamictons (interpreted as Pliocene(?)/early Pleistocene till), reportedly greater than 600 ft thick, has been mapped in the region ofthe Grasshopper Creek valley and the Horse Prairie basin (Turner and others, 1989). Exotic blocks also are present in the Beaverhead Group east of Bannack, and in the Flathead Formation near Argenta.

Possible origins for diamictons and exotic blocks include glacial processes, fluvial processes, colluvial processes, mass-movements (landslides), and flows (debris flows and mudflows). During the early 1900's, when initial geologic studies of the Rocky Mountains were completed, geologists favored a glacial origin for unusual boulder deposits (e.g. Emmons and Calkins, 1913; Blackwelder, 1915; Atwood and Atwood, 1948, p. 607-608). Little was known then about the number and extent of Pleistocene glacial advances or the timing of canyon cutting in relation to Pleistocene glaciations. However, modern classifications of glacial advances indicate that in most glaciated valleys of the Rocky Mountains, glaciers of the Bull Lake (Early Wisconsin) glaciation (Holmes and Moss, 1955) flowed farthest from their source areas (Richmond, 1965). On this basis, Madole and Shroba (1979) stated that any diamictons that are more extensive than till of the Bull Lake Glaciation are probably non-glacial in origin. Furthermore, geomorphic studies indicate that the regional period of canyon cutting that isolated high-level diamictons in the southern Rocky mountains occurred prior to all known Pleistocene glaciations (Scott, 1975), and the northern Rocky Mountains appear to have had a similar history. In summary, modern studies have demonstrated that many boulder deposits originally mapped as glacial drift during the early 1900's are, in fact, non-glacial deposits, or else their glacial origin is suspect (Richmond, 1965, 1970; Madole, 1982). Consequently, diamictons in southwest Montana should be examined carefully, with due regard for problems of explanation and extrapolation (Schumm, 1991). Interpretations of origin should be based on sedimentologic data and characteristics of depositional sedimentary environments (Reinecke and Singh, 1980).

Diamictons interpreted as Pliocene(?)/early Pleistocene glacial till by Turner and others (1989) are far beyond the end moraines of known glaciers, and Ruppel and other (1983) have mapped non-glacial Tertiary basin-fill deposits (map unit Tt; tuffaceous sedimentary rocks) in many of the areas mapped as till by Turner and others (1989, fig. 1). Therefore, it is likely that these diamictons are non-glacial.

East of Bannack, exotic blocks have been described north of Grasshopper Creek, near the top of the Beaverhead group (Pearson and Childs, 1989). The blocks consist of Madison Limestone and are as much as 1 mi long. The blocks had been previously interpreted as klippe related to thrust faulting, although Pearson and Childs (1989, p.57) suggest the blocks were emplaced by processes that included "sliding, rolling, and gliding down a slope".

One of the most puzzling examples of diamictons and exotic blocks occurs in the normally medium-to-coarse-grained Middle Cambrian Flathead Sandstone near Argenta, MT (R.C. Pearson, pers. commun, 9/94). Quartzite boulders (some rounded) have been recognized in the Flathead at two localities about 1 mi apart. At the first site, in a small valley along Rattlesnake Creek upstream from Argenta on the north side of the road (SE 1/4, NE 1/4 sec. 23, T. 6 S., R. 11 W.), boulders as long as 30 ft exhibit smooth edges and percussion marks (small round fractures formed by high-velocity impacts; Reinecke and Singh, 1980, p. 143). This area was mapped as Quaternary terraces deposited along north-trending faults (Myers, 1952), although the deposits appear to be part of the Cambrian unit. The second site is at the top of the ridge south of the Renamine (W ½ sec. 18, T. 6 S., r. 10 W.), where numerous well-rounded quartzite boulders up to 3 ft long form the crest of the ridge, near the top of the Flathead formation. In addition, Cambrian rock sequences between these two sites show drastic changes in thickness within short distances which maybe explained by faults (Myers, 1952).

