



Cenozoic geology and geomorphology of the Dry Creek Valley, Gallatin County, Montana
by Gary Claude Hughes

A thesis submitted in partial fulfillment of the requirements for a degree of MASTER OF SCIENCE in
Earth Science

Montana State University

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Abstract:

The Dry Creek Valley is a northern extension of the Three Forks basin and is bordered on the east by the Bridger Range and on the west by the Horseshoe Hills. The northern trend of the valley coincides with that of the Bridger Fault zone.

Continental Tertiary basin-fill deposits of fluvial, lacustrine, and eolian origin (Bozeman Group, Robinson, 1963) overlie pre-basin rocks with erosional and angular unconformity in the Dry Creek Valley. The Bozeman Group is represented by two unconformable and lithologically distinct depositional sequences. It is subdivided into two formations: the Renova Formation (Kuenzi and Fields, 1971), a predominantly fine-grained deposit of Oligocene age (30.6 ± 1.2 mybp); and the Sixmile Creek Formation (Robinson, 1967), a predominantly coarse-grained deposit of late Miocene (?) to middle Pliocene (?) age (8.9 ± 0.4 mybp). The Renova Formation is characterized by a fine-grained alternating sequence of limestone and mudstone. It represents a succession of low energy lacustrine and floodplain sediments that were deposited under a humid climate (Robinson, 1963). The Sixmile Creek Formation is characterized by a coarsegrained sequence of channel sandstones and conglomerates, mudstones, and structureless conglomeratic sandstones. Sixmile Creek strata represent high energy ephemeral channel and sheetflood-alluvial fan detritus which were deposited under arid conditions.

Rocks of the Bozeman Group generally dip northeastward into the Bridger Fault zone. Basin-filling and basin excavation were probably related to sporadic movements along the Bridger Fault accompanied with alternating humid-arid conditions. Bozeman Group strata are unconformably overlain by thin Quaternary deposits of diverse origin.

Directly following basin formation (middle Eocene (?), Robinson, 1963), an early Tertiary erosional topography of mature relief developed in the Dry Creek Valley. It was formed by eastward through-flowing streams that were maintained by a humid climate (Robinson, 1963). By the Oligocene, drainage was impaired and Renova deposition began to partially bury the early Tertiary topography. Post-Renova erosion (middle Miocene) removed an unknown volume of Renova strata. By late Miocene (?) time, Sixmile Creek deposition began and continued into the middle or late Pliocene (?). By late Pliocene, the area was filled with debris and much of the early Tertiary topography was buried. A late Tertiary surface developed on Sixmile Creek sediments. Consequent streams were subsequently established on this surface. By latest Pliocene or early Quaternary time, a new cycle of erosion was initiated. During basin excavation, Dry Creek and some of its tributaries were superimposed through the Tertiary covermass onto underlying prebasin rocks forming steep-walled canyons. The development of the present topography is intimately related to the history of dissection of the late Tertiary surface by fluvial systems.

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by

GARY CLAUDE HUGHES

A thesis submitted in partial fulfillment
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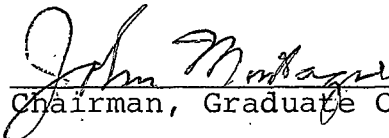
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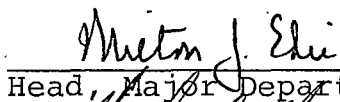
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ABSTRACT

The Dry Creek Valley is a northern extension of the Three Forks basin and is bordered on the east by the Bridger Range and on the west by the Horseshoe Hills. The northern trend of the valley coincides with that of the Bridger Fault zone.

Continental Tertiary basin-fill deposits of fluvial, lacustrine, and eolian origin (Bozeman Group, Robinson, 1963) overlie pre-basin rocks with erosional and angular unconformity in the Dry Creek Valley. The Bozeman Group is represented by two unconformable and lithologically distinct depositional sequences. It is subdivided into two formations: the Renova Formation (Kuenzi and Fields, 1971), a predominantly fine-grained deposit of Oligocene age (30.6 ± 1.2 mybp); and the Sixmile Creek Formation (Robinson, 1967), a predominantly coarse-grained deposit of late Miocene(?) to middle Pliocene (?) age (8.9 ± 0.4 mybp). The Renova Formation is characterized by a fine-grained alternating sequence of limestone and mudstone. It represents a succession of low energy lacustrine and floodplain sediments that were deposited under a humid climate (Robinson, 1963). The Sixmile Creek Formation is characterized by a coarse-grained sequence of channel sandstones and conglomerates, mudstones, and structureless conglomeratic sandstones. Sixmile Creek strata represent high energy ephemeral channel and sheetflood-alluvial fan detritus which were deposited under arid conditions.

Rocks of the Bozeman Group generally dip northeastward into the Bridger Fault zone. Basin-filling and basin excavation were probably related to sporadic movements along the Bridger Fault accompanied with alternating humid-arid conditions. Bozeman Group strata are unconformably overlain by thin Quaternary deposits of diverse origin.

Directly following basin formation (middle Eocene (?), Robinson, 1963), an early Tertiary erosional topography of mature relief developed in the Dry Creek Valley. It was formed by eastward through-flowing streams that were maintained by a humid climate (Robinson, 1963). By the Oligocene, drainage was impaired and Renova deposition began to partially bury the early Tertiary topography. Post-Renova erosion (middle Miocene) removed an unknown volume of Renova strata. By late Miocene (?) time, Sixmile Creek deposition began and continued into the middle or late Pliocene (?). By late Pliocene, the area was filled with

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INTRODUCTION

Location

Mountain ranges of southwestern Montana are separated by broad intermontane basins. These basins owe their existence to tensional forces activated in the aftermath of the Laramide orogeny. They acquired their present dimensions by middle or late Eocene time and subsequently served as catchments for clastic material shed from surrounding highlands.

The Dry Creek Valley is a northern extension of one of the largest basins in southwestern Montana, the Three Forks basin, and it shares many of the features that characterize the intermontane basins (Fig. 1). The Dry Creek Valley is surrounded by highlands and is bounded on one side by a high-angle fault or fault zone. The valley is also partially filled with two unconformable depositional sequences of continental Tertiary strata which are partially covered by relatively thin Quaternary deposits.

