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Geology of the Sweetwater Canyon Area and Origin of Interbasinal Canyons, Southwestern Montana

James Carl Peterson
Western Michigan University

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I am grateful to Mr. John Anderson, Mr. Vern Schwartz, and other ranchers for their courtesy and hospitality. I am especially grateful to my wife, Carol, for assistance in the field, typing of the manuscript, and moral encouragement.

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Geology

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INTRODUCTION

Mountain ranges in southwestern Montana are separated by broad valleys which are commonly termed intermontane basins. These basins are partially filled with two unconformable depositional sequences of continental Tertiary strata (Kuenzi and Fields, 1968, 1971) that record major episodes of basin filling in the Late Eocene through Early Miocene and Late Miocene to Late Pliocene. Basins west of the Continental Divide are presently drained by the headwaters of the Columbia River, and those east of the divide by the Missouri River and its tributaries. Connecting the basins is a series of narrow, sinuous, hard-rock canyons which have been eroded into rocks commonly ranging in age from Precambrian to Cretaceous (Fig. 1).

Previous investigators (Atwood, 1916; Pardee, 1950; Alden, 1953; Lowell, 1957) have agreed that the interbasinal canyons are post-depositional features that formed during a late Cenozoic erosional episode. Most workers also consider superposition of streams from a Tertiary covermass to be the method of canyon formation. No positive evidence, however, has previously been found to support the postulation that the canyons are late Cenozoic features, and a divergence of opinion exists as to whether superposition was initiated in the Pliocene or Pleistocene.
Fig. 1. Index maps of southwestern Montana. A. Outline of southwestern Montana (crosshatched). B. Intermontane basins (stippled and lettered) and interbasinal canyons (numbered). Key to canyons: 1-3, outlet to the Great Plains, Gates of the Rocky Mountains, canyon at Hauser dam; 4, Canyon Ferry; 5, Lombard canyon; 6, canyon at Trident; 7, Madison canyon; 8, Hebgen canyon; 9, Jefferson canyon; 10, Ruby canyon; 11, Sweetwater canyon; 12, Clark canyon; 13, Lima canyon; 14, canyon at Wise River; 15, canyon north of Melrose; 16, canyon south of Melrose; 17, canyon at Bannock. Key to basins: a, Hilger valley; b, Townsend valley; c, Clarkston basin; d, Three Forks basin; e, Madison valley; f, Hebgen valley; g, Jefferson basin; h, lower Ruby basin; i, upper Ruby basin; j, Sweetwater basin; k, Beaverhead basin; l, Lima valley; m, Centennial valley; n, Grasshopper valley; o, Melrose valley; p, Deer Lodge pass; q, Big hole basin (modified after Pardee, 1950 and Alden, 1953).
In order to resolve these uncertainties a detailed study was made of the geology of the Sweetwater canyon area (Fig. 1) which lies in the headwaters of the Missouri River drainage system. Detailed mapping in the Sweetwater canyon area and radiometric dates obtained from the U.S. Geological Survey demonstrate, for the first time, a late Cenozoic origin for a canyon within the Missouri River system. Furthermore, the time of formation of Sweetwater canyon can be used to postulate that other interbasinal canyons in the Missouri River drainage system are also late Cenozoic features.
GEOLOGY OF THE SWEETWATER CANYON AREA

Location and Previous Investigations

The Sweetwater canyon map area lies in Madison County, Montana, approximately 20 miles southeast of Dillon and about 20 miles southwest of Alder (Fig. 2). The map area comprises 36 square miles and includes parts of the Sweetwater and upper Ruby basins. The basins are bordered by the Ruby Mountains on the north and west, the Blacktail Mountains on the south, and the Gravelly Range on the east. The Sweetwater and upper Ruby basins are connected by Sweetwater canyon, a narrow gorge cut into resistant rocks (Fig. 2).

In 1871, Ferdinand V. Hayden headed a geological party through the upper Ruby basin and described the rocks exposed in Sweetwater canyon (Hayden, 1872). No modern studies of the area were carried out until 1947, when John A. Dorr and Walter H. Wheeler began investigations in the upper Ruby basin, immediately adjacent to the Sweetwater canyon area. The results of their study, largely paleontological, were published in 1964 (Dorr and Wheeler, 1964). Monroe (1974) has completed a detailed stratigraphic and paleontologic restudy of part of the upper Ruby basin.
Fig. 2. Index map and generalized geologic map of the Sweetwater canyon area and vicinity (modified after Ross et al., 1955). Fold axes and fault traces are omitted. Heavily outlined area encloses that part of the Sweetwater canyon area covered by the detailed geologic map in Plate 1.
Methods of Investigation

During the summer of 1973, 25 days were spent in the field collecting samples and mapping with the aid of areal photographs. Quaternary deposits and pre-basin rocks were mapped only in a reconnaissance manner, but Tertiary strata, and their contacts with other rocks, were mapped in detail. The map data were later transferred to 7 1/2 minute topographic quadrangle maps, and the final map was drafted on reverse-reading cronaflex autopositives of the 7 1/2 minute quadrangles. Three stratigraphic sections were measured using a Jacob staff and tape measure. Samples were collected at each change in lithology. No fossils were collected in the map area, but faunal lists and age interpretations for fossils from University of Montana fossil vertebrate localities located in, and adjacent to the map area were obtained (Stewart Monroe, written communication).

Laboratory investigations included study of rock samples with a binocular microscope and petrographic examination of 40 thin sections. Mudstone samples were analyzed for clay content by X-ray diffraction, using both oriented and unoriented sample mounts.

Terminology

Nomenclature used in this report for sand, gravel and mud mixtures; sand, silt and clay mixtures; and terrigenous-
carbonate mixtures follows Folk (1974). However, rocks composed of silt and clay mixtures are designated mudstones, except in rocks composed predominantly of silt-sized grains, which are designated siltstones. Determination of sorting values and textural maturity follows Folk (1974), and a Powers (1953) roundness chart was used for determining roundness.

The following abbreviations are used: MV refers to University of Montana vertebrate localities. P-87-B and similar symbols are designations entered in my field notes. The first letter designates the data collector (Peterson), and the last letter specifies the sample collected. The number refers to the location of data collection and corresponds to a numbered point on an areal photograph.

Pre-basin Rocks

Precambrian metamorphic rocks are exposed in outcrops adjacent to the Sweetwater and upper Ruby basins, and in Sweetwater canyon (Fig. 2; Pl. 1). No pre-basin rocks younger than Precambrian exist in the map area, but Paleozoic and Mesozoic strata occur at the eastern margin of the upper Ruby basin. The Precambrian rocks belong to the Pre-Cherry Creek Group, and consist largely of coarse-grained banded gneiss, and smaller amounts of schist and amphibolite. Petrographic analysis of a typical sample (thin section P-204-A) showed the rock to be a light-colored, banded,
biotite-hornblende-quartz-feldspar gneiss with minor amounts of magnetite, garnet, and zircon. The quartz, comprising approximately 25 percent of the rock, is commonly fractured, and shows evidence of strain. Potassium feldspar, largely microcline, is far more abundant than plagioclase, and constitutes about 60 percent of the rock.

Foliation in the Pre-Cherry Creek strata, which generally parallels original bedding (Heinrich, 1960) strikes northeast and generally dips northwest at 60 to 90 degrees. These multiply deformed rocks are probably 3.1 ± 0.3 billion years old, and were last metamorphosed 1.6 billion years ago (Giletti, 1966).

Tertiary Stratigraphy, Bozeman Group

Continental Tertiary basin-fill deposits of fluvial, lacustrine, and eolian origin crop out in the Sweetwater canyon area, in both the Sweetwater and upper Ruby basins. These rocks comprise the Bozeman Group (Robinson, 1963) and have a thickness of greater than 3000 feet (Monroe, 1974). The strata of the Bozeman Group unconformably overlie the Precambrian metamorphic rocks of the Pre-Cherry Creek Group and are in turn unconformably overlain by a thin veneer of Quaternary deposits. Tertiary basin-fill strata range in age from Early Oligocene to Early and possibly Middle Pliocene (Monroe, personal communication) and are separated into two lithologically distinct mappable units (Pl. 1).
These map units are assigned to the Renova Formation (Kuenzi and Fields, 1971), which consists chiefly of fine-grained strata ranging in age from Late Eocene through Early Miocene, and the Sixmile Creek Formation (Robinson, 1967), which consists chiefly of coarse-grained deposits, and ranges in age from Late Miocene to Middle Pliocene. In the Sweetwater canyon area the two formations are separated by an unconformity recording a Middle Miocene episode of erosion (Monroe, 1974).

Renova Formation

Name, stratigraphic position, and thickness

The lower sequence of the Bozeman Group has been named the Renova Formation in the Jefferson basin, where the natural unity of the sequence was demonstrated (Kuenzi and Fields, 1971). In the upper Ruby basin, the predominantly fine-grained strata of the Renova Formation lie unconformably on pre-basin rocks, and are in turn unconformably overlain by the chiefly coarse-grained strata of the Sixmile Creek Formation. In the upper Ruby basin, Renova strata reach a thickness of at least 1800 feet (Monroe, 1974).

Distribution and topographic expression

Strata of the Renova Formation crop out over an area of approximately 5 square miles in the Sweetwater canyon map area. These rocks are exposed in the upper Ruby basin...
in a band about a mile wide along the course of Sweetwater Creek as it passes through Sweetwater canyon, and in smaller patches to the south (Pl. 1). Renova strata are not exposed in the Sweetwater basin but probably underlie Sixmile Creek strata.

Because of their fine-grained nature and poor induration, Renova deposits are slope formers, and exposures are generally poor. These slopes are locally interrupted, however, by small ledges due to thin layers of sandstone interbedded with the finer-grained strata.

**Measured sections and lithology**

Two sections of Renova strata were measured and designated Measured Section A and Measured Section B. Section A exposes 110 feet of strata and was measured in the upper Ruby basin in the NE 1/4, NW 1/4, sec. 17; the SW 1/4, NW 1/4, sec. 17, T. 9 S., R. 5 W. The base of the section is covered with alluvium, and the top is unconformably overlain by Sixmile Creek strata (Pl. 1; Fig. 3; See Appendix for lithologic descriptions). Although Renova strata are characteristically poorly indurated and friable, a localized area of these deposits is extensively altered, causing them to be very well indurated. These rocks, mapped as a separate unit, will be referred to as "altered Renova" strata. Measured Section B exposes 132 feet of altered Renova strata and was measured in Sweetwater canyon in the
Fig. 3. Measured Section A of Renova Formation strata. P-82-B refers to thin section designation; small numbers at hachures are at 10 foot intervals; larger numbers refer to lithologic descriptions in Appendix (See Pl. 1 for location).
NE 1/4, SW 1/4, sec. 4, T. 9 S., R. 5 W., (Pl. 1; Fig. 4; See Appendix for lithologic descriptions). Based on the two measured sections which have a combined thickness of 242 feet, Renova strata in the Sweetwater canyon area are composed of approximately 69 percent montmorillonite mudstone, 14 percent vitric siltstone, 12 percent arkose and vitric arkose, 5 percent vitric arenite and feldspathic vitric arenite, and trace amounts of conglomerate and chert. All gradations exist texturally and mineralogically between the major rock types.