Coarse, poorly-sorted boulder deposits conflict with the depositional environment for the Flathead, which commonly has been described as "slow but steady marine invasion across a subaerial erosion surface" (Robinson, 1963, p. 17). Regional studies indicate thickness variations that suggest that several topographic highs or islands were present in the Flathead sea, and perhaps Argenta was near the marginsof steep topographic slopes that generated mass movements. However, a possible (but outrageous) hypothesis is that the meteorite that caused the Beaverhead impact structure resulted in the unusual boulder deposits in the Flathead. The age constraints on the meteorite impact include the Cambrian, so it is possible that a meteorite could have struck the sea after the Flathead Sandstone had consolidated, and a tidal wave could have piled up (and caused percussion marks on) boulders at Argenta. If this suggestion has merit, these sedimentary deposits would date the time of meteorite impact at about 540 Ma.

GIANT GARNETS OF SWEETWATER PASS

Garnets (not rubies) can be found scattered throughout creek bottoms in the Ruby Range, east of Dillon, and along the shores of Ruby Reservoir. These garnets generally are dark red, brownish-red, or purplish-red and are the size of pin-heads to wheat grains, although dodecahedral garnets as much as 10 inches in diameter occur in residual garnet placer deposits on ridges near Sweetwater Pass, which was the original source for some of the scattered garnet grains that occur downstream.

Almandine garnet (iron-aluminum garnet; probably the most common variety of garnet) commonly occurs in mica schists formed by metamorphism of shale. In this case, lakebeds several billions of years old were buried deeply (several miles), the clay minerals recrystallized to high-temperature minerals (mostly mica and garnets) and now occur in a black, platy, mica schist and amphibolite. In some areas, where conditions were just right, a rock called "garnetite" was formed, which consists of massive garnet. Although Ruby Range garnets are abundant and large in size, they are so highly fractured that few of these stones are useful for jewelry. The best garnets for jewelry are those that have already been transported away from the range, and fractured portions of the crystals have been removed by erosion, although these tend to be quite small. It is possible to obtain larger clear pieces of garnet by rolling coarse fragments of garnet in a tumbling machine for a few days.

Other occurrences of large almandine crystals include green-coated dodecahedrons as large as 6" in diameter from chlorite schist in the Sedalia mine, near Saida, Colorado (Sinkankas, 1964, p. 535), and very large crystals from chlorite schist in Madagascar (Dana, 1949, p. 596).

GOLD NUGGETS

Gold nuggets are Montana's most sought-after geological curiosity, and several thousand have been found over the years, mostly in west-central Montana. Despite the popularity of metal detectors, the largest nuggets were mostly found during the late 1800's and early 1900's by gold placer miners (Table 1). However, in 1989 a 29 oz gold nugget was found in Cooley Gulch in the Highland Mountains 15 mi south of Butte. The nugget (named "Montana Centennial Nugget") was found by the Stratton Brothers while placer mining. The nugget was bought by Crown Buttes Mines and donated to Montana Tech's Mineral Museum, where it is currently on display. The nugget apparently is the largest nugget found in Montana since 1927, when a 57 oz nugget was found in McClellan Gulch, near Lincoln, MT.

Little research has been done on the modes of occurrence and processes of formation Montana's gold nuggets, despite obvious economic implications. Many of the largest gold nuggets have been found, not in placer stream gravels, but in decomposed rock near drainage divides in non-glaciated areas, and a surprising number come from contact zones between granitic stocks and Paleozoic sedimentary rocks. For example, Montana's largest nugget (178 oz) came from a contact zone between an outlier of the Cretaceous Blackfoot City stock and Mission Canyon Limestone on an unglaciated drainage divide at an elevation of 6,400 ft at the head of Deadwood gulch (9 mi N of Elliston, MT; Loen, 1990). In many cases, such nugget-bearing ground is characterized by "a peculiar reddish color" (Alderson, 1908), probably caused by accumulations of hematite. In addition, nuggets commonly are attached to bedrock bya "white cement" (Alderson, 1908), which probably is caliche. Deposits having these characteristics (hematite and caliche) in non-glacial areas are likely well-developed soils, including paleosols developed during the Tertiary Period. Loen (1989) has pointed out that the Tertiary was favorable for the chemical release of gold form source rocks and concentration in regolith, and many of Montana's large gold nuggets could well occur in eluvial material that started forming during the warm, wet climatic intervals of the Miocene, or earlier. In some cases, these old Tertiary placers have been disrupted by Pleistocene glaciers, and nuggets are recovered from till, such as along Gold Creek in the Flint Creek Range (Loen, 1994).