The Dry Creek Valley is bounded on the east by the Bridger Range and on the west by the Horseshoe Hills (Plate I; Fig. 2). The low hills of the Maudlow structural basin are its northern margin. The southern end of the Dry Creek Valley is delineated by south-facing bluffs composed of Cenozoic basin-fill strata. The latter boundary is

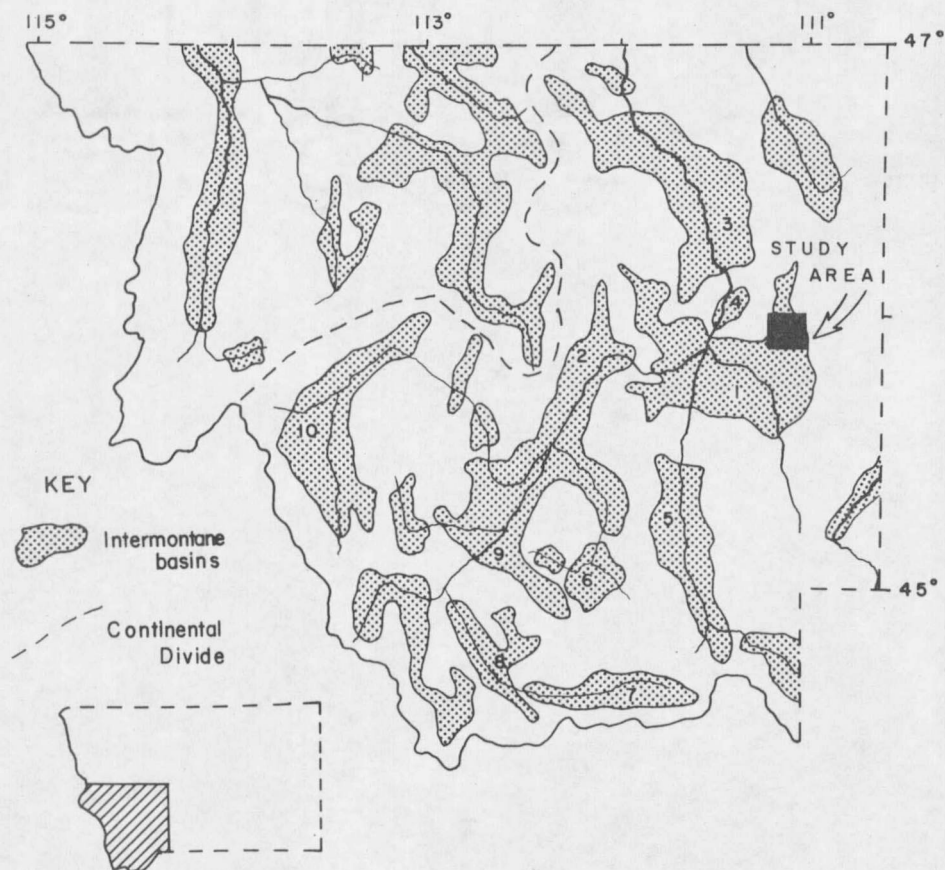


Figure 1. Index maps of intermontane basins of southwestern Montana. Key to basins: 1. Three Forks basin; 2. Jefferson basin; 3. Townsend Valley; 4. Clarkston basin; 5. Madison Valley; 6. upper Ruby basin; 7. Centennial Valley; 8. Lima Valley; 9. Beaverhead basin; 10. Big Hole basin (modified from Peterson, 1974).

marked by an abrupt increase in elevation, from the main floor of the Three Forks basin to the Dry Creek Valley (Plate I).

Previous Investigations

The first extensive geological mapping of the entire Three Forks basin was done by Peale (1896). His work was of a reconnaissance nature but his observations and ideas concerning basin geology are still useful.

Following Peale (1896), many of the studies concerned with Cenozoic strata were paleontological. Douglass (1903) described Miocene and Pliocene faunas that were collected from the Madison Bluffs area, ten miles west of Bozeman. Wood (1933, 1938) and Dorr (1956) described faunas collected from upper Tertiary strata near Anceney.

Hackett and others (1960) conducted a regional study of the groundwater resources of the eastern Three Forks basin. A brief but adequate description of Cenozoic stratigraphy and geologic history was included. Robinson (1961, 1963, 1967) systematically studied and subdivided Cenozoic stratigraphy in the Three Forks basin with an emphasis on Tertiary rocks. He introduced the term "Bozeman Group" to encompass the post-orogenic Tertiary basin-fill rocks and also assigned formation names to the lower and

upper depositional sequences. Kuenzi and Fields (1971) extended Bozeman Group terminology to the Jefferson basin. They further consolidated lower Bozeman Group terminology using formation and member terms and produced a viable depositional model and history for these deposits. Montagne (1960; and later unpublished works) has contributed toward the understanding of the late Cenozoic geomorphic history of the Madison Valley-Norris Hills area and portions of the Three Forks basin.

The works of Robinson, Kuenzi and Fields, and Montagne have greatly added to the knowledge of regional Tertiary stratigraphy, structure, and geologic history, and the ideas presented in this report are based largely on the ideas of these people.

The unpublished works of Mifflin (1963), Glancy (1964), Feichtinger (1970), and Schneider (1970) have also contributed to the knowledge of Cenozoic stratigraphy and history of the Three Forks basin. Their works especially added to the understanding of local Tertiary depositional environments.

The studies of Klemme (1949), Verrall (1955), and McMannis (1955) were mainly concerned with the pre-basin stratigraphy, structure, and geologic history of areas

directly adjacent to the Dry Creek Valley. These workers also made significant contributions toward the understanding of the Cenozoic history of their respective areas.

Purpose

The Dry Creek Valley is one of the last areas within the Three Forks basin to receive attention directed toward the stratigraphy, structure, and geologic history of the Cenozoic basin-fill sediments. In light of this fact, a stratigraphic-geomorphic study was conducted in order to refine the mapping of the Cenozoic rocks, interpret their depositional environments, and describe and interpret the Cenozoic structure and landforms of the area. By integrating these descriptions and interpretations, the Cenozoic history of the Dry Creek Valley was developed.

Methods of Investigation

In order to accomplish the goals of this study, 125 square km of the Dry Creek Valley were mapped over a period of four months during the summer and fall of 1979. The pre-basin rocks were mapped in a reconnaissance manner only, because they had already been mapped in detail by Klemme (1949), Verrall (1955), McMannis (1955), and Hackett and others (1960). However, the Tertiary and Quaternary

deposits and their contacts were mapped in detail by pace and compass method.

One composite section was measured using a Jacob staff and tape measure and samples were collected at every change in lithology. Elsewhere, samples were obtained from poor exposures too small to measure and where composition could not be determined in the field. Fossils diagnostic of age of the rocks were not found, although radiometric dates were obtained from volcanic ash that crops out at two locations within the map area. Paleocurrent directions were determined by measuring the orientation of cross-bedding with a Brunton compass and by measuring the orientation of imbricated clasts.

Laboratory investigations involved study of 43 rock samples with binocular and petrographic microscopes. Some of the carbonate-rich rocks were dissolved in dilute hydrochloric acid to determine the amount and composition of the insoluble residue and the amount of calcium carbonate.