**Mudstone** The mudstones of the Renova Formation are commonly light gray when dry and light olive when wet. Alternating wet and dry periods cause swelling and shrinkage of clay minerals, which results in a cracked, popcorn-like weathered surface. Due to a mixture of clay, silt, and sand-sized particles, sorting is poor ($\phi > 1.50$ phi units). Thin sections indicate the presence of approximately 20 percent sand composed predominantly of quartz, potassium feldspar, metamorphic rock fragments, and volcanic glass; lesser amounts of plagioclase, mudstone clasts, and chert; and trace quantities of biotite, garnet, and opaques (Pl. 2, figs. 1, 2, 5).

Quartz occurs in angular grains ranging in size from coarse silt to sand. It is characteristically cracked, strained, and show undulose extinction. Potassium feldspar,
Fig. 4. Measured Section B of altered Renova strata.
P-181-A and similar designations refer to thin sections; small numbers at hachures are at 10 foot intervals; larger numbers refer to lithologic descriptions in Appendix (See Pl. 1 for location).
EXPLANATION OF PLATE 2

Photomicrographs of Rocks From the
Renova Formation (1-6) and Altered Renova Strata (5,6)
(magnification 35x)

Figure 1. Plain light. Sandy mudstone (P-170-A). Coarse silt and sand-sized grains of quartz (q), microcline (m), unaltered volcanic glass (u), and severely altered volcanic glass (a) in a montmorillanite matrix (dark).

Figure 2. Crossed nicols. Same as Fig. 1.

Figure 3. Crossed nicols. Granular muddy medium sandstone: immature arkose (P-135-A). Granule-sized metamorphic rock fragment composed of quartz (q), potassium feldspar (k), and plagioclase (p) with angular sand-sized grains in a mud matrix. Note the abundant pore space (black).

Figure 4. Plain light. Muddy medium sandstone: immature vitric arkose (P-82-B). Sand-sized angular grains of quartz (q), feldspar (f), biotite (b) and mudstone clasts (mc) in a finer mud matrix (dark).

Figure 5. Plain light. Sandy mudstone (P-181-A). Silt-sized angular grains of quartz (q), microcline (m), and volcanic glass (v) in a montmorillanite matrix (dark).

Figure 6. Plain light. Muddy coarse sandstone: immature vitric arkose (P-181-J). Sand-sized subangular grains of quartz (q), microcline (m), altered volcanic glass (a) and a metamorphic rock fragment (mrf) in a montmorillanite matrix (gray).
predominantly microcline, is often perthitic and occurs in angular silt and sand-sized fragments. It varies from fresh to severely altered, and is the most common sand-sized constituent. Plagioclase is present in small amounts and ranges in composition from $\text{An}_{18}$ to $\text{An}_{28}$. Roughly one-half of the quartz and feldspar is included in metamorphic rock fragments, the component parts of which are identical to the monomineralic grains.

The occurrence of angular to rounded silt and sand-sized grains of chert and mudstone clasts, of essentially the same composition and texture as the host rock, are localized. Biotite in small flakes, garnet and magnetite occur with regularity but are present only in trace quantities.

Optical examination of volcanic glass present in Renova mudstones shows that it occurs in two distinct forms: mud-sized angular shards and sand-sized subrounded vesicular grains (Pl. 2, figs. 1, 2). The angular shards appear as white, clear, elongate fragments which have suffered little abrasion or alteration, except for slight corrosion at their borders. The larger vesicular grains appear as brownish, cloudy, equant fragments which are severely altered and abraded. Some of these grains have elongated vesicles, and apparently represent altered pumice grains.

X-ray diffraction analysis of both oriented and unoriented samples of the clay fraction indicated that the
clay is composed predominantly of montmorillonite. An un­treated disoriented sample exhibited a (001) lattice spacing of 15 Angstrom units; and glycolated and dessicated samples showed (001) spacings of 18 and 9 Angstrom units, respect­ively (Fig. 5). Montmorillonite composes up to 90 percent of some rock samples.

Siltstone As the percentage of silt- and sand-sized grains increases, the mudstones of the Renova Formation grade into siltstones. These rocks are characteristically light gray when dry and light olive when wet. Due to the mixture of clay, silt and sand-sized grains, sorting is poor ($\sigma > 1.50$ phi units). Thin sections reveal that the composition of the coarse fraction of these rocks is essentially identical to the mudstones described above.

Arkose, vitric arkose, and conglomerate All gradations exist between very fine arkoses and pebble conglomerates. These rocks are commonly yellowish gray on a fresh surface, but weather to light gray and yellow. The sandstones in the Renova strata occur as lenticular bodies within mudstones, and rarely exceed 5 feet in thickness. Within these bodies, gradations from fine sandstone to pebble conglomerate com­monly occur within a few inches. The largest grains are pebble-sized, and range up to about an inch in diameter.

The arkoses vary from immature to submature, depending on the amount of matrix. Cementing agents are either ab-
Fig. 5. Diffractograms of the (001) spacing of montmorillonite from mudstone sample P-82-A (unoriented mount). a, dessicated sample; b, glycolated sample; c, sample at room temperature and humidity. CuK$_\alpha$ radiation, 500 cps., scanning speed 10 min., chart speed 30" per hr., 30kv, 15ma.
sent or consist of calcite or silica (Pl. 2, figs. 3, 4, 6). Sorting values are commonly in excess of 1.00 phi units, and grains are subangular to angular.

Thin sections indicate that arkoses, vitric arkoses, and conglomerates of the Renova Formation are composed predominantly of quartz, potassium feldspar, metamorphic rock fragments and volcanic glass; lesser amounts of mudstone clasts, plagioclase and chert; and trace quantities of garnet, chlorite, muscovite, biotite and opaques (Pl. 2, figs. 3, 4, 6; Fig. 6; Table 1). The mineralogical character of the major components is essentially the same as that of the coarse fraction of the mudstones, described above.

**Vitric arenite and feldspathic vitric arenite** All gradations exist between arkose and vitric arenite. The vitric arenites are commonly light olive to light gray on a fresh surface and weather to a light greenish gray. Most contain matrix that encloses angular to subangular very fine to medium sand-sized grains. Sorting values exceed 1.50 phi units.

Devitrified volcanic glass is the predominant component of the vitric arenites and composes up to approximately 60 percent of the rock. Other common constituents are metamorphic rock fragments, and monomineralic grains of microcline, quartz, plagioclase, and lesser amounts of chert, garnet and opaques.
Fig. 6. Mineralogical composition of 12 selected sandstones of the Bozeman Group. Numbers 1-3, Renova; 4-6, altered Renova; 7-12, Sixmile Creek. Key to thin sections: 1, P-23-A; 2, P-82-E; 3, P-135-A; 4, P-181-I; 5, P-181-J; 6, P-181-Q; 7, P-82-E; 8, P-87-A; 9, P-107-A; 10, P-185-A; 11, P-185-E; 12, P-185-G. Key to poles of triangle: Q, all quartz; F, all feldspar, gneiss and granitic rock fragments; R, all other rock fragments and volcanic glass. Determinations of at least 300 appropriate grains were made on each thin section (classification from Folk, 1974).
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<td>vitric arkose</td>
<td>vitric arkose</td>
<td>9</td>
<td>13</td>
<td>19</td>
<td>19</td>
<td>3</td>
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<td>10)</td>
<td>P-185-A</td>
<td>vitric arenite</td>
<td>vitric arenite</td>
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<td>7</td>
<td>6</td>
<td>42</td>
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<td>11)</td>
<td>P-185-E</td>
<td>vitric arenite</td>
<td>vitric arenite</td>
<td>13</td>
<td>9</td>
<td>4</td>
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<td>12)</td>
<td>P-185-G</td>
<td>feldspathic</td>
<td>feldspathic</td>
<td>16</td>
<td>24</td>
<td>6</td>
<td>21</td>
<td>22</td>
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Opal Opal occurs only locally in Renova strata, and is present in beds that parallel the enclosing strata in thicknesses that range from a few inches to a few feet. The opal is pale green, microcrystalline, brittle, and breaks with conchoidal fracture.

Altered Renova strata

Location, previous investigations, and measured section A localized body of Renova strata, exposed over an area of 1 1/2 square miles, has been altered, causing these rocks to be very well indurated and appear different from other Renova strata. The altered Renova strata are exposed along the walls of Sweetwater canyon (Pl. 1) where they form steep cliffs due to extreme lithification. A section of altered Renova strata, designated Measured Section B, was measured in Sweetwater canyon in the NE 1/4, SW 1/4, sec. 4, T. 9 S., R. 5 W., and consists of 132 feet of exposed rock. The base of the section is covered with alluvium, and the top forms the rim of the canyon (Pl. 1; Fig. 4; See Appendix for lithologic descriptions).

Previous workers have studied the physical characteristics of these rocks only in a cursory manner, and have considered them to be igneous in origin. Hayden (1872) referred to the altered Renova strata as "variegated porphyries" and added that..."the sides of the porphyritic walls show a regular bedding-like strata, in layers from an inch
to a foot or more in thickness." Dorr and Wheeler (1964) referred to these rocks as "altered rhyolite."

Physical features and lithology Altered Renova strata overlie Precambrian pre-basin rocks with angular unconformity (Pl. 3, fig. 1). Due to the alteration, these strata are anomalous in topographic expression and color. Steep cliffs commonly show extensive exposures of purple, yellow, gray and blue-gray rocks. Some of the rocks are banded with distinct color rings and are sold as "Montana agate" or "onyx."

In hand specimen these rocks differ in appearance from other Renova strata, but thin sections indicate that they are of sedimentary origin and are essentially identical to Renova strata found elsewhere (Pl. 2, fig. 5; Fig. 6; Table 1). Although the origin of the alteration is obscure, these modified rocks appear to be baked, perhaps by an igneous body concealed in the subsurface. No evidence of hydrothermal activity is found, however.

Environment of deposition

Kuenzi (1974) has concluded that Renova basin-fill deposits in the Jefferson basin record fine-grained meander-belt fluvial systems and associated flood-basin and pond depositional systems. Since Renova strata in the Jefferson and Sweetwater basins are in part lithologically and chron-
EXPLANATION OF PLATE 3

Figure 1. Horizontal altered Renova strata lying with angular unconformity over almost vertical Precambrian rocks of the Pre-Cherry Creek Group in the NW 1/4, SW 1/4, sec. 4, T. 9 S., R. 5 W.

Figure 2. Typical exposure of Sixmile Creek strata in the Sweetwater basin. Vitric arenite capped by conglomeratic arkose in the SE 1/4, SE 1/4, sec. 22, T. 9 S., R. 6 W.
ologically equivalent, it is postulated that a similar assemblage of environments existed in the Sweetwater canyon area during deposition of Renova strata. The mudstones and thin lenticular sandstone bodies are interpreted to record flood-basin and crevasse splay deposition. Thicker sandstone bodies and micritic limestones, interpreted to record point bar and pond deposition in the Jefferson basin, were not observed in the Sweetwater canyon map area.

Age, fossils and correlation

In the upper Ruby basin, fossil mammals indicate that exposed strata of the Renova Formation range in age from Early Oligocene through Early Miocene (Stewart Monroe, written communication). Assemblages of vertebrate fossils have been collected by Monroe from three localities in, and adjacent to the Sweetwater canyon map area. The localities, MV 7234, MV 7252, and MV 7355 (Pl. 1) all contain Early Miocene fossils.