A popular concept is that nuggets "grow" in streams by chemical accretion processes (Boyle, 1980). However, detailed studies of nuggets and placer grains and flakes in west-central Montana (Loen, 1993; 1994) could not verify this concept, and support the interpretation that gold nuggets have weathered naturally from lode gold deposits, and then accumulated nearly in place. The best evidence that nuggets weather naturally from host rocks is the common occurrence of primary mineral inclusions, including vein quartz crystals, iron oxides, and sulfide minerals (in polished section).

ORIGIN OF VIRGINIA CITY/ALDER GULCH PLACER GOLD

Alder Gulch is one of the most productive gold placers (for its size) in the world (Douglass, 1905; Lyden, 1948; Shawe and Wier, 1989). Yet, prospectors have struggled without success for more than 130 years to develop viable lode mines in the placer source area at the head of Alder Gulch (Alderson, 1908). Mass-balance characteristics of the placer are remarkable (Loen, 1992). About 2.5 million oz of gold were derived from deposits mapped as Quaternary alluvium (Vitaliano and Cordua, 1979; 2-3 Ma), from a source area covering 38-46 mi^2. This equals 1.2 million oz/Ma, or more than one ounce of gold per year (alternatively, 400,000 to 1 million oz were derived per cubic mile of rock eroded). At this rate, one should be able to watch nuggets tumble from outcrops! Such impossibility makes one suppose that the gold had been washed in from some other source area, although there are little or no data supporting such a speculation (and, in fact, a 38 oz nugget has been found in the headwaters; table 1).

The key to understanding Alder Gulch is concentrating on the age and origin of the auriferous gravel. The only constraint on the age of the gravel is that is overlies ash beds (correlated with Oligocene to early Miocene Renova Fm; Fields and others, 1985) in the Ruby Valley (Winchell, 1914, p. 58), and accumulation continued throughout the Quaternary because the valley was not glaciated. Therefore, the gravels could have accumulated since the middle Miocene (15 Ma), or earlier. Considering this time span, mass-balance calculations (see Loen, 1992, p. 1628)suggest that source rocks contained near the crustal abundance of gold for regionally metamorphosed rocks (1.5-10.4 ppb Au; Crocket, 1991, table 1.4). In conclusion, there is not necessity for unusually rich source rocks at Alder Gulch--the 2.5 million ounces of placer gold is adequately explained by 15 million years of gradual fluvial erosion and concentration of gold from Archean source rocks having essentially background gold contents (this tentative conclusion should be tested by collection of sedimentologic data on placer gravels from the headwaters to Alder, and by measurements of the rate of change of gold particle morphology in Alder Gulch; see Loen, 1993).

RINGING ROCKS

On Dry Mountain, east of the Continental Divide (between Butte and Whitehall) is a heap of rusty-brown boulders that ring like bells when tapped with a hammer. Little indication of anything unusual is given by the composition, appearance, and age of the rocks. They are an extremely tough, coarse-grained variety of mafic monzonite (Prostka, 1966; Butler, 1983). This rock forms a rim on a roughly circular body of granite, about half a mile across (in sec. 4 and 9, T. 2 N., R. 5 W.). The rocks are bare except for scattered lichens, and weathering has affected only the outer inch of the ringing boulders. Many of the rocks have weathered into irregular forms, partly controlled by joints. Age dating has given an age of 78.2±3.1 Ma (Prostka, 1966), roughly the same age as other plutons in the Boulder Batholith. Yet granite boulders of about the same age in other areas, such as granites at Homestake Pass, thud rather than chime. A rock quarry was once developed at the Ringing Rocks, although in 1970 the claim was declared null and void (Berg, 1974, p. 15).

Some of the rocks have better musical qualities than others. For instance, the rocks with the best tone generally are large (4-7 ft), rather flat, and have protruding points or ribs. Also, the best "ringers" are lying free on the rock pile, rather than being anchored in soil. The pitch of the stones varies from a deep "Liberty Bell" sound to high-pitched chimes.

Seventy-nine measurements of pitch were done of different ringing rocks using an electronic tuner. Each of the 12 notes in the chromatic scale were detected (abundance ranges from 1 to 22%). B was the most commonly recorded not (22%) followed by E (14%) and C (13%). In some cases, different parts of the same rocks give different musical pitches and tone qualities. For example one boulder gave B, D# and E notes when struck if different places. However, no correlation was evident between pitch and boulder shape or size. Considerable confusion on the part of the electronic tuner indicates that the rocks produce a complex mixture of musical overtones (harmonics) that also are typical of forged iron bells.