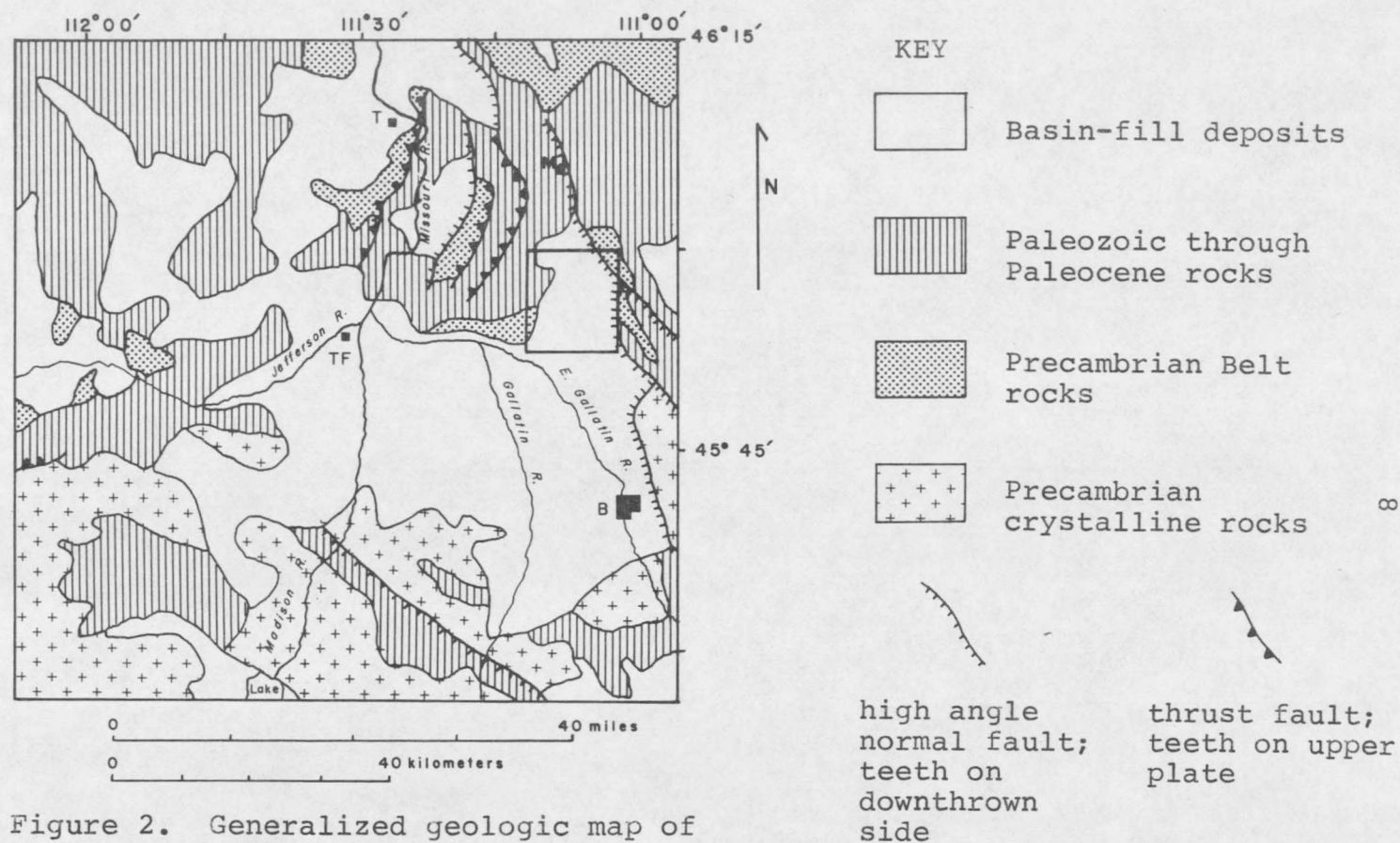
Rock classification in this study follows that of Folk (1974). However, rocks composed of silt and clay mixtures are designated mudstones.

PRE-CENOZOIC HISTORY

Precambrian Through Mesozoic Depositional History

Cenozoic strata in the Dry Creek Valley unconformably overlie rocks that range in age from late Precambrian through late Cretaceous. These pre-basin rocks are characterized by a wide variety of lithologies and structures. Older Precambrian crystalline rocks do not occur in the map area and, therefore, will not be discussed. Figure 2 shows the distribution of rocks in the Three Forks basin. A generalized stratigraphic section of the Dry Creek Valley area is illustrated in Figure 3.

Rocks of the Precambrian Belt Supergroup crop out along the northern margin of the Three Forks basin. They attain a thickness of 3000 m in the area. This unit consists of coarse arkosic sandstone and conglomerate and is designated the LaHood Formation (McMannis, 1963). This coarse facies wedges out abruptly into very fine-grained strata to the north, while the entire Belt section thickens in this direction (McMannis, 1963; Robinson, 1961). The LaHood Formation was deposited, in part, by turbidity currents which flowed down the southern flank of an embayment that stretched eastward from the Cordilleran geosyncline (McMannis, 1955; Bonnet, 1979).



Age		Stratigraphic Unit		Description	Thickness (meters)
Quaternary	Pinedale or younger (?)	Young alluvium		Angular to rounded gravel and finer deposits on present flood plains of streams	0-15(?)
		Debris-flow & Fan conglomerates		Large cobbles and boulders, consist of mainly LaHood arkoses	Unknown
		Old alluvium		Rounded gravels on former floodplains. Occur above the present elevation of drainages	0-5
	Late Pliocene early Quaternary	Fan & Pediment Gravel		Sheets & wedges of coarse unsorted angular to subrounded cobbles and boulders; occur high above present drainage	0-15(?)
Tertiary	Late	Bozenan Group	Sixmile Creek Fm	Pale-orange mudstones & coarse-grained cross-bedded & massive sandstones & conglomerates	Up to 1800
	Early		Renova Fm	White to light-gray tuffaceous limestones, marls & pale orange mudstones & fine-grained sandstones	
Cretaceous	Late	Livingston Group		Siltstone, shale & andesitic sandstones and conglomerates	Up to 4267
		Colorado Fm		Black shale, rusty gray-green sandstone and siltstones	366-731
	Early	Kootenai Fm		Orange siliceous sandstone, varicolored mudstones and limestone	118-136
Jurassic		Morrison FM		Red, yellow & brown mudstone, siltstone and sandstone	34-135
		Ellis Group	Swift Fm	Yellow calcareous sandstone with basal pebbly zone.	15-30
			Rierdon Fm	Massive gray oolitic limestone w/overlying shale beds	0-35
			Sawtooth Fm	Fine-grained, dark gray limestone interbedded w/shale	6-44
Permian		Phosphoria Fm		Dolomitic limestone, brown chert, dark phosphatic limestone, yellow siltstone and light-colored quartzitic sandstone	0-8
Pennsylvanian		Quadrant Fm		Light colored quartzitic sandstone and subordinate dolomitic limestones	47-76
		Amsden Fm		Red sandstone and mudstone grading upward into pink and gray limestone and quartzitic sandstone	3-58

Figure 3. Stratigraphic section of the Dry Creek Valley area (modified from McMannis, 1955, 1965; Robinson, 1963; and Aram, 1979).