Locality MV 7234 includes:

Mercoidodontidae
  cf. Merychys arenarum

Locality MV 7252 includes:

Castoridae
  Palaeocastor cf. fosser
Leporidae
  cf. Palaeolagus sp.
Equidae
  Parahippus sp.
  Anchitherium sp.
Hypotragulidae
  cf. Nanotragulus sp.
Cervidae  
cf. Blastomeryx sp.  
Camelidae  
cf. Oxydactylus sp.  
Merycoidodontida  
cf. Ticheleptus sp.  
cf. Merychyas arenarum  
cf. Phenacocoelus stouti  

Locality MV 7355 includes:

Equidae  
Parahippus or Anchitheium  
Hypertragulidae  
cf. Nanotragulus sp.  

Monroe also collected Early Oligocene fossil vertebrates from Renova strata in the upper Ruby basin, but not within the Sweetwater canyon map area.  

The Renova Formation, in the Sweetwater canyon map area correlates in lithology and stratigraphic position with the Milligan Creek, Dunbar Creek, and Climbing Arrow Formations in the Three Forks basin (Robinson, 1963), the Climbing Arrow and Dunbar Creek Formations in the Toston quadrangle (Robinson, 1967), the Renova Formation in the Jefferson basin (Kuenzi and Fields, 1971), the Renova Formation in the lower Ruby basin (Petkewich, 1972), and the Passamari Formation in the upper Ruby basin (Dorr and Wheeler, 1964). It is at least in part contemporaneous with the various formations in these basins.  

Sixmile Creek Formation  

Name, stratigraphic position and thickness  

The upper sequence of the Bozeman Group was named the
Sixmile Creek Formation in the Toston quadrangle by Robinson (1967). In the Sweetwater canyon map area, the predominantly coarse-grained strata of the Sixmile Creek Formation lie unconformably on either pre-basin rocks or Renova strata, and are unconformably overlain by Quaternary deposits. The Sixmile Creek basin-fill deposits reach a thickness of at least 1300 feet in the upper Ruby basin (Monroe, 1974).

**Distribution and topographic expression**

Sixmile Creek strata are exposed over an area of approximately 6 square miles in the Sweetwater and upper Ruby basins. The best exposures in the upper Ruby basin occur in a band about 1/2 mile wide which extends from the northeastern to the southwestern corner of the map area (Pl. 1). In the Sweetwater basin the best exposures are confined to the southeastern part of the basin. Elsewhere, Sixmile Creek strata are mantled with a few inches to several feet of Quaternary deposits and soil.

Sixmile Creek strata are poorly indurated and commonly form slopes; however, resistant ledges are locally produced where the rocks are cemented (Pl. 3, fig. 2).

**Measured section and lithology**

A 177 foot section of Sixmile Creek strata, designated Measured Section C, was measured in the upper Ruby basin in the SW 1/4, NE 1/4, sec. 18, T. 9 S., R. 5 W. (Pl. 1; Fig.7;
Fig. 7. Measure? Section C of Sixmile Creek Formation strata. P-185-A and similar designations refer to thin sections; small numbers at hachures are at 10 foot intervals; larger numbers refer to lithologic descriptions in Appendix (See Pl. 1 for location).
See Appendix for lithologic descriptions). Based on Measured Section C and other measured sections, the Sixmile Creek Formation in the Sweetwater canyon map area consists of approximately 10 percent conglomerate; 50 percent vitric arenite and feldspatic vitric arenite; 34 percent arkose and vitric arkose; 4 percent clayey limestone; 1 percent montmorillonite mudstone. All textural and mineralogical gradations exist between the major rock types.

Arkose, vitric arkose, and conglomerate Coarse-grained arkosic rocks of the Sixmile Creek Formation commonly display a light gray to tan weathered surface, and are gray to orange-brown on a fresh or wet surface. Most of these rocks are cemented and form resistant ledges.

Angular to subangular grains ranging from fine sand to cobbles up to 10 inches in diameter occur in the arkosic rocks. Sorting values vary from moderate ($\sigma= 0.60$ phi units) to poor ($\sigma > 1.50$ phi units), and the rocks are either immature or submature. Cement, if present, is characteristically calcite (Pl. 4, fig. 3).

The arkosic rocks are composed predominantly of quartz, potassium feldspar and metamorphic rock fragments; lesser amounts of plagioclase, chert, volcanic glass, and mudstone clasts; and trace amounts of magnetite, biotite, muscovite, chlorite, hornblende and garnet (Fig. 6; Table 1). The character of these components is essentially the same as in pre-basin rocks, as well as other Tertiary strata.
EXPLANATION OF PLATE 4

Photomicrographs of Rocks From the Sixmile Creek Formation and Pliocene Basalts (magnification 35x)

Figure 1. Plain light. Medium sandstone: submature vitric arenite (P-180-A). Sand-sized angular unaltered shards (u) and subrounded altered vesicular grains (a) of volcanic glass. Note the sharp appearance of the shards and the elongated vesicles in the larger grains.

Figure 2. Crossed nicols. Same as Fig. 1.

Figure 3. Plain light. Slightly granular medium sandstone: calcite-cemented submature arkose (P-179-A). Sand-sized subangular grains of quartz (q), microcline (m), metamorphic rock fragments (mrf), and mudstone clasts (mc), in a calcite cement (gray).

Figure 4. Plain light. Clayey limestone (P-185-C). Silt and sand-sized angular grains of quartz (q), and metamorphic rock fragments (mrf), floating in a microcrystalline calcite cement. Note local pockets of coarsely crystalline calcite.

Figure 5. Plain light. Olivine basalt (P-184-T). Euhedral phenocryst of olivine (o), surrounded by small plagioclase laths (white) and magnetite (black) in a fine-grained groundmass. Sample taken near base of Timber Hill lava flow.

Figure 6. Plain light. Vesicular olivine basalt (P-184-T). Abundant nearly circular vesicles (white), surrounded by minute plagioclase laths (white), and magnetite (black) in a fine-grained groundmass. Sample taken near the top of the Timber Hill lava flow (Pl. l).
Vitric arenite and feldspathic vitric arenite Tuffaceous rocks of the Sixmile Creek Formation are commonly gray on a wet or fresh surface, and weather light gray. These rocks are poorly consolidated, but commonly are capped by calcite-cemented arkoses, which form ledges and hold up the vitric arenites below (Pl. 3, fig. 2). Cross-stratification is locally present.

Vitric arenites and feldspathic vitric arenites contain at least 50 percent volcanic detritus, all of which is glass (Fig. 6; Table 1). The glass occurs in two distinct forms, both described previously in the section on mudstones of the Renova Formation. Median grain sizes range from silt to coarse sand. The grains are angular to sub-rounded, and all rocks are submature, with sorting values exceeding 1.00 phi units (Pl. 4, figs. 1,2).

Siltstone and mudstone The siltstones and mudstones of the Sixmile Creek Formation are essentially the same as those of the Renova Formation. They form slopes, contain abundant volcanic glass, but comprise only a very small portion of Sixmile Creek strata.

Clayey limestone Rocks with more than 50 percent calcium carbonate make up only a small portion of Sixmile Creek strata. These rocks are typically gray on a fresh or wet surface, and commonly weather to white. Many are well indurated, and form resistant ledges.
Microcrystalline and coarsely crystalline calcite is present, in a mixture containing terrigenous clay, silt, and sand-sized particles (Pl. 4, fig. 4). Terrigenous detritus is similar to that found in other Tertiary strata.

Environment of deposition

Kuenzi (1974) concluded that Sixmile Creek basin-fill deposits in the Jefferson basin record alluvial fan deposition and locally coarse-grained meanderbelt fluvial systems. Because Sixmile Creek strata in the Jefferson basin and the Sweetwater canyon map area are similar in lithology and age, it is probable that a similar assemblage of environments existed in both basins during Sixmile Creek deposition. The coarse-grained Sixmile Creek strata in the Sweetwater canyon area, however, are interpreted to represent alluvial fan deposition. No meanderbelt deposits have been observed.

Age, fossils and correlation

In the upper Ruby basin, fossil mammals indicate that Sixmile Creek strata range from Late Miocene to Early and possibly Middle Pliocene in age (Stewart Monroe, written communication). Vertebrate fossils have been collected by Monroe and others from 11 localities in, and adjacent to the Sweetwater canyon map area. Fossils from localities MV 6639, MV 6641, MV 6642, MV 6645, MV 7229, and MV 7353 (Pl. 1) are Late Miocene; those from MV 7357 are Early
Pliocene; and fossils from MV 7239, MV 7240, MV 7241, and MV 7358 are apparently Early Pliocene, but possibly Middle Pliocene in age. The taxa obtained from these localities are listed below.

Locality MV 6639 includes:

- Canidae
  - *Aelurodon* cf. *saevus*
- Equidae
  - *Merchippus seversus*
- Camelidae
  - *Aepycamelus* sp.

Locality MV 6641 includes:

- Antilocapridae
  - *Merycodus* cf. *loxoferus*
- Equidae
  - *Merychippus* sp.

Locality MV 6642 includes:

- Equidae
  - *Merychippus seversus*

Locality MV 6645 includes:

- cf. *Calippus placidus*

Locality MV 7229 includes:

- Rhinocerotidae
  - cf. *Aphelops* sp.
- Chalicotheriidae
  - gen. and sp. indet.
- Equidae
  - *Merychippus seversus*

Locality MV 7353 includes:

- Leporidae
  - *Hypolagus* sp.
- Mustelidae
  - *Brachypancis pachycephalus*
- Equidae
  - *Hypohippus* cf. *affinis*
  - *Merychippus isonesus*
Antilocapridae
  *Merycodus* cf. *necatus*
Camelidae
  *Aepycamelus* cf. *stocki*

Locality MV 7357 includes:

Equidae
  cf. *Pliohippus* sp.

The combined collections from MV 7239, MV 7240, MV 7242, and MV 7358 include:

Comphotheriidae
  ? *Tetralophodon* sp.
Equidae
  *Pliohippus* sp.
Camelidae
  *Magatylopus* sp.

The Sixmile Creek Formation in the Sweetwater canyon map area correlates in lithology and stratigraphic position with the Sixmile Creek Formation in the Toston quadrangle (Robinson, 1967), the "Madison Valley Formation" in the Madison Valley (Douglas, 1907; Dorr, 1956), the Sixmile Creek Formation in the lower Ruby basin (Petkewich, 1972), the "Madison Valley Equivalent" in the upper Ruby basin (Dorr and Wheeler, 1964), Tertiary deposits in the Lima basin (Hough, 1958), the Deer Lodge basin (Konizeski, et al., 1958), and the Flint Creek basin (Fields and Rasmussen, 1969). It is approximately contemporaneous, at least in part, with various deposits in these basins.

**Origin of mineralogical components, Bozeman Group**

The detrital components of both the Renova and Sixmile Creek Formations indicate more than one source. Approxi-
mately one-half of the terrigenous grains are metamorphic in origin and one-half are volcanic.