Ringing rocks also occur in the Appalachian

Table 1. Montana gold nuggets (compiled from Alderson, 1908, Lyden, 1948, and unpub. data).

Locality	Weight (troy ounces)	Date of Discovery
Deadwood Gulch	178	October, 1865
Nelson Gulch	100	July 4, 1865
Highland Gulch	70	1871
Highland Gulch	60	Jan. 24, 1908
McClellan Gulch	57	1927
McClellan Gulch	47.7	April 28, 1879
Alder Gulch	38	1860's
California Gulch	32	1800's
Bilk Gulch	32	1800's
Cooley Gulch	29	1989
Confederate Gulch	27	April, 1871
Gold Creek (Pineau mine)	27	early 1900's
Scratchgravel Hills	27.5	1876
Scratchgravel Hills	24	1875
Gold Creek (Master mine)	24	early 1900's
Scratchgravel Hills	18.75	1875

Mountains of Pennsylvania and New Jersey. Studies of Appalachian ringing rocks suggest that the ringing quality is produced in rocks that are under large internal stresses (Gibbons and Schlossman, 1970). The stress apparently is caused by the weathering of the outer inch of so of the otherwise fresh, dry rock. A volume change accompanies weathering reactions, as water is added to the structure of minerals (pyroxene, feldspar) to form alteration minerals. This causes an expansion of the outer shell of the boulders and a corresponding tension in the unweathered core. The tension increases the resonant frequency of the material enough to produce a ringing effect, and the ringing note will vary according to boulder size, shape, and the degree of weathering. This explanation makes sense at Ringing Rocks, because the musical boulders display light-colored weathering rinds 1 inch thick, and thoroughly weathered boulders occurring in wetter, shaded areas do not ring.

RIVERS RUNNING IN REVERSE

In Montana, a land characterized by geologic upheavals, it should be no surprise that some rivers have drastically changed course, or even reversed their flow direction. In fact, the modern drainage pattern developed relatively recently (within the last 2-3 Ma), and consists of patched-together segments of earlier river systems. Processes that have modified the drainage system include block faulting, extrusion of volcanic flows, glaciation, stream capture caused by headward erosion, and Pleistocene stream incision(possibly related to climatic change). Little research has been done on the history of Montana's drainage development, although such work might have significant economic, structural, and environmental implications.

The idea has long been proposed that regional drainage in southwest Montana previously was south to the Snake River (e.g. Atwood, 1917), although the actual course of paleovalleys has never been mapped out in detail. Remnants of a high-level gravel deposits suggest that the overall drainage pattern in the Dillon region may have once (4-10 million years ago) flowed from northwest to southeast (Sears and others, 1989), rather than the current northeastward direction towards the Missouri River. More work is needed, but there is little doubt that the early drainage nets of the intermontane basins have been greatly disrupted. The Big Hole River, for example flows north in the Tertiary Big Hole basin, then flows southeastward through mainly Quaternary stream canyons before emptying into the Jefferson River in the Tertiary Jefferson basin. Portions of the river in different Tertiary basins were most likely separated prior to downcutting and integration of the stream system during the Pleistocene.

In some localities there is evidence of stream reversal, although details are unclear. For example, gold placer deposits along Grasshopper Creek, near Bannack, occur in high-level stream terraces ½ mi northwest of their likely source, the Bannack mining district. Grasshopper Creek currently flows southeast, so the gold occurrence indicates that Grasshopper Creek once drained south through the Tertiary basin to the west (Pearson and Childs, 1989, p. 54). This stream diversion may have been related to late Tertiary block faulting or basalt volcanism. Problematic gold placer deposits in paleovalleys have also been mined in the headwaters of Rochester Creek in the Highland Mtns (Lyden, 1948; Sahinen, 1939).