Mississippian	Late	Big Snowy Group		Cherty limestone, red & yellow siltstone & sandstone; purples & pale yellow dolomites and limestones	0-132
	Early	Madison Group	Mission Canyon Fm	Gray thick bedded limestone	131-289
			Lodgepole Fm	Yellow-gray think bedded argillaceous limestone	229-247
Devonian	Late	Sappington Fm		Yellow sandstone grading downward into silty & sandy limestone; basal black shale	14-30
		Three Forks Fm		Upper orange siltstone; medial green shale; lower orange limestone & siltstone	47
		Jefferson Fm		Brown dolomite with subordinate black & gray dolomite & gray limestone	151-189
		Maywood Fm		Yellow, orange & red calcareous siltstone with thin beds of dolomite	0-13
Cambrian	Late	Snowy Range Fm	SagePebble Congl.Mbr.	Fine-grained limestone pebble conglomerate	37-62
			Dry Creek Shale Mbr.	Gray green fissile shale	13-23
			Pilgrim Fm	Gray & orange dolomite, subordinate gray limestone	111-132
	Middle	Park Fm		Greenish gray shale	57-113
		Meagher Fm		Gray & black limestone with orange mottling	112-113
		Wolsey Fm		Olive & brown micaceous shale, with interbeds of glauconitic sandstone & limestone	46-64
		Flathead Fm		Pine quartzitic sandstone	36-43
PE	Algonkian	Belt Series (LaHood Fm)		Brown coarse micaceous arkose & conglomerate interbedded w/argillites & siliceous limestones	2133-3050
	Archean	Metamorphic Rocks		Greiss, schist, amphibolite, pegmatite, Metaquartzite	Unknown

Figure 3. (continued)

The lower contact of the LaHood Formation is thought to be a fault or fault zone (Robinson, 1961; McMannis, 1955, 1963). The Willow Creek Fault, as it has been called, has an eastward trend and was active during late Precambrian, late Cretaceous, and possibly Cenozoic time. Although it has since been buried by younger Cenozoic deposits, the trace of the fault can be identified with the aid of gravity data (McMannis, 1955; Hackett and others, 1960; Robinson, 1961; Davis and others, 1965). The Pass Fault in the Bridger Range may be related to this fault (McMannis, 1955).

Stable cratonic conditions began in the early Paleozoic and persisted into Mesozoic time. Rocks deposited during this time crop out along the east flank of the Horse-shoe Hills and also occur high on the west flank and along the east side of the Bridger Range. The Paleozoic rocks consist mainly of marine carbonates and attain a thickness of 1524 m. Mesozoic rocks are predominately marine shales and sandstones and are also approximately 1524 m thick (Fig. 3; Robinson, 1961). The rocks deposited in both eras increase in thickness by 300% within 167 kilometers to the southwest, indicating that miogeosynclinal conditions existed nearby (Schmidt, 1975).

Laramide Orogeny

The Laramide orogeny had begun by late Cretaceous time and persisted into the Eocene (Robinson, 1961; McMannis, 1955). Intrusive and volcanic activity accompanied compressive forces which deformed and uplifted strata (Fig. 4). Thick wedges of detritus composed of volcanoclastic debris were generated from the rising highlands. The Livingston Group is an example of such a synorogenic deposit (McMannis, 1955; Roberts, 1963).

Folds and faults of "Laramide age" can be observed in the Horseshoe Hills, Maudlow basin, and the Bridger Range. Similar folds and faults may exist beneath the Cenozoic deposits in the Dry Creek Valley, but have since been eroded and buried.

Basin Origin

The basins of western Montana formed in the aftermath of the Laramide orogeny. The oldest basin-fill deposits in the Three Forks basin are middle to late Eocene in age. Therefore, the Three Forks basin already existed at this time (Robinson, 1963).

Tectonic movements must have formed the Three Forks basin. The faceted west flank of the Bridger Range and the abrupt rise in elevation of the Gallatin Range along the

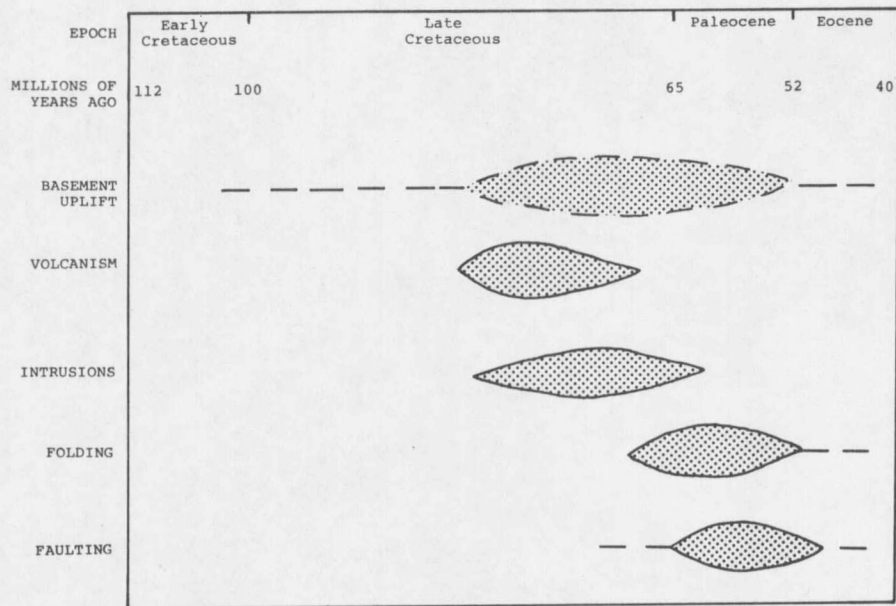


Figure 4. Timing of Laramide events (modified from Schmidt, 1975).

eastern and southern basin margins, respectively, indicate the presence of high-angle faults or fault zones (McMannis, 1955; Robinson, 1961; Davis and others, 1965). Further, the oldest Tertiary rocks in the Three Forks basin are alluvial fan and lacustrine deposits, indicating that interior drainage existed soon after basin formation. In light of these facts, Robinson (1963) believed that the basin was born closed and that the initial relief was primarily due to tectonism, not erosion.

In light of the foregoing discussion, it is probable that the Dry Creek Valley, a northern extension of the Three Forks basin, owes its origin to tectonism also. The fact that the valley lies directly adjacent to the Bridger Range front fault and that Tertiary strata are characterized by an eastward dip indicates that tectonic downdropping must have at least initiated and accompanied the formation of this valley.

REGIONAL TERTIARY STRATIGRAPHY

The Bozeman Group was defined by Robinson (1963, p. 61-62) as "... Tertiary fluvial, eolian, and lacustrine rocks which accumulated in the basins of western Montana after the Laramide orogeny ..." It consists of two unconformable, lithologically distinct depositional sequences (Fig. 5; Kuenzi and Fields, 1971). The Bozeman Group does not include synorogenic deposits such as the Beaverhead Formation or any rocks related to the Livingston Group.

Renova Formation

The lower depositional sequence consists of predominantly fine-grained strata of which conglomerate is an insignificant component. In the Three Forks basin, Robinson (1963) subdivided this lower unit into four mappable units and assigned each to formational status. In the Jefferson basin, Kuenzi and Fields (1971) further consolidated lower Bozeman Group terminology by naming the lower sequence the Renova Formation and designating some of Robinson's (1963) formations as members (Fig. 5). It is logical to repeat the latter classification in the Three Forks basin.