Metamorphic rock fragments occur in fine sand to pebble-sized grains, and are identical in composition and mineralogical character to the Pre-Cherry Creek rocks exposed along the margins of the basin. Monomineralic grains of quartz, microcline, plagioclase (An 18-28), biotite, muscovite, hornblende, garnet, magnetite, zircon and chlorite also show the same mineralogic character as crystals of the same species occurring in Pre-Cherry Creek rocks. The mineralogic similarity between Tertiary and pre-Tertiary rocks does not, however, eliminate an outside source, or dictate that internal sedimentation was the only method of basin filling, because Pre-Cherry Creek and similar metamorphic rocks are extensive in southwestern Montana (Heinrich, 1960).

Two types of sedimentary rock fragments are found in the Tertiary strata of the Bozeman Group. Both the chert and mudstone clasts occur locally, and are lithologically similar to rock types within the Tertiary sequence. It is concluded that they represent reworked Tertiary deposits.

Volcanic glass occurs, in the form of both fresh shards and severely altered grains, almost invariably in the fine-grained rocks of the Bozeman Group. Both indicate a volcanic source, but different histories may be represented by the two radically different types. The fresh, clear shards
show little evidence of abrasion, are mostly silt-sized, and may indicate eolian deposition. The altered pumice grains, however, are sand and granule-sized and moderately to well rounded. They can be interpreted to indicate alluvial deposition.

Montmorillonite, which is the chief component of the clay fraction of both formations, has an obscure origin. Carroll (1970) stated that montmorillonite occurs as bentonite in altered volcanic ash beds, but is also common as an alteration product of igneous and metamorphic minerals of suitable composition in an alkaline environment. Ross and Henricks (1945) indicated that bentonites derived from altered volcanic glass commonly retain the structure of the volcanic ash almost perfectly. They also indicated that montmorillonite derived from alteration of igneous and metamorphic rocks is possible, given a sufficiently large amount of ferromagnesian minerals and dry, alkaline conditions.

Petrographic study of the montmorillonite in mudstones from the Bozeman Group show that it is, in some cases, intimately associated with volcanic glass (Pl. 2, figs. 1, 2, 5, 6; Pl. 4, figs. 1, 2). This relationship suggests that the montmorillonite may be an alteration product of the glass, formed either 1) in place at the site of deposition, or 2) in soils derived from the glass. Not all montmorillonite is associated with volcanic glass, however, and much
of the glass does not show deeply corroded borders. Therefore, the possibility that the montmorillonite was derived from other silicate rocks cannot be ruled out. It is possible that the montmorillonite is polygenetic.

The origin of the clayey limestone in the Sixmile Creek Formation is problematic. All gradations exist between grain-supported calcite-cemented sandstones and rocks containing terrigenous grains floating in a calcium carbonate matrix. Two possibilities exist for the latter. Either the clayey limestones record 1) primary calcium carbonate precipitation, or 2) they represent caliche, formed from secondary calcium carbonate crystal growth and expansion between grains.

According to Blatt et al., (1972), investigators disagree on the criteria for recognition of ancient caliche, but Reeves (1970) stated that cracks, nodules, and sporadic lenses of parent material are characteristic. None of the Sixmile Creek rocks have been observed to have these structures, but the possibility that they are caliche rocks cannot be ruled out. The evidence suggests, however, that these rocks represent contemporaneous calcium carbonate precipitation and deposition of terrigenous grains.

Tertiary Volcanic Rocks

Distribution and large-scale features

Tertiary volcanic rock bodies are exposed and occupy
approximately 2 square miles in the Sweetwater canyon area (Pl. 1). They are basaltic in composition, concordantly overlie the youngest Sixmile Creek strata, and represent the erosional remnants of a lava flow broken by faults and cut by Sweetwater canyon (Fig. 8). The basalts, given the informal name "Timber Hill lava flow", occupy four large areas aligned in a southwest-northeast direction, and form two detached buttes on either side of the canyon. The flow is 34 feet thick where measured in the SE 1/4, NW 1/4, sec. 18, T. 9 S., R. 5 W. (Pl. 1) and maintains a relatively constant thickness. The basalt ranges in color from dark gray to black. At its base the flow contains few vesicles, but they increase in number upward, and are abundant at the top. Twenty vesicles measured in the NE 1/4, NW 1/4, sec. 13, T. 9 S., R. 5 W., have an average elongation direction of N. 43° E (Pl. 1) and a standard deviation of 24 degrees. Grain size increases slightly from bottom to top, but composition does not change significantly in vertical section. Parting that defines layers ranging from 1/4 inch to 1 foot in thickness is present locally, but most of the flow has a blocky nature (Pl. 5, fig. 1). The basalts are also characterized by local columnar jointing (Pl. 5, fig. 2).

**Petrography**

The lava is a vesicular olivine basalt which contains small anhedral to euhedral phenocrysts of olivine, augite,
Fig. 8. Northeast-southwest structure section across the Timber Hill lava flow and Sweetwater canyon showing the rocks cut by normal faults and by Sweetwater canyon (vertical exaggeration 10x).
EXPLANATION OF PLATE 5

Timber Hill lava flow

Figure 1. View of the basaltic lava flow showing rough horizontal parting and the blocky nature of the basalt in the NE 1/4, NW 1/4, sec. 18, T. 9 S., R. 5 W.

Figure 2. Columnar jointing in the basalt in the SE 1/4, NW 1/4, sec. 24, T. 9 S., R. 6 W.
and feldspar that constitute about 10 percent of the rock. Zoned olivine composes approximately 70 percent of the phenocrysts and commonly occurs as anhedral crystals with corroded borders. It is partly altered to antigorite and commonly bordered by magnetite. Augite composes about 20 percent of the phenocrysts and occurs as comparatively fresh prisms. Feldspar constitutes approximately 10 percent of the phenocrysts and is a zoned labradorite (An 58-68). Feldspar crystals are comparatively fresh.

The bulk of the basalt is fine-grained, hypocrystalline groundmass consisting of about 60 percent plagioclase laths, 20 percent minute grains of augite, 10 percent magnetite and 10 percent glass (Pl. 4, figs. 5,6).

**Age and correlation**

Samples of basalt were collected at two locations in the Sweetwater canyon area and radiometrically dated by the United States Geological Survey (R.F. Marvin, written communication). Collection locality 1 is located on the north rim of the canyon in the SE 1/4, NE 1/4, sec. 7, T. 9 S., R. 5 W., and locality 2 is in the SE 1/4, NE 1/4, sec. 13, T. 9 S., R. 5 W. (Pl. 1). Potassium-argon whole rock analysis indicated ages of 4.2 ± 0.2 million years and 3.8 ± 0.4 million years respectively.

On the basis of petrographic and stratigraphic evidence, the basalts of the Timber Hill lava flow may be
correlated with basalts of the Lima region, described by Scholten et al. (1955). These basalts cap Tertiary strata in the Lima region and are petrographically similar to those in the Sweetwater canyon area. Scholten et al. (1955), considered the Lima region basalts to be Late Pliocene or Pleistocene in age, and showed that they were approximately contemporaneous with basalts of the Snake River region in central Idaho. They did not imply, however, that any of the basalts of the Lima region are actual extensions of individual flows in the Snake River plains.

**Quaternary Deposits**

Three types of Quaternary deposits overlie Tertiary strata: 1) stream valley alluvium; 2) undifferentiated mantle, and 3) rounded stream gravel. They are mapped (as a single unit) only where they extensively cover Tertiary strata. Areas where Tertiary rocks outcrop sporadically from beneath a thin veneer of Quaternary cover are mapped as Tertiary (Pl. 1).

Stream valley alluvium, produced by present streams and their predecessors, is confined to present-day stream valleys and represents the thickest Quaternary deposits in the area. The alluvium occupies approximately three square miles, and consists mainly of sand and gravel, which, for the most part, probably represents reworked Tertiary deposits.
Undifferentiated mantle consists of a thin veneer of sand and gravel, and reduces Tertiary exposures considerably. The mantle represents alluvial fan deposits, and other colluvial debris.

A thin veneer of rounded stream gravels partially cover Tertiary strata and are found on top of the Timber Hill lava flow. They are identical to modern stream gravels and probably were deposited by a late Cenozoic river system.

Structure

Attitude and folds

In the Sweetwater canyon area, Tertiary strata have a general southwesterly dip of approximately 7 degrees, except where locally disturbed by faulting or folding. Renova and Sixmile Creek strata are structurally concordant, and within the map area, the unconformity between the two formations is erosional (Pl. 1, section D-F).

Two areas of local deformation were observed within the map area. In section 4, T. 9 S., R. 5 W., altered Renova strata show highly variable attitudes and dips up to 80 degrees are common. The strata are highly altered and fractured, but the deformation is local. Adjacent altered Renova strata are not disrupted.

Two possible mechanisms may be responsible for the alteration and deformation. A buried igneous intrusive
body may have baked (thereby altering) the Renova strata, and caused deformation during emplacement. If this is the case, the limits of alteration and deformation should coincide, but they do not. Elsewhere altered Renova beds are not deformed, and are conformable with unaltered Renova strata.

Another possible explanation is that deformation reflects recurrent movement along buried faults. Such an explanation was first brought forth by Robinson (1963) to explain floded Tertiary strata in the Three Forks basin, and later by Kuenzi and Fields (1971) to explain similar structure in the Jefferson basin. The deformation of altered Renova strata in the Sweetwater canyon area, however, is more intense than that in the Three Forks or Jefferson basins. This may reflect the brittle nature of the altered Renova strata, which would fracture under stresses that could be more readily absorbed by more poorly consolidated unaltered sediments.

In section 34, at the northwest corner of the map area, Tertiary strata are folded into a broad arch, only part of which lies within the map area. The fold plunges to the southeast, and apparently is part of a broad anticline which lies chiefly in adjacent parts of the upper Ruby basin (Stewart Monroe, oral communication).
Observable faults

Pre-basin rocks, Tertiary basin-fill and volcanic rocks, and rounded Quaternary gravels are displaced in Section 19, T. 9 S., R. 5 W., and Sections 11, 13, 14 and 24, T. 9 S., R. 6 W. (Pl. 1, Section A-C; Fig. 8) by a northwestward-trending normal fault. The southwest block is upthrown, and forms a linear fault scarp which constitutes the southwest border of Sweetwater basin. Although total movement along this fault is unknown, over 700 feet of displacement has taken place since emplacement of the lava flow (4.2 million years ago) and subsequent deposition of overlying Quaternary gravels. The fault can be traced into the upper Ruby basin for about one mile, where it displaces Tertiary strata and is finally buried by alluvium.

Approximately 1 1/4 miles to the south, and parallel to the described fault above, another normal fault displaces all rock bodies and rounded Quaternary deposits (Pl. 1, Section A-C; Fig. 8). It shows a post 4.2 million years displacement of approximately 250 feet, with the southwest block upthrown. This fault cannot be traced into the upper Ruby basin, but produces a prominent scarp where it offsets the lava flow and overlying Quaternary gravels.

Inferred faults

In section 5, T. 9 S., R. 5 W., a northeastward-trending series of small-scale normal faults is inferred
(Pl. 1). These faults have downdropped the southeast blocks and have displaced the basaltic lava flow. A magnetic survey normal to the inferred faults by Val Chandler and the writer indicated that small displacements have occurred, possibly as slump blocks off the edge of the main igneous body. These faults, however, cannot be traced out of this local area.