ROCK GLACIERS

Montana's ice glaciers melted away thousands of years ago, but another type of glacier, called "rock glaciers", or "block streams" have been accumulating in many of the mountain ranges of southwest Montana. Rock glaciers, consisting of masses of unsorted, loose rocks commonly surrounding a buried ice core, occur in glacial cirques and along the sides of most glacial valleys in the Anaconda, Highland, Tobacco Root, and Pioneer Mtns. Loose rock for rock glaciers is supplied, with the help of freeze/thaw cycles, form fractured rock outcrops in the cirque headwall or along the valley walls. Rock glaciers in Montana range in size from talus fields showing minor evidence (arcuate ridges) of downslope transport, to lobate and tongue-shaped features more than 1 mi long. The study of rock glacier growth over time helps to understand climatic fluctuations, because the amount of rock delivered to rock glaciers depends on the number and intensity of freeze/thaw cycles.

In southwest Montana, notable rock glaciers occur along most alpine valleys of the Anaconda Range (Wallace and others, 1992, p. 8; Note: rock glaciers and protalus ramparts are not shown on map), and along upper tributaries to Fish Creek in the Highland Mtns. In addition, rock glaciers as much as 1 mi long have been mapped in the upper headwaters of the South Boulder River, in the Tobacco Root Mtns (O'Neill, 1983). In the Pioneer Mtns, block streams occur on the southwest flank of Baldy Mtn, along Farlin Creek, and at the head of East Fork Dyce Creek (Pearson and Zen, 1985).

CONCLUSION

Many geological mysteries remain to be solved in western Montana. Investigations of the curiosities presented here mostly are still in the data-collection stage and several years of additional work are needed before reliable explanations can be formed, particularly regarding regional drainage development, origins for diamictons and exotic blocks, and processes of gold placer formation. Additional detailed geologicmapping is needed in most areas. Also, there is a need for a means of communicating southwest Montana's geology to the public, who increasingly are involved in decisions regarding the use of public lands and geologic resources.

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REGIONAL GEOPHYSICAL SETTING OF BEAVERHEAD COUNTY, MONTANA AND ADJACENT AREAS

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DISCUSSION

Aeromagnetic and gravity anomaly maps compiled from digital data sets published by the U.S. Geological Survey (Bankey, 1992; McCafferty, 1992) provide perspectives on subsurface manifestations of structure and lithology associated with major geologic features in the region (Kulik and Perry, 1988; Ruppel, 1993). Discontinuous northwest and northeast gravity lineations parallel the McCartney and Ruby range fault zones, respectively; comparable lineations suggest similar structures elsewhere in the subsurface. A prominent composite gravity low that exceeds 25 mGal in amplitude is associated with thick Tertiary sedimentary rocks of the Big Hole basin. To the northwest, parallel, but discontinuous northeast-trending lineations in the gravity and aeromagnetic anomaly data are attributed to faulting in the Great Falls tectonic zone (GFTZ) described by O'Neill and Lopez (1985). Interpretation (Kleinkopf, in press) of regional aeromagnetic and gravity anomaly data suggest that the GFTZ is a tectonic boundary that separates the Sapphire crustal block on the west from the Boulder batholith crustal block on the east. A distinctive complex gravity low is associated with granitic terrane of the Pioneer batholith. Similarly, complicated aeromagnetic anomaly patterns reflect different lithologies of the intrusive complex. Horseshoe-shaped patterns may reflect magmatic zonation of the Pioneer batholith, in part, possibly caused by destruction of magnetization by hydrothermal alteration (Hanna and other, 1993). Plots of locations of gold (Au) and silver (Ag) occurrences taken from the USGS digital MRDS (Mineral Resource Data System), are overlain on the anomaly maps in order to show spatial relations of mineralized areas with anomaly patterns that might be diagnostic for mineral occurrences in other areas.

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HOT SPRING GOLD IN SOUTHWEST MONTANA?

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ABSTRACT

Repeatedly broken and re-cemented siliceous breccias in a volcanic center in the upper part of Medicine Lodge Creek indicate prolonged hydrothermal activity. The center is a source for the Medicine Lodge or Challis volcanics in Medicine Lodge basin. Most of it is concealed by younger gravels, but it includes hydrothermally altered rhyolitic and basaltic rocks as well as the siliceous, jasperoidal breccias, and is overlain by hot spring and hot pond limestones. The volcanic center has most of the characteristics of those with associated epithermal gold, and may have been the source of the placer gold in Jeff Davis Creek. The only known mineral deposit associated with it, however, is the Sweeney or Bonanza II lead silver deposit.

Other hot spring deposits are widespread in southwest Montana. Some of them have been the sites of long continued hydrothermal activity, and should be considered as possible sources of gold, silver, and other mineral resources.

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