Rocks of the Renova Formation indicate that low energy floodplain and pond environments were dominant during

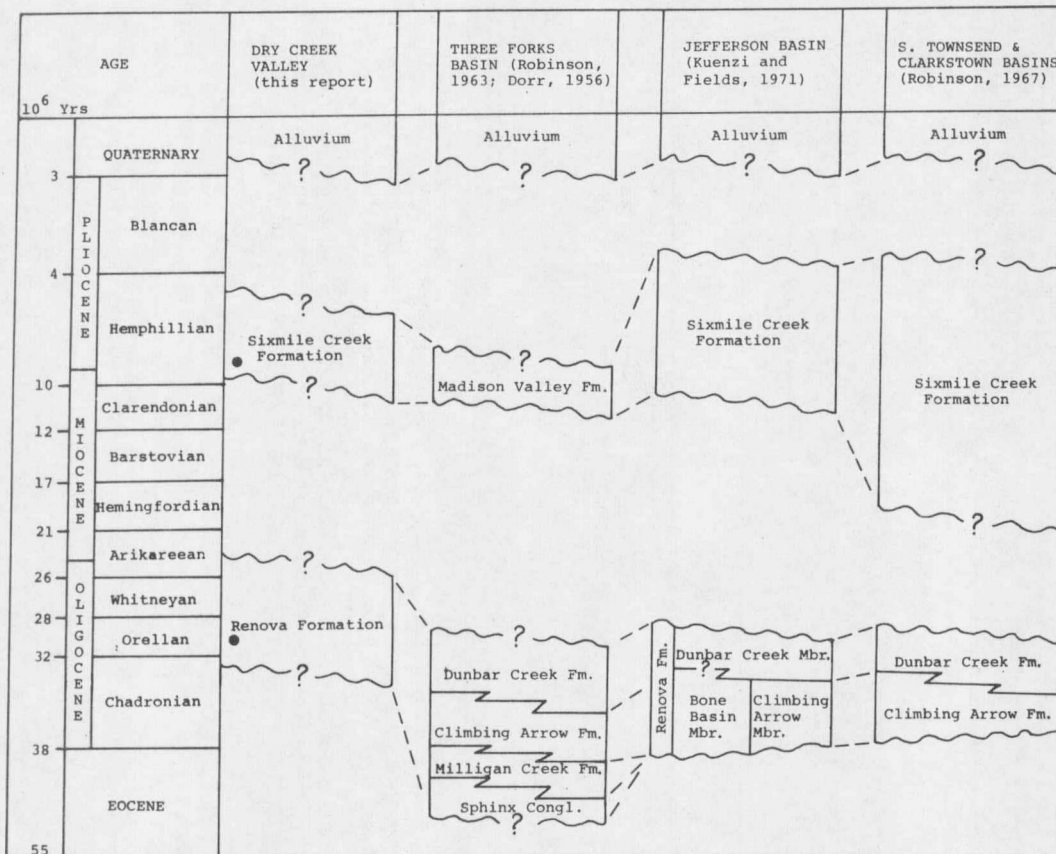


Figure 5. Rock-stratigraphic correlation and age of the Bozeman Group in the Dry Creek Valley, Three Forks, Jefferson, Townsend, and Clarkston basins. Note the difference between the stratigraphic terminology used in the Three Forks basin and that used in the Jefferson basin. • represents the stratigraphic position of a radiometrically dated ash bed (modified from Kuenzi and Fields, 1971; absolute dates obtained from Dawson, 1976).

Renova deposition. Mineralogic and textural data suggest that most of the Renova sediments were deposited under a relatively humid climate (Robinson, 1963; Kuenzi and Fields, 1971).

The age of the Renova Formation varies slightly from basin to basin, but ranges from middle Eocene to early Miocene (Robinson, 1960; Fields, 1972). Vertebrate fossils of Oligocene age are especially common in this formation (Robinson, 1960).

Radiometric dates obtained from volcanic ash units within the Renova Formation support the relative ages indicated by fossil remains. A potassium-argon date of 50.4 ± 2.1 mybp (early middle Eocene) was obtained from ash taken from Climbing Arrow strata near Shoddy Springs, northwest of Three Forks, Montana. Another ash bed within Renova strata located 2.5 km west of Menard rendered a potassium-argon date of 30.6 ± 1.2 mybp (middle Oligocene; Appendix II).

Middle Tertiary Unconformity

Since the earliest paleontologic investigations, geologists have suspected that there was a regional middle Tertiary unconformity in the Cenozoic basins of southwestern Montana, which separated the two depositional sequences of

the Bozeman Group. Its occurrence was indicated by the abundant discoveries of early Oligocene and late Miocene vertebrates, but few of intervening age (Robinson, 1960). The later works of Robinson (1961, 1963, 1967), Kuenzi and Fields (1971), and Rasmussen (1973) confirmed the existence of a middle Miocene unconformity by detailed mapping and intensive fossil collecting. The nature of this unconformity was found to be erosional in the North Boulder and Three Forks basins but may also be angular in the upper Ruby, Beaverhead, Jefferson, Townsend, and Clarkston basins (Robinson, 1960; Rasmussen, 1973).

In the Three Forks basin, the unconformity occurs in the vicinity of the Madison Bluffs area. Oligocene rocks occur west of this area and late Miocene and Pliocene rocks occur to the east (Robinson, 1960). The unconformity in the Dry Creek Valley occurs about 2.5 km west of Menard, although its location is only approximate (Fig. 6).

Fields (1972) and Robinson (1960) attributed the presence of the unconformity to erosion by through-flowing streams that developed in response to a change toward a more humid climate. The climate at this time was humid enough to establish and maintain through-flowing drainage nets which evacuated much of the Renova Formation.