**Basin Origin**

The origin of the Sweetwater and upper Ruby basins is obscure, but both tectonic and erosional factors were probably important in their delineation. Evidence for tectonic control in Sweetwater basin includes its northwestward elongation parallel to the linear front of faulted pre-basin rocks on the southwestern border. Although only late Tertiary movement can be demonstrated along this fault, earlier movement may have produced a basin along the down-dropped side, or provided a zone of weakness, allowing erosion to delineate the basin. No evidence for tectonic control is evident for that part of the upper Ruby basin within the area mapped, but the thickness (Burfiend, 1967) of Tertiary deposits within the basin exceeds 3000 feet. Such a thickness indicated that the basin was a long-term site for continental sedimentation, and suggests recurrent movement along faults marginal to the basin. According to Burfiend (1967) gravity data suggest a steep normal fault
along the eastern margin of the upper Ruby basin, outside the Sweetwater canyon map area.

Cenozoic Geologic History: Sweetwater Canyon Area

The following geologic history of the Sweetwater canyon area is based largely on data previously discussed. Where gaps exist in the rock record, data from other basins, or inferences drawn from the study area, are used to complete the reconstruction.

The Sweetwater and upper Ruby basins were delineated following Laramide deformation (Fig. 9A). Normal faulting probably provided the framework for the basins, but erosional factors presumably also contributed to their development. The pre-basin erosional surface was probably developed by the Late Eocene (Kuenzi and Fields, 1971).

By the Early Oligocene an aggrading drainage system was developed, and deposition of strata of the Renova Formation took place in meanderbelts and adjacent flood basins. Drainage was through-flowing during at least part of Renova basin filling (Kuenzi, 1974), but it is unknown whether the upper Ruby and Sweetwater basins were connected. Renova strata continued to accumulate, gradually burying an irregular erosion surface, well into Early Miocene time (Fig. 9B). If younger Renova strata were deposited, they have since been eroded, or are buried by younger rocks.

After deposition of the youngest Renova strata in the
Fig. 9 Schematic summary of major erosional and depositional events in the upper Ruby basin within the Sweetwater canyon map area. Key to diagrams: A, delineation of basin by Late Eocene; B, deposition of Renova Formation, Late Eocene through Early Miocene; C, erosion in Middle Miocene; D, deposition of Sixmile Creek Formation, Late Miocene to Late Pliocene; E, erosion in the late Cenozoic.
Early Miocene, a change in stream regimen occurred, which resulted in the removal of a large volume of Renova strata from the upper Ruby basin (Fig. 9C). Beginning in the Late Miocene, and continuing until at least Late Pliocene (Kuenzi and Fields, 1971; Petkewich, 1972) alluvial fans formed at the margins of the Sweetwater and upper Ruby basins, and extended basinward, forming the Sixmile Creek Formation (Fig. 9D). Drainage was probably through-flowing during the early part of this episode of basin filling, and it is likely that the Sweetwater and upper Ruby basins were connected, and functioned as a unit. Movement along normal faults may have closed the Sweetwater-upper Ruby basin from time to time, but rapid sedimentation may have filled the basin to a level nearly equal with the upthrown blocks, periodically opening drainage.

By the Late Pliocene, the Sweetwater and upper Ruby basins were filled, and Sixmile Creek strata were continuous between the two basins. At this time basaltic lava flowed northeastward across a low area on the Sixmile Creek surface. Sometime following extrusion of the lava flow, 4.2 ± 0.2 million years ago, a drastic change in stream regimen occurred, which initiated downcutting and basin excavation. A meandering stream cut down through the lava flow, the underlying Tertiary sediments, and became superposed on pre-basin metamorphic rocks to form Sweetwater canyon. This episode of basin excavation, asso-
associated with canyon formation, has continued until the present. Displacement along northwest-southeast trending normal faults occurred following the initiation of canyon cutting.

Summary and Conclusions, Sweetwater Canyon Area

The multi-faceted study presented above leads to the following summary statements and conclusions about the geology of the Sweetwater canyon area:

1. Precambrian metamorphic rocks of the Pre-Cherry Creek Group outcrop in and around the Sweetwater and upper Ruby basins. These pre-basin rocks consist chiefly of quartz-feldspathic gneiss, with lesser amounts of schist and amphibolite.

2. Pre-basin rocks are unconformably overlain by basin-fill deposits of the Bozeman Group, represented by two lithologically and paleontologically distinct depositional sequences, the Renova Formation and the Sixmile Creek Formation. The two formations are separated by an erosional unconformity.

3. The rocks of the Renova Formation yield fossils ranging in age from Early Oligocene through Early Miocene, and consist chiefly of fine-grained deposits. Measured sections (242 feet) indicate that these rocks consist of 69 percent mudstone, 14 percent siltstone, and 17 percent sandstone.
4. The strata of the Sixmile Creek Formation yield fossils ranging in age from Late Miocene to possibly Middle Pliocene and consist chiefly of coarse-grained deposits. Measured sections (554 feet) indicate that these rocks consist of 10 percent conglomerate, 84 percent sandstone, 4 percent limestone and marl, and 2 percent siltstone and mudstone.

5. The coarse-grained nature of the Sixmile Creek deposits, relative to the fine-grained nature of the Renova deposits, suggests that either a change in relief, and/or a change in climate took place between Early Miocene and Late Miocene time.

6. A large volume of Renova deposits, delineated as a separate map unit, have been altered, causing them to become especially well indurated. Their sedimentary origin is evident, but the agent responsible for their modification is obscure.

7. A late Tertiary basaltic lava flow concordantly overlies rocks of the Bozeman Group. The flow has been radiometrically dated at $4.2 \pm 0.2$ and $3.8 \pm 0.4$ million years old.

8. Tertiary basin-fill deposits and volcanic rocks are structurally concordant except where locally deformed by faults and folds. All rocks dip southwesterly at approximately 7 degrees, except locally, where dips as high as 80 degrees have been recorded.
9. The geologic history of the Sweetwater canyon area includes two periods of basin filling with erosional intervals before, between and after each depositional phase. The depositional episodes took place in the Late Eocene through Early Miocene and Late Miocene to Late Pliocene. Erosional periods are recorded in the pre-Late Eocene, Middle Miocene and post-Middle Pliocene. The post-Middle Pliocene erosional episode has continued to the present.

10. Sweetwater canyon is a result of stream superposition during the late Cenozoic, and was formed sometime after 4.2 million years ago. This provides positive evidence, for the first time, that any canyon in the Missouri River drainage system formed after deposition of Tertiary sediments and during the late Cenozoic episode of erosion.

11. Late Cenozoic faulting in the Sweetwater canyon area postdates 4.2 million years, the initiation of canyon formation and basin excavation.

12. The geology of the Sweetwater and upper Ruby basins generally correlates with other basins in southwestern Montana in terms of stratigraphy and structure (Douglas, 1907; Dorr, 1956; Hough, 1958; Robinson, 1963, 1967; Dorr and Wheeler, 1964; Konizeski, et al., 1968; Fields and Rasmussen, 1969; Kuenzi and Fields, 1971; Petkewich, 1972), and suggests that these two basins share a common geologic history with other Cenozoic basins. Thus, new data from the Sweetwater canyon area can add to the regional geologic history of the northern Rocky Mountains.
ORIGIN OF INTERBASINAL CANYONS

Canyon Features

Intermontane basins east of the Continental Divide in southwestern Montana are presently drained by the Missouri River and its headwaters through a series of interbasinal canyons (Fig. 1). The canyons in the downstream portion of the Missouri River system apparently are not significantly deeper features than those in the headwaters (Table 2). The median canyon depth is 1000 feet, with the smallest canyon, at Trident, being approximately 600 feet deep, and the largest, Gates of the Rocky Mountains, about 1800 feet in depth. Neither canyon lies in the headwaters (Figs. 1, 10). The canyons range in length from approximately 2 to almost 20 miles, Ruby canyon being the shortest and the outlet to the Great Plains the longest (Figs. 1, 10).

Cross profiles of interbasinal canyons show a characteristic V-shape, which is interrupted commonly by small terraces along the canyon walls. Some of these terraces have been correlated with benches in adjacent basins (Atwood, 1916).

The canyons commonly are sinuous. The median sinuosity value is 1.50, and most canyons yield values that range from 1.20 to 1.85. Lombard canyon, commonly called the "Horseshoe Bends", is the most sinuous with a sinuosity
TABLE 2. SUMMARY OF INTERBASINAL CANYON FEATURES (See Figs. 1 and 10).

<table>
<thead>
<tr>
<th>CANYON NAME OR LOCATION</th>
<th>CANYON DEPTH (ft.)</th>
<th>STREAM LENGTH (mi.)</th>
<th>SINUOSITY (1/d)*</th>
<th>CONNECTING RIVER</th>
<th>ADJACENT BASINS CONNECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>outlet to the Great Plains</td>
<td>1600</td>
<td>17</td>
<td>1.50</td>
<td>Missouri</td>
<td>valley at Craig: Great Plains</td>
</tr>
<tr>
<td>Gates of the Rocky Mountains</td>
<td>1800</td>
<td>20</td>
<td>1.85</td>
<td>Missouri</td>
<td>Hilger valley: valley at Craig</td>
</tr>
<tr>
<td>Canyon Ferry at Lauser dam</td>
<td>1500</td>
<td>7</td>
<td>1.35</td>
<td>Missouri</td>
<td>Prickly Pear basin: Hilger valley</td>
</tr>
<tr>
<td>Canyon Ferry at Hilger valley</td>
<td>1000</td>
<td>8</td>
<td>1.35</td>
<td>Missouri</td>
<td>Townsend valley: Prickly Pear basin</td>
</tr>
<tr>
<td>Lombard canyon at Townsend valley</td>
<td>900</td>
<td>10</td>
<td>2.25</td>
<td>Missouri</td>
<td>Clarkston basin: Townsend valley</td>
</tr>
<tr>
<td>canyon at Trident</td>
<td>600</td>
<td>4</td>
<td>1.20</td>
<td>Missouri</td>
<td>Three Forks basin: Clarkston basin</td>
</tr>
<tr>
<td>Madison canyon at Clarkston basin</td>
<td>1700</td>
<td>15</td>
<td>1.40</td>
<td>Madison</td>
<td>Madison valley: Three Forks basin</td>
</tr>
<tr>
<td>Hebgen canyon at Madison valley</td>
<td>1500</td>
<td>8</td>
<td>1.70</td>
<td>Madison</td>
<td>Hebgen basin: Madison valley</td>
</tr>
<tr>
<td>Jefferson canyon at Three Forks basin</td>
<td>1400</td>
<td>7</td>
<td>1.50</td>
<td>Jefferson</td>
<td>Jefferson basin: Three Forks basin</td>
</tr>
<tr>
<td>Ruby canyon at Clarkston basin</td>
<td>900</td>
<td>2</td>
<td>1.20</td>
<td>Ruby</td>
<td>upper Ruby basin: lower Ruby basin</td>
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<tr>
<td>Sweetwater canyon at upper Ruby basin</td>
<td>800</td>
<td>4</td>
<td>1.45</td>
<td>Sweetwater Creek</td>
<td>Sweetwater basin: upper Ruby basin</td>
</tr>
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<td>Clark canyon at Beaverhead basin</td>
<td>800</td>
<td>15</td>
<td>1.40</td>
<td>Beaverhead</td>
<td>Lima valley: Beaverhead basin</td>
</tr>
<tr>
<td>Lima canyon at Centennial valley</td>
<td>1000</td>
<td>3</td>
<td>1.35</td>
<td>Red Rock</td>
<td>Centennial valley: Lima valley</td>
</tr>
<tr>
<td>Wise River canyon north of Melrose at Deer Lodge Pass</td>
<td>1200</td>
<td>15</td>
<td>1.30</td>
<td>Big Hole</td>
<td>Big Hole basin: Deer Lodge Pass</td>
</tr>
<tr>
<td>Melrose canyon south of Melrose</td>
<td>1000</td>
<td>5</td>
<td>1.80</td>
<td>Big Hole</td>
<td>Deer Lodge Pass: Melrose valley</td>
</tr>
<tr>
<td>canyon at Bannock</td>
<td>800</td>
<td>3</td>
<td>1.20</td>
<td>Big Hole</td>
<td>Melrose valley: Beaverhead basin</td>
</tr>
</tbody>
</table>

*Sinuosity (1/d) refers to stream length divided by straight-line distance.
Fig. 10. Stream profiles showing relative interbasinal canyon lengths and depths: A, Missouri River from the Great Plains to Three Forks; B, Jefferson-Beaverhead-Red Rock Rivers from Three Forks to Lima canyon; C, Jefferson-Ruby Rivers and Sweetwater Creek from Three Forks to Sweetwater canyon (continued on next page). (See Fig. 1 for geographic location of canyons).
Fig. 10 (continued). Stream profiles showing relative interbasinal canyon sizes: D, Jefferson-Big Hole Rivers from Three Forks to the Big Hole basin; E, Madison River from Three Forks to Hebgen canyon; F, Jefferson-Beaverhead Rivers and Grasshopper Creek from Three Forks to the canyon at Bannock. (See Fig. 1 for geographic locations of canyons).
value of 2.25 (Pl. 6, fig. 1).

Interbasinal canyons are typically positioned without regard to zones of weakness, and many cut across regional structural trends. According to Lowell (1957) Jefferson canyon is cut into resistant rocks which are almost surrounded by Tertiary sediments (Pl. 6, fig. 2).

The floors of the interbasinal canyons have been eroded to topographic levels far below high-level Tertiary exposures in adjacent basins. For example, the Ruby River flows through Ruby canyon at an altitude of 5300 feet, and nearby Tertiary deposits attain elevations in excess of 6000 feet (Pl. 7, fig. 1). In the Clarkston basin, Tertiary sediments above an altitude of 5000 feet are present near the outlet canyon, which has been eroded down to 3900 feet above sea level.

No Tertiary sediments have been found within any of the interbasinal canyons. In the Jefferson canyon area, however, basin-fill deposits are found at an altitude of 5600 feet on a flat area on the north side of the canyon (Lowell, 1957). In addition, quartzite cobbles presumed to be Quaternary in age were found on top of the ridge that was dissected to form Ruby canyon (Alden, 1953). Similar rounded gravels are present on top of the lava flow through which Sweetwater canyon was cut.

The canyons are cut into resistant rocks, which, with one exception, range in age from Precambrian to Upper Cre-
EXPLANATION OF PLATE 6

Interbasinal Canyons

Figure 1. Lombard canyon as viewed northward from a hill near Lombard. Note the sinuosity of the Missouri as it flows from the Clarkston basin into the Townsend valley.

Figure 2. Jefferson canyon as viewed westward toward the Jefferson basin.
EXPLANATION OF PLATE 7

Interbasinal Canyons

Figure 1. Ruby canyon as viewed from the upper Ruby basin northward to the lower Ruby basin beyond. The Ruby reservoir is in the foreground.

Figure 2. Sweetwater canyon as viewed from the Sweetwater basin eastward to the upper Ruby basin in the background.
taceous. The exception, Sweetwater canyon, is cut into rocks of Tertiary age, as well as older rocks below.

Processes Responsible for Canyon Formation

Canyons may be produced as a result of 1) headward erosion, 2) antecedence or 3) superposition. It is possible to eliminate headward erosion as a mechanism of formation for most of the interbasinal canyons, because the canyons cut across resistant rocks and do not follow zones of weakness. For example, semiconsolidated Tertiary sediments are continuous from the Jefferson into the Three Forks basin north of the Jefferson canyon area, and almost continuous south of the canyon (Lowell, 1957; Robinson, 1963). If the Jefferson River had evolved by headward erosion it most likely would have developed in the less resistant Tertiary sediments rather than in the older, more resistant rocks.

Some investigators have suggested that the interbasinal canyons are antecedent (Scholten et al., 1955; Freeman et al., 1958). Although no evidence exists to nullify antecedence as a possible agency for canyon formation, no known evidence supports it, and the data summarized below strongly support superposition.

Almost all previous workers have considered the canyons to be superposed. Remnants of basin-fill deposits at altitudes as high as the tops of the canyons, and near can-
yon rims (Lowell, 1957) suggest that the adjacent basins were filled to a level as high as the top of the canyons. The sinuous nature of many canyons suggests that meandering streams flowing from one basin to the next across a Tertiary basin-fill covermass were superposed in the canyon areas. If superposition is accepted, then the range in canyon depths (600 to 1800 feet) may be interpreted to reflect different thicknesses of Tertiary covermass that had to be removed before entrenchment into resistant rocks could begin.

Age of the Canyons

The interbasinal canyons of southwestern Montana are apparently superposed, and originated from entrenchment of meandering streams flowing over a high-level Tertiary covermass. Detailed mapping and paleontologic work by a number of investigators (Robinson, 1963, 1967; Kuenzi and Fields, 1968, 1971; Petkewich and Hoffman, 1969; Monroe, 1974) has demonstrated that the basins and canyons in the Missouri River drainage system in general share a common geologic history that includes major episodes of basin filling in the Late Eocene through Early Miocene and Late Miocene to Middle Pliocene; and major episodes of erosion by integrated drainage systems in the pre-Late Eocene, Middle Miocene, and late Cenozoic (Fig. 9). No one has ever doubted that the interbasinal canyons formed during an erosional episode,
and all workers have agreed that the canyons formed during the same erosional interval, in the late Cenozoic (Table 3).

According to Atwood (1916) streams were superposed during the Pliocene, but Pardee (1950) concluded simply that superposition occurred after Tertiary basin-filling. Alden (1953) indicated that the Missouri and its tributaries cut canyons as a result of regional uplift in late Tertiary and Quaternary time, and Lowell (1955, 1957) stated that canyon formation has continued from Pliocene to Recent.

Local studies have been no more definitive than the regional investigations. For example, some investigators have stated simply that canyon formation was initiated after basin filling (Pardee, 1925; Berry, 1943). Others call for canyon origin in the Late Pliocene and/or Quaternary (Emmons and Calkins, 1913; Eakins and Honkala, 1952; Lorenz and McMurtrey, 1956; Freeman et al., 1958; Andretta and Alsup, 1960; Robinson, 1961, 1963; Reshkin, 1963). Some workers favor a Pliocene origin (Ross, 1959; Richard, 1966), whereas others favor Quaternary (Scholten et al., 1955; Hackett et al., 1960; Konizeski et al., 1968; Kuenzi and Richard, 1969) as the time of canyon formation (Table 3).

Many of the above investigators (Robinson, 1961, 1963; Reshkin, 1963; Richard, 1966; Konizeski et al., 1968; Kuenzi and Richard, 1969) have postulated a late Cenozoic canyon origin based on the fact that no Tertiary deposits
<table>
<thead>
<tr>
<th>Author and Date</th>
<th>Area Studied</th>
<th>Time of Canyon Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emmons and Calkins, 1913</td>
<td>Phillipsburg Quadrangle</td>
<td>Pliocene or Pleistocene</td>
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<tr>
<td>Atwood, 1916</td>
<td>regional</td>
<td>Pliocene</td>
</tr>
<tr>
<td>Pardee, 1925</td>
<td>Canyon Ferry</td>
<td>after Pliocene deposition</td>
</tr>
<tr>
<td>Berry, 1943</td>
<td>Three Forks sheet</td>
<td>after basin filling</td>
</tr>
<tr>
<td>Pardee, 1950</td>
<td>regional</td>
<td>after basin filling</td>
</tr>
<tr>
<td>Enkens and Honkala, 1952</td>
<td>Missoula valley</td>
<td>Pliocene</td>
</tr>
<tr>
<td>Alden, 1953</td>
<td>regional</td>
<td>Pliocene or Pleistocene</td>
</tr>
<tr>
<td>Scholten et al., 1955</td>
<td>Lima region</td>
<td>Quaternary</td>
</tr>
<tr>
<td>Lowell, 1955</td>
<td>regional</td>
<td>after basin filling</td>
</tr>
<tr>
<td>Lorenz and McMurrery, 1956</td>
<td>Townsend valley</td>
<td>Pliocene or Pleistocene</td>
</tr>
<tr>
<td>Lowell, 1957</td>
<td>regional</td>
<td>Pliocene or Pleistocene</td>
</tr>
<tr>
<td>Freeman et al., 1958</td>
<td>Lombard canyon</td>
<td>Late Plio. or Early Pleist.</td>
</tr>
<tr>
<td>Rose, 1959</td>
<td>Flathead region</td>
<td>Pliocene</td>
</tr>
<tr>
<td>Andretta and Alsup, 1960</td>
<td>Morris-Elk Creek area</td>
<td>Pliocene or Pleistocene</td>
</tr>
<tr>
<td>Hackott et al., 1960</td>
<td>Logan canyon</td>
<td>Pleistocene</td>
</tr>
<tr>
<td>Robinson, 1961</td>
<td>Three Forks basin</td>
<td>Late Plio. or Early Pleist.</td>
</tr>
<tr>
<td>Robinson, 1963</td>
<td>Three Forks basin</td>
<td>Late Plio. or Early Quat.</td>
</tr>
<tr>
<td>Reshkin, 1963</td>
<td>Jefferson canyon</td>
<td>Late Plio. or Early Pleist.</td>
</tr>
<tr>
<td>Richard, 1966</td>
<td>Jefferson canyon</td>
<td>Pliocene</td>
</tr>
<tr>
<td>Konizeski et al., 1968</td>
<td>Deer Lodge valley</td>
<td>Quaternary</td>
</tr>
<tr>
<td>Kuonzi and Richard, 1969</td>
<td>Jefferson canyon</td>
<td>Quaternary</td>
</tr>
</tbody>
</table>
have been found in the canyons. Others suggested a late Cenozoic origin because they assumed that the basins were closed throughout Tertiary basin filling (Emmons and Calkins, 1913; Atwood, 1916; Pardee, 1925, 1950; Eakins and Honkala, 1952; Alden, 1953; Scholten et al., 1955) and were unaware of the Middle Miocene erosional episode and its potential as a time of canyon formation.

Despite the agreement on the time of canyon origin, previous investigations have yielded no positive evidence, because Tertiary rocks have not been found either filling the canyons or being cut by the canyons. Therefore, the new information from Sweetwater canyon (Fig. 8; Pl. 7, fig. 2) provides the first conclusive evidence that any canyon in the Missouri River drainage system formed in the late Cenozoic, and lends credence to the hypothesis made by previous workers that other canyons in southwestern Montana are late Cenozoic features. Reasons for extending the age of Sweetwater canyon to other canyons are summarized below.