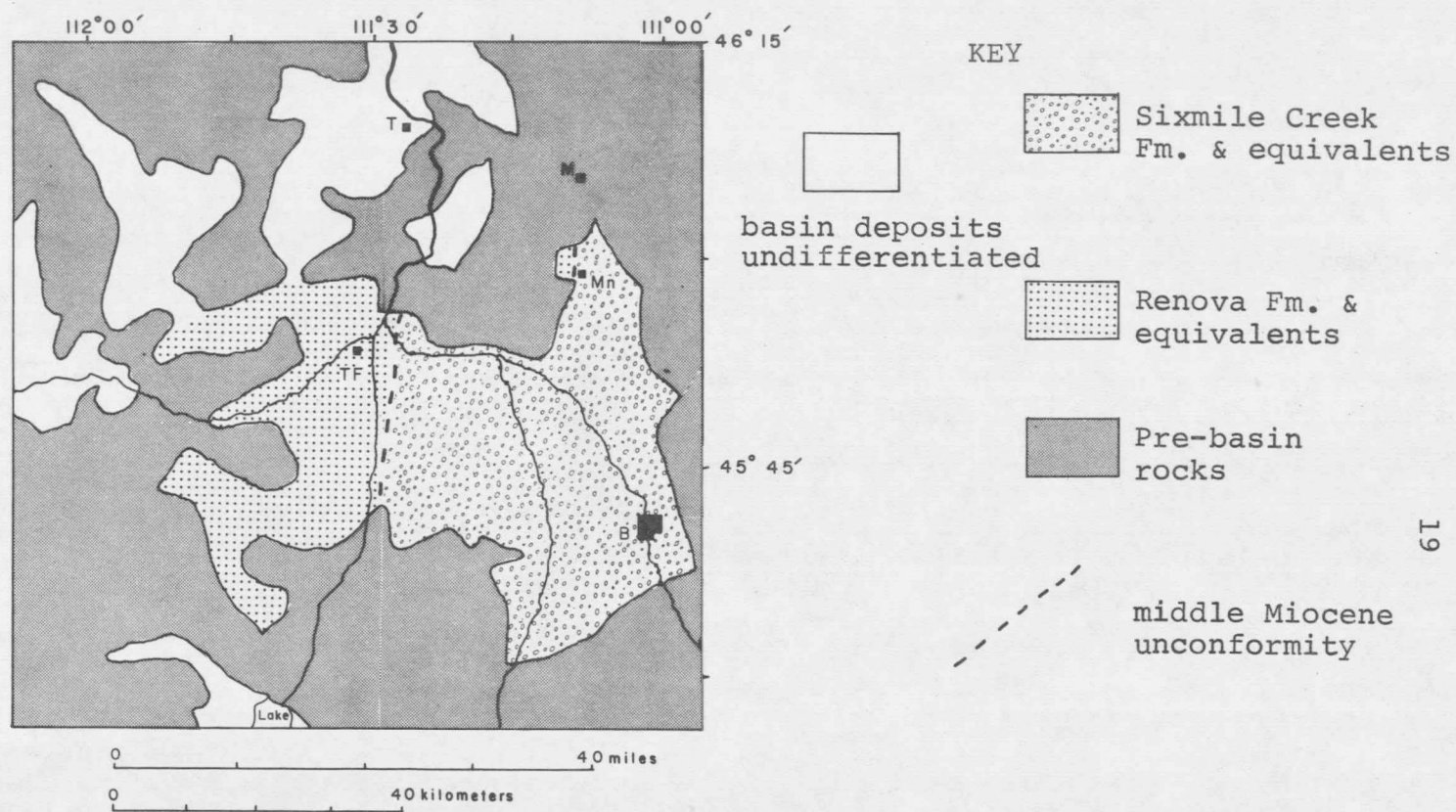


Figure 6. Generalized map of the Three Forks basin showing the approximate location of the middle Miocene unconformity. B= Bozeman; Mn= Menard; M= Maudlow; T= Toston; TF= Three Forks (after Robinson, 1960, 1961).

Sixmile Creek Formation

The upper depositional sequence of the Bozeman Group unconformably overlies the Renova Formation and consists of predominantly coarse-grained strata of which conglomerates are characteristic. This upper sequence was named the Sixmile Creek Formation by Robinson (1967) from exposures in the Townsend basin. No members have been assigned to this formation.

In the Three Forks basin, the upper sequence was called the Madison Valley formation by Douglass (1903) and Dorr (1956), but a type section was not designated according to the method prescribed by the Stratigraphic Code (Fields, 1979 pers. comm.; Hedberg, 1976). Consequently, the term "Sixmile Creek Formation" was used for the upper depositional sequence in this report (Fig. 5). It was also extended into the Jefferson, upper Ruby, and Sweetwater basins (Kuenzi and Fields, 1971; Monroe, 1974; Peterson, 1974).

Sixmile Creek strata represent a complex of ephemeral and perennial stream channel, overbank, and alluvial fan deposits (Kuenzi and Fields, 1971). The coarseness of Sixmile Creek deposits suggests that high-energy channel environments were more important during Sixmile Creek

deposition than during Renova deposition. Textural and mineralogical data suggest that a more arid climate predominated during Sixmile Creek deposition than during Renova deposition (Kuenzi and Fields, 1971; Kuenzi, 1974).

The age of the Sixmile Creek Formation varies slightly from basin to basin. Fossil vertebrate remains indicate that Sixmile Creek strata range from late Miocene to middle Pliocene (Kuenzi and Fields, 1971; Monroe, 1974). Vitric ash within Sixmile Creek strata in the southern Dry Creek Valley yielded a potassium-argon date of 8.9 ± 0.4 mybp (early Pliocene; Appendix II).

TERTIARY STRATIGRAPHY OF THE DRY CREEK VALLEY

Introduction

Continental Tertiary basin-fill deposits of fluvial, lacustrine, spring, and possibly eolian origin sporadically crop out in the Dry Creek Valley. These rocks compose the Bozeman Group and attain thicknesses greater than 915 m (Robinson, 1963; Davis and others, 1965). Basin-fill strata unconformably overlies Precambrian through Mesozoic rocks and are, in turn, unconformably overlain by a thin veneer of very late Tertiary or Quaternary deposits. The middle Tertiary unconformity may also occur within these basin-fill sediments.

Strata assigned to the Renova Formation occur only in the northwest corner of the map area. They consist of an alternating limestone-mudstone sequence and may represent Oligocene lacustrine and floodplain environments.

Sixmile Creek strata crop out along the western and southern margins of the area. Coarse-grained sandstones, conglomerates, and mudstones were deposited by ephemeral streams and sheetfloods which formed a complex of flood-basin and alluvial fan environments. The Sixmile Creek Formation was deposited under the arid climate of late Tertiary time (Kuenzi and Fields, 1971).

Spring deposits crop out at the southwestern margin of the study area. Limestones and conglomeratic limestones are the prevailing rock types, some of which contain ostracodes and fresh water algae. Geomorphic and structural relations indicate that they may be equivalent in age to the Sixmile Creek Formation.

Tertiary Renova Formation

Name, Stratigraphic Position, and Thickness

The lower depositional sequence of the Bozeman Group was named the Renova Formation in the Jefferson basin, where the natural unity of the sequence was demonstrated (Kuenzi and Fields, 1971). Monroe (1974) and Peterson (1974) extended this terminology into the upper Ruby and Sweetwater basins, respectively. The term Renova Formation has not been formally used in the Three Forks basin prior to this study.

Renova strata overlie Paleozoic and Mesozoic rocks with angular unconformity and presumably underlie Sixmile Creek strata with erosional unconformity. The total thickness of the Renova Formation in the map area is unknown.

Distribution and Topographic Expression

Renova strata crop out in one laterally

discontinuous exposure 2.8 km northwest of Menard. At this location, the Renova Formation forms a small but prominent northwest trending ridge. Its occurrence in other areas is only hinted at by the presence of limestone rock fragments which occur as colluvium. Most of the formation is poorly indurated and commonly forms slopes.

Measured Section and the
Location of the Unconformity

One section of Renova strata was measured 2.8 km northwest of Menard (NW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 27, T.3N., R.4E.; lower part of Section A-22, Appendix I). The section consists of 23.5 m of alternating limestone and tuffaceous marl (37%), tuffaceous mudstone (62%), and vitric ash (1%; Fig. 7; Appendix I). The base of the section is covered and the top is unconformably (?) overlain by the Sixmile Creek Formation. The nature and location of this upper contact (unconformity) is uncertain and deserves some discussion.