Sweetwater canyon possesses features common to other canyons (Table 1). Had canyons other than Sweetwater formed during the Eocene or Middle Miocene erosional episodes, they would either contain Tertiary sediments or probably would be much deeper than Sweetwater canyon. Since this is not the case, the other canyons were most likely cut at approximately the same time as Sweetwater canyon, during
the late Cenozoic period of erosion. Considering superposition as the most likely method of formation, the age of various canyons may differ slightly due to location and differing amounts of Tertiary strata which had to be removed before entrenchment into older rocks could begin (Fig. 10), but owing to the speed of this geomorphic process relative to geologic time, the canyons can be considered approximately contemporaneous. Therefore, it is concluded, for the first time on the basis of positive evidence, that interbasinal canyons in the Missouri River drainage system are late Cenozoic features which post-date late Tertiary basin filling, and are approximately contemporaneous with Sweetwater canyon (an integral part of that system) which had its origin less than 4.2 million years ago.

Resolution of Drainage Problems

The problem

If one assumed that drainage was internal during Tertiary basin filling, as some workers did (Atwood, 1916; Alden, 1953), then a late Cenozoic origin for interbasinal canyons in southwestern Montana poses no problem. Recent work, however, has established that drainage was at least periodically through-flowing during the Tertiary. Robinson (1960, 1967), Kuenzi and Richard (1969), Kuenzi and Fields (1971), Petkewich (1972), Rasmussen (1973) and Monroe (1974),
demonstrated a regional erosional unconformity that records a Middle Miocene episode of erosion and basin excavation. Moreover, Kuenzi (1974) demonstrated that a permanent eastward drainage system was maintained during at least parts of both the early and late Tertiary episodes of basin filling. These studies thus indicate that drainage was through-flowing in southwestern Montana during at least parts of both episodes of basin filling, as well as during the erosional episodes in the early and middle Tertiary.

The geologic evidence not only requires that through-flowing drainage existed in southwestern Montana periodically throughout the Tertiary, but it also dictates that the interbasinal canyons did not form until the late Cenozoic. How was through-flowing drainage possible before formation of the interbasinal canyons?

**A solution**

The apparent contradiction can be resolved by the following interpretation of the late Cenozoic geologic history in southwestern Montana (Fig. 11).

Following Middle Miocene erosion and basin excavation of Renova strata by an integrated drainage system, basin-fill deposition of the upper Tertiary Sixmile Creek strata was initiated under through-flowing drainage conditions in the Late Miocene. The rocks in the present canyon areas did not exist as topographic highs (Fig. 11A).
Fig. 11 (part 1). Block diagrams of late Cenozoic events in interbasinal canyon areas: A, deposition of initial Sixmile Creek Formation strata (Ts) under through-flowing drainage conditions, with alluvial fan deposition at basin margins and coarse-grained meanderbelt deposition along the axes of the basins; B, disintegration of drainage by faulting, causing closed basins to develop (continued on next page).
Fig. 11 (part 2). Block diagrams of late Cenozoic events in interbasinal canyon areas: C, internal sedimentation filling basins to level of low areas on basin margins and development of through-flowing drainage; D, superposition of streams onto pre-basin rocks, cutting interbasinal canyons and excavating basins.
As basin filling proceeded, pre-basin rocks locally were repeatedly uplifted along steep faults, which blocked stream courses and eventually produced closed basins (Fig. 11B).

Following disintegration of the drainage system and formation of closed basins, internal sedimentation (which continued through the Middle Pliocene) eventually filled the basins to elevations equal with the lowest point on the basin rim, where spillover could occur. Eventually all basins were filled to a level such that an integrated, meandering, through-flowing drainage system developed and flowed across a high-level aggradational surface. Streams flowed from basins, filled with a thick sequence of Tertiary deposits, to former divide areas, buried beneath thinner (but variable) thicknesses of Tertiary strata (Fig. 11C).

A drastic change in stream regimen occurred in the Late Pliocene or Early Pleistocene, but not significantly earlier than 4.2 million years ago. Downcutting was initiated and streams were superposed from a Tertiary cover-mass onto pre-basin rocks. Thus the interbasinal canyons were cut, and the present episode of basin excavation was initiated (Fig. 11D).

According to the above interpretation, interbasinal canyons formed either 1) where Tertiary drainage courses were temporarily blocked by late Tertiary faulting, or 2) in areas elsewhere along basin margins that became topographic lows after late Tertiary faulting blocked the
original drainage courses.

Summary and Conclusions

Study of interbasinal canyons in southwestern Montana, and of Sweetwater canyon in particular, has provided evidence in support of the following conclusions and summarizing statements.

1. Interbasinal canyons in southwestern Montana have a common geologic history, and were formed by superposition in the late Cenozoic.

2. The formation of Sweetwater canyon took place less than 4.2 million years ago.

3. Other interbasinal canyons are approximately contemporaneous with Sweetwater canyon.

4. In order to reconcile late Cenozoic canyon formation with earlier through-flowing drainage, block faulting during late Tertiary basin filling is postulated to have formed closed basins, which filled to elevations equal with the lowest point on basin margins, allowing integration of drainage. It was from this high-level Tertiary covermass that superposition of interbasinal canyons took place.
APPENDIX

MEASURED SECTIONS

Three selected sections of Tertiary strata were measured with a Jacob staff and sampled at each change in lithology (Figs. 3, 4, 7). Each section has been assigned a letter designation, and the lines of traverse are plotted on Plate 1.

Samples from the measured sections were studied using a binocular microscope and petrographic and X-ray diffraction methods. Where thin sections were utilized in the descriptions, their identification numbers are indicated under the appropriate unit descriptions. The rock descriptions include a five-fold Folk (1974) name: grain size, cementing agents, textural maturity, miscellaneous transported constituents and clan designation. If applicable; dry color, weathered color, wet color if different from dry color, stratification, induration, composition, primary and secondary structures, special features, and topographic expression are included.

MEASURED SECTION A - RENOVA FORMATION

Measured Section A is a composite section of Renova strata measured in the upper Ruby basin in the NE 1/4, NW 1/4, sec. 17; the SW 1/4, NW 1/4, sec. 17, T. 9 S., R. 5 W.
(Pl. 1). The base of the section is covered with alluvium, and the top is unconformably overlain by Sixmile Creek strata (See Fig. 3 for corresponding columnar section).

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Calcitic sand montmorillanite mudstone. Brownish gray, light brown when wet; friable; angular to subangular silt and sand-sized fragments of quartz, feldspar, biotite and metamorphic rock fragments; more sandy from 125-140; more calcitic from 130-140; forms slope.</td>
<td>24.9</td>
<td>115.1-140.0</td>
</tr>
<tr>
<td>9. Muddy medium sandstone: immature vitric arkose (P-82-B). Yellowish gray, greenish gray when wet; moderately indurated; angular to subangular medium sand-sized grains of quartz, feldspar, metamorphic rock fragments, biotite, chert and mudstone clasts; forms small ledge.</td>
<td>1.0</td>
<td>114.1-115.1</td>
</tr>
<tr>
<td>8. Montmorillanite mudstone. Brownish gray, grayish brown when wet. Same lithology as number 1.</td>
<td>29.4</td>
<td>84.7-114.1</td>
</tr>
<tr>
<td>7. Covered</td>
<td>10.0</td>
<td>74.7-84.7</td>
</tr>
<tr>
<td>6. Sandy montmorillanite mudstone. Yellow green to olive gray when wet; angular to subangular silt and sand-sized fragments of quartz, feldspar and metamorphic rock fragments; forms slope.</td>
<td>10.0</td>
<td>64.7-74.7</td>
</tr>
<tr>
<td>5. Montmorillanite mudstone. Like unit 1.</td>
<td>3.2</td>
<td>61.5-64.7</td>
</tr>
<tr>
<td>4. Opal. Light olive, olive when wet; breaks with concoidal fracture; contains dendritic intergrowths of magnetite; forms thin ridge.</td>
<td>1.0</td>
<td>60.5-61.5</td>
</tr>
</tbody>
</table>
RENOVA FORMATION

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Muddy medium sandstone: calcitic immature arkose (P-23-A).</td>
<td>10.5</td>
<td>50.0-60.5</td>
</tr>
<tr>
<td>Grayish yellow, weathers rusty yellow, brownish yellow when wet;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>well indurated; subangular fine sand-sized grains of quartz, feldspar,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>chert and metamorphic rock fragments; forms ledge.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Covered</td>
<td>20.0</td>
<td>30.0-50.0</td>
</tr>
<tr>
<td>1. Montmorillanite mudstone. Grayish yellow green to light olive, light</td>
<td>30.0</td>
<td>0-30.0</td>
</tr>
<tr>
<td>grayish olive when wet; sparse angular to subangular silt and sand-sized</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fragments of quartz and feldspar; more sandy from 15.5-21.5; forms slope.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MEASURED SECTION B - ALTERED RENOVA STRATA

Measured Section B was measured in Sweetwater canyon in the NE 1/4, SW 1/4, sec. 4, T. 9 S., R. 5 W. (Pl. 1). It exposes 132 feet of altered Renova strata. The base of the section is covered with alluvium, and the top is eroded (See Fig. 4 for corresponding columnar section).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose. Like unit 4.</td>
<td>5.2</td>
<td>126.8-132.0</td>
</tr>
<tr>
<td>16.</td>
<td>Montmorillanite sandy mudstone. Grayish purple, brownish purple when wet; well indurated; angular to subrounded silt and sand-sized fragments of quartz, feldspar, altered and unaltered volcanic glass, biotite, magnetite and muscovite; forms cliff.</td>
<td>5.8</td>
<td>121.0-126.8</td>
</tr>
<tr>
<td>15.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose. Like unit 4.</td>
<td>6.9</td>
<td>114.1-121.0</td>
</tr>
<tr>
<td>14.</td>
<td>Montmorillanite mudstone. Like unit 1, but gray, and brownish gray when wet.</td>
<td>22.3</td>
<td>91.8-114.1</td>
</tr>
<tr>
<td>13.</td>
<td>Coarse sandstone: siliceous submature vitric arkose (P-181-Q). Yellowish gray weathers to brownish yellow, brownish gray when wet; well indurated; angular to subrounded coarse sand-sized grains of quartz, feldspar, chert, metamorphic rock fragments and devitrified volcanic glass; forms cliff.</td>
<td>7.8</td>
<td>84.0-91.8</td>
</tr>
<tr>
<td>12.</td>
<td>Montmorillanite mudstone. Similar to unit 1.</td>
<td>11.5</td>
<td>72.5-84.0</td>
</tr>
</tbody>
</table>
## ALTERED RENOVA STRATA

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose. Like unit 4.</td>
<td>4.5</td>
<td>68.0-72.5</td>
</tr>
<tr>
<td>10.</td>
<td>Montmorillonite mudstone. Similar to unit 1.</td>
<td>10.2</td>
<td>57.8-68.0</td>
</tr>
<tr>
<td>9.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose. Like unit 4.</td>
<td>6.0</td>
<td>51.8-57.8</td>
</tr>
<tr>
<td>8.</td>
<td>Montmorillonite mudstone. Like unit 1 but light yellow gray, grayish yellow when wet.</td>
<td>2.8</td>
<td>49.0-51.8</td>
</tr>
<tr>
<td>7.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose. Like unit 4.</td>
<td>5.9</td>
<td>43.1-49.0</td>
</tr>
<tr>
<td>6.</td>
<td>Muddy coarse sandstone: immature vitric arkose (P-181-J). Gray, weathers to brownish gray, brownish gray when wet; well indurated; angular to subrounded coarse sand and granule-sized grains of quartz, feldspar, metamorphic rock fragments, devitrified volcanic glass, biotite, garnet, and zircon; volcanic glass contains abundant feldspar spherulites; banded; forms cliff.</td>
<td>3.1</td>
<td>40.0-43.1</td>
</tr>
<tr>
<td>5.</td>
<td>Montmorillonite mudstone. Same as unit 1.</td>
<td>5.0</td>
<td>35.0-40.0</td>
</tr>
<tr>
<td>4.</td>
<td>Muddy coarse sandstone: slightly calcitic immature vitric arkose (P-181-I). Brownish yellow, yellowish brown when wet; well indurated; angular to subangular coarse sand-sized grains of quartz, feldspar, metamorphic rock fragments, both unaltered and devitrified volcanic glass, biotite, garnet and magnetite; contains stringers</td>
<td>3.0</td>
<td>32.0-35.0</td>
</tr>
</tbody>
</table>

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# ALTERED RENOVA STRATA

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>of calcite; volcanic glass contains abundant feldspar spherulites; secondary alteration bands are present; forms cliff.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Montmorillonite mudstone. Like unit 1, but light gray, weathers to yellowish gray; medium gray when wet; slightly calcitic.</td>
<td>9.7</td>
<td>22.3-32.0</td>
</tr>
<tr>
<td>2. Sandy siltstone: immature vitric arkose (P-181-F). Grayish brown, brown when wet; well indurated; angular and subangular coarse silt and very fine sand-sized grains of quartz, feldspar, metamorphic rock fragments, biotite, mudstone clasts, devitrified volcanic glass and magnetite; volcanic glass contains abundant feldspar spherulites; local pods of calcite; forms cliff.</td>
<td>3.8</td>
<td>18.5-22.3</td>
</tr>
<tr>
<td>1. Montmorillonite mudstone (P-181-A). Purple-gray, purple-brown when wet; well indurated; sparse angular and subangular silt and sand-sized grains of quartz, feldspar, metamorphic rock fragments and devitrified volcanic glass; volcanic glass contains abundant feldspar spherulites; forms cliff.</td>
<td>18.5</td>
<td>0-18.5</td>
</tr>
</tbody>
</table>
MEASURED SECTION C - SIXMILE CREEK FORMATION

Measured Section C was measured in the upper Ruby basin in the SW 1/4, NE 1/4, sec. 18, T. 9 S., R. 5 W. (Pl. 1) and exposes 177 feet of the Sixmile Creek Formation. The base and top of the section are covered by alluvium (See Fig. 7 for corresponding columnar section).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness Feet above base</th>
<th>feet</th>
<th>in feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.</td>
<td>Muddy medium sandstone: immature vitric arkose. Like unit 14, slightly gravelly from 160.2 to 165.0.</td>
<td>16.8</td>
<td>160.2-177.0</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>Slightly pebbly muddy medium sandstone: submature feldspathic vitric arenite. Like unit 15, but slightly more pebbly.</td>
<td>7.5</td>
<td>152.7-160.2</td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>Muddy medium sandstone: immature vitric arkose. Like unit 14.</td>
<td>28.7</td>
<td>124.0-152.7</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Slightly pebbly muddy medium sandstone: submature feldspathic vitric arenite. Like unit 15 but more pebbly.</td>
<td>3.1</td>
<td>120.9-124.0</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Muddy medium sandstone: immature vitric arkose. Like unit 14.</td>
<td>2.4</td>
<td>118.5-120.9</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Slightly pebbly muddy medium sandstone: submature feldspathic vitric arenite (P-185-G). Light brownish orange, orange brown when wet; friable; angular to sub-angular coarse silt to medium sand-sized grains of quartz, feldspar, unaltered and devitrified volcanic glass, metamorphic rock fragments, biotite, hornblende, garnet and magnetite; forms slope.</td>
<td>14.3</td>
<td>104.2-118.5</td>
<td></td>
</tr>
</tbody>
</table>

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## SIXMILE CREEK FORMATION

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.</td>
<td>Muddy medium sandstone: immature vitric arkose. Light yellow gray, olive when wet; friable; angular medium sand-sized grains of quartz, feldspar, fresh and devitrified volcanic glass, metamorphic rock fragments, biotite, garnet, hornblende and magnetite; forms ledge.</td>
<td>20.7</td>
<td>83.5-104.2</td>
</tr>
<tr>
<td>13.</td>
<td>Muddy medium sandstone: immature vitric arenite. Like unit 7, but finer grained.</td>
<td>9.6</td>
<td>73.9-83.5</td>
</tr>
<tr>
<td>12.</td>
<td>Slightly pebbly muddy medium sandstone: immature arkose. Like unit 5.</td>
<td>1.8</td>
<td>72.1-73.9</td>
</tr>
<tr>
<td>11.</td>
<td>Muddy medium sandstone: immature vitric arenite. Like unit 7.</td>
<td>6.6</td>
<td>65.5-72.1</td>
</tr>
<tr>
<td>10.</td>
<td>Slightly pebbly muddy medium sandstone: immature arkose. Like unit 5.</td>
<td>5.1</td>
<td>60.4-65.5</td>
</tr>
<tr>
<td>9.</td>
<td>Muddy medium sandstone: immature vitric arenite. Like unit 7, but grades upward from fine sandstone to medium sandstone.</td>
<td>3.5</td>
<td>56.9-60.4</td>
</tr>
<tr>
<td>8.</td>
<td>Slightly pebbly muddy medium sandstone: immature arkose. Like unit 5.</td>
<td>11.7</td>
<td>45.2-56.9</td>
</tr>
<tr>
<td>7.</td>
<td>Muddy medium sandstone: immature vitric arenite (P-185-E). Light yellow gray, olive gray when wet; friable; angular to subangular coarse silt to medium sand and rare granule-size grains of quartz, feldspar, metamorphic rock fragments, fresh and devitrified volcanic glass, biotite, hornblende, and magnetite; forms small ledge.</td>
<td>2.9</td>
<td>42.3-45.2</td>
</tr>
</tbody>
</table>
### SIXMILE CREEK FORMATION

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Thickness in feet</th>
<th>Feet above base</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Muddy medium sandstone: immature vitric arenite. Like unit 1.</td>
<td>6.8</td>
<td>35.5-42.3</td>
</tr>
<tr>
<td>5. Slightly pebbly muddy medium sandstone: immature arkose (P-185-D). Light olive gray, olive gray when wet; friable; angular to subrounded medium sand to rare granule-sized grains of quartz, feldspar, metamorphic rock fragments, fresh and devitrified volcanic glass, biotite, hornblende and magnetite; forms ledge.</td>
<td>5.5</td>
<td>30.0-35.5</td>
</tr>
<tr>
<td>4. Muddy medium sandstone: immature vitric arenite. Like unit 1.</td>
<td>19.8</td>
<td>10.2-30.0</td>
</tr>
<tr>
<td>3. Clayey limestone (P-185-C). Yellow gray, brown gray when wet; moderately indurated; rare angular and subangular silt to fine sand-sized fragments of quartz, feldspar and metamorphic rock fragments; forms ledge.</td>
<td>4.3</td>
<td>5.9-10.2</td>
</tr>
<tr>
<td>2. Clayey limestone. Buff, light yellow gray when wet; well indurated; rare angular silt and sand-sized fragments of quartz and feldspar; forms ledge.</td>
<td>3.3</td>
<td>2.6-5.9</td>
</tr>
<tr>
<td>1. Muddy medium sandstone: immature vitric arenite (P-185-A). Light olive gray, olive gray when wet; friable; angular to subangular medium sand-sized grains of quartz, feldspar, metamorphic rock fragments, fresh and devitrified volcanic glass; biotite, hornblende and garnet; forms ledge.</td>
<td>2.6</td>
<td>0-2.6</td>
</tr>
</tbody>
</table>
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Atwood, W.W., 1916, The physiographic conditions at Butte, Montana, and Bingham County, Utah, when the copper ores in these districts were enriched: Econ. Geology, v. 11, p. 697-740.


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Monroe, Stewart, 1974, Tertiary stratigraphy of the upper Ruby River basin, southwestern Montana: Geol. Soc. America, Abs. with Programs (Rocky Mountain Sec.), v. 6, no. 5, p. 460.


PLATE 1

Map of Sweetwater canyon area

Copies may be obtained from:

James Carl Peterson
Geology Department
Western Michigan University
Kalamazoo, Michigan
49001
GEOLOGIC MAP AND
SWEETWATER CANYON

Vertical exaggeration of
Contour interval 2

EXPLANANAT

Q
Undifferentiated mantle (in
stream alluvium, alluvial fa
and gravel, and eolian d

Timber Hill lava flow, b
at 4.2 and 3.8 million ye

Ts
Sixmile Creek Formation

Pleistocene to Recent

Upper Miocene to Middle Miocene

Extrusive rocks

Uncompahgre Group
GEOLOGIC MAP AND SECTIONS
SWEETWATER CANYON AREA

VERTICAL EXAGGERATION OF SECTIONS 2X
CONTOUR INTERVAL 20 FEET

EXPLANATION

Q
Undifferentiated mantle (includes stream alluvium, alluvial fan sand and gravel, and eolian deposits

Timber Hill lava flow; basalt dated at 4.2 and 3.8 million years old

Ts
Sixmile Creek Formation
Timber Hill lava flow; basalt dated at 4.2 and 3.8 million years old

Sixmile Creek Formation

Renova Formation

Tr-normal strata

Tar-altered strata

Pre-Cherry Creek Group

CONTACT: long-dashed where approximately located; short-dashed where indefinite; questioned where questionably located

FAULT: dashed where approximately located; questioned where questionably located; dotted where concealed. U-upthrown & D-downthrown side

STRIKE and DIP of strata

STRIKE and DIP of foliation

ORIENTATION of vesicles

LOCATION of radiometrically dated rock samples

MV7234 University of Montana fossil vertebrate locality

○ Early Pliocene

○ Late Miocene

○ Early Miocene

Line of geologic section: interpretation of depth of...
CONTACT: long-dashed where approximately located; short-dashed where indefinite; questioned where questionably located

FAULT: dashed where approximately located; questioned where questionably located; dotted where concealed.
U-upthrown & D-downthrown side

STRIKE and DIP of strata

STRIKE and DIP of foliation

ORIENTATION of vesicles

LOCATION of radiometrically dated rock samples

MV 7234 University of Montana fossil vertebrate locality

- Early Pliocene
- Late Miocene
- Early Miocene

Line of geologic section: interpretation of depth of basin fill based in part on geophysical data from Burfeind (1967) and J.R. Orgill (unpublished)

TRAVERSE LINE and letter of measured section

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