The middle Tertiary unconformity in the Menard area was first described by Klemme (1949) and later by Verrall (1955) as occurring at the base of a 0.9 m thick conglomerate bed. Hackett and others (1960) were the first geologists to map its location. The location of the unconformity was "arbitrarily set" at the top of the uppermost

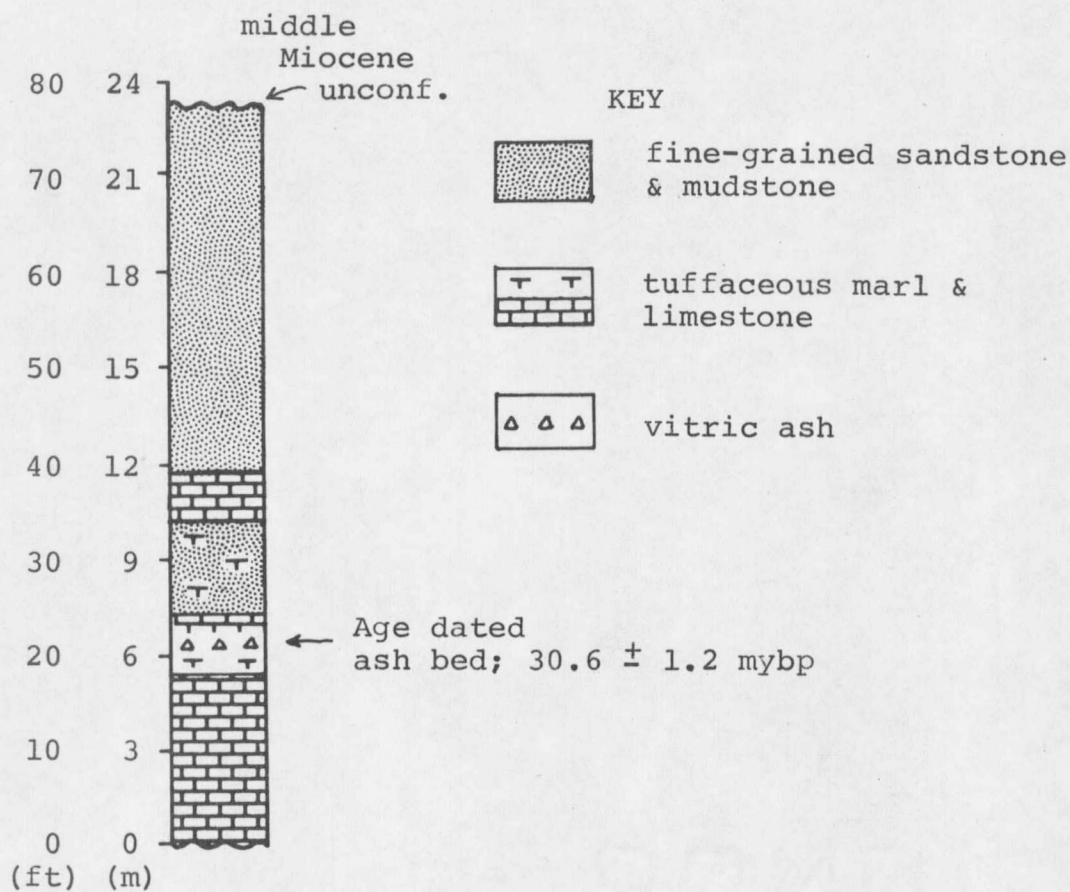


Figure 7. Stratigraphic column illustrating the succession of lithologies observed in the Renova Formation. This section represents the lower 23 m of measured section A-22 (Appendix I).

ostracode-bearing limestone. Robinson (1961), however, contended that previous workers used incomplete evidence to suggest the presence of the unconformity. He believed that the entire Tertiary section west of Menard was part of the upper depositional sequence. Available evidence presented in this report suggests that both Tertiary depositional sequences crop out west of Menard.

Vitric ash near the base of the measured section has yielded a potassium-argon date of 30.6 ± 1.2 mybp, a middle Oligocene age (Fig. 7; Appendix II). Rocks of this age have traditionally been assigned to the Renova Formation, the lower depositional sequence.

The upper depositional sequence (Sixmile Creek Formation) is also present in the Menard area. Approximately 16 m stratigraphically above the aforementioned 30.6 my ash bed is a 0.9 m thick conglomerate. The detrital clasts consist mainly of Tertiary rock fragments. Above this conglomerate, pale orange tuffaceous mudstones are associated with coarse fluvial sandstones and structureless to thickly bedded conglomeratic sandstones containing Paleozoic and Mesozoic clasts. These deposits have been assigned to the Sixmile Creek Formation because of their predominant coarse texture (Robinson, 1967; Kuenzi and

Fields, 1971). They represent ephemeral stream and alluvial fan sediments and seem to be lithogenetically related to other confirmed Sixmile Creek rocks which many workers believed were deposited under arid conditions (Kuenzi, 1974; Kuenzi and Fields, 1971; Robinson, 1961, 1967). Fossil vertebrates in other areas indicate that arid conditions prevailed from late Miocene into Pliocene time (Robinson, 1967; Kuenzi and Fields, 1971). Therefore, Sixmile Creek strata in the Dry Creek Valley are interpreted to be late Miocene through early or middle Pliocene in age also.

If this reasoning is valid, then the two depositional sequences (Renova and Sixmile Creek strata) are present in the Menard area. The unconformity is assumed to be present because of its regional nature (Robinson, 1960; Rasmussen, 1973). It is presumably an erosional unconformity because structural discordance has not been observed.

The Renova-Sixmile Creek contact (unconformity) has not been precisely located. It must occur in a 0.3 km-wide northwest trending zone which has its southwest flank bordering on the ridge where the middle Oligocene ash bed occurs. The northeast margin of this zone borders on the first outcrops of ephemeral stream deposits (Fig. 8).

The contact has been tentatively placed at the base

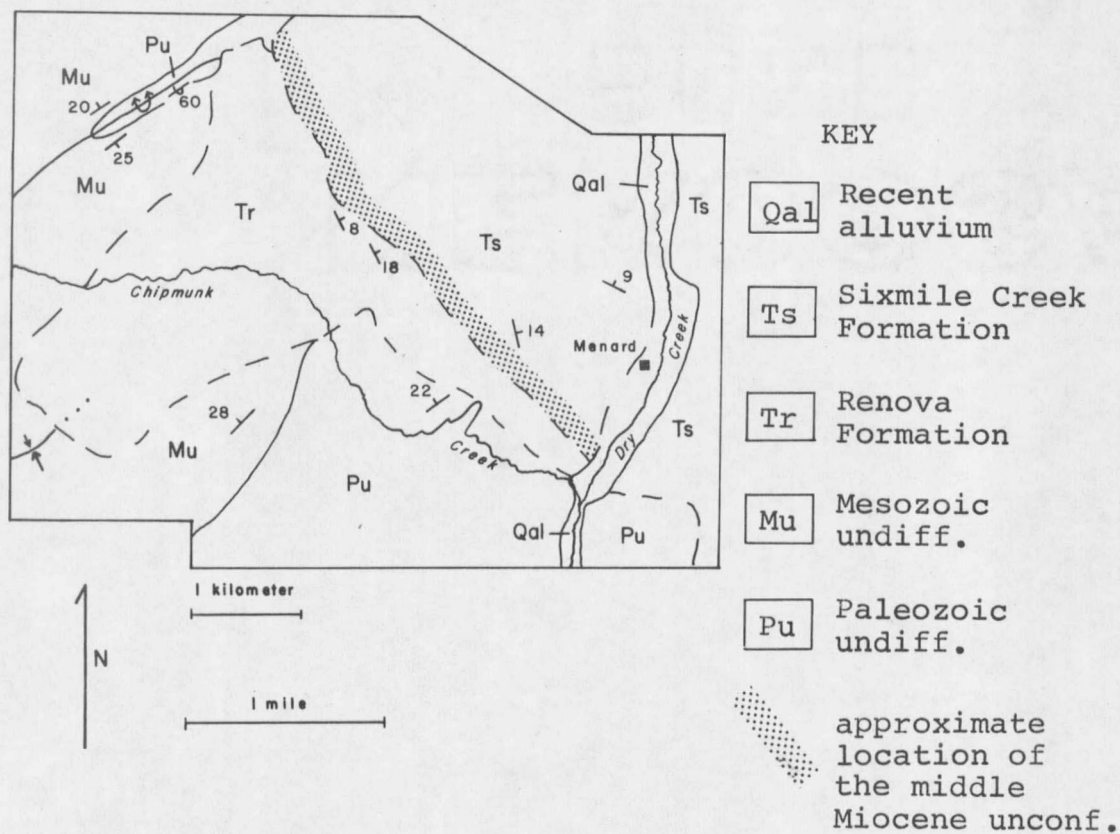


Figure 8. Generalized geologic map of the Menard area. The dashed line directly southwest of the stippled pattern is the tentative location of the Renova-Sixmile Creek contact.

of the 0.9 m thick conglomerate that occurs at measured section A-22 (Appendix I) and at the top of the last very dense lacustrine limestone southeast of this area (Plate I).

Lithology and Mode of
Deposition

Biosparites and Tuffaceous Biomicrites. Biosparites range from white to very light gray and are very dense. Porosity is low because most of the pores are filled with coarse anhedral calcite. Biosparites are consistently fine-grained, the sparry cement being less than 0.0625 mm in diameter. Ostracode fragments range up to 1 mm in diameter and are well sorted. These rocks are composed of approximately 65% fine sparry cement, 30% ostracode shell fragments, and subordinate amounts of calcite vug fillings and hematite staining.

Tuffaceous biomicrites are characteristically very light gray. Lime mud composes 60% of the rock, while ostracode shells constitute 20% and range up to 0.8 mm in diameter. Some of the bioclasts are aligned. Gastropods occur at the outcrop but not in thin sections. Glass shards are commonly less than 0.125 mm in diameter and compose 15% of the rock. Vug fillings of spar and hematite staining occur in subordinate amounts.

The biosparites and tuffaceous biomicrites are thought to have been deposited in a lacustrine environment. The thinly bedded and dense nature of the limestones and the presence of ostracodes support this interpretation.

Tuffaceous Mudstones. Tuffaceous mudstones are characteristically grayish orange and very porous and loosely packed. They are structureless to thickly bedded in outcrop. Grain sizes less than 0.0625 mm in diameter characterize these deposits, although fine sand grains do occur. Moderate sorting and angular to subrounded grains also characterize the tuffaceous mudstones. These rocks are composed of 45% detrital material and 45% glass shards. Much of the detrital material is too small to identify, although the sand grains are composed of varying amounts of quartz, plagioclase, and lithic fragments. Calcite constitutes 5 to 10% of the rock.

The mode of deposition of the tuffaceous mudstones is somewhat obscure. Inasmuch as these rocks are interbedded, in part, with the lacustrine limestones, the mudstones may be lacustrine in origin. They could also be overbank or flood-plain deposits that filled the preceding lake or pond, although associated channel deposits were not found.

Vitric Ash. Vitric ash is very light gray and very porous and loosely packed. The ash bed is 15 cm thick, massive, and is interbedded with tuffaceous marls. Glass shards make up 60 to 70% of the deposit. They are fresh and isotropic to slightly devitrified around the edges. They range up to 0.5 mm in diameter with keeled and sub-rectangular shapes being common. Detrital grains occur in subordinate amounts. The ash has a refractive index of 1.508 ± 0.002 . This may indicate that the ash is composed of 69% SiO_2 and, therefore, rhyolitic in composition (George, 1924).

The association of the ash bed with ostracode-bearing tuffaceous biomicrites strongly suggests that the ash was blown into a lake or small pond. Why the ash has remained so unaltered is uncertain.

Environment of Deposition:
Renova Formation

Rocks of the Renova Formation indicate a complex of lacustrine and possibly floodplain depositional environments. Robinson (1963) and Kuenzi and Fields (1971) contended that rocks of this age were deposited under more humid conditions than the overlying Sixmile Creek Formation.

Age, Fossils, and Correlation

A potassium-argon date was obtained from a sample of the vitric ash previously described. The age is 30.6 ± 1.2 mybp (middle Oligocene; Appendix II). In the Menard area, Tertiary basin-fill strata are characterized by a general northeastward tectonic dip. The ash sample was taken near the base of the Renova measured section which, in turn, is the westernmost exposure of Renova strata in the map area. Therefore, this deposit represents the oldest exposed Tertiary deposit in the study area.

Fossils diagnostic of age were not found. Ostracodes and gastropods are common in the lacustrine deposits.

The age of the Renova Formation in the Dry Creek Valley correlates very well with younger Renova strata elsewhere. The Renova Formation in the Dry Creek Valley is equivalent in age to the Dunbar Creek Formation and the Dunbar Creek Member in the Three Forks area and Jefferson basin, respectively (Fig. 5; Robinson, 1963; Kuenzi and Fields, 1971). Renova strata in the upper Ruby basin range from early Oligocene to early Miocene in age (Monroe, 1974).

Tertiary Sixmile Creek Formation

Name, Stratigraphic Position, and Thickness

The Sixmile Creek Formation was named by Robinson (1967) for the coarse-grained upper depositional sequence of the Bozeman Group in the Townsend basin. Kuenzi and Fields (1971), Monroe (1974), and Peterson (1974) extended the term "Sixmile Creek Formation" into the Jefferson, upper Ruby, and Sweetwater basins, respectively. The term Sixmile Creek Formation has not been formally used in the Three Forks basin prior to this study.

Sixmile Creek strata unconformably overlie the Renova Formation west of Menard. They may also unconformably overlie Precambrian through Paleozoic rocks in the southwestern portion of the map area and in the vicinity of Accola. The Sixmile Creek Formation is unconformably overlain by a thin veneer of younger coarse unconsolidated gravels. The total thickness of Sixmile Creek strata is unknown but is at least 331.9 m thick in the composite section.

Distribution and Topographic Expression

Sixmile Creek strata are best exposed along the southern, western, and northwestern margins of the map area.

The rocks crop out in swales and channels that have been cut deep enough to expose them. The best exposures occur along the southern bluffs east of Foster Creek and northwest of Menard (Appendix III). Elsewhere, Sixmile Creek rocks are poorly exposed or are completely covered by younger unconsolidated gravels and soil.

Sixmile Creek strata are poorly indurated and commonly form slopes. However, resistant ledges are locally produced where rocks are entirely cemented. The best expression of these deposits occurs on south-facing slopes.

Measured Section

A composite section, representing the lower 331.9 m of the Sixmile Creek Formation, was measured west and northwest of Menard (Appendix I). Only 45 m of the 331.9 m measured were exposed.

Figure 9 is a stratigraphic column that represents the measured portion of the Sixmile Creek Formation. The percentages of rock types in the composite section are: coarse sand and conglomerate, 33%; cross-bedded medium to coarse-grained sandstone, 8%; fine-grained sandstone and mudstone, 56%; vitric ash, 2%; and tuffaceous marl, 1%. These percentages are not believed to be representative of the entire Sixmile Creek Formation in the Dry Creek Valley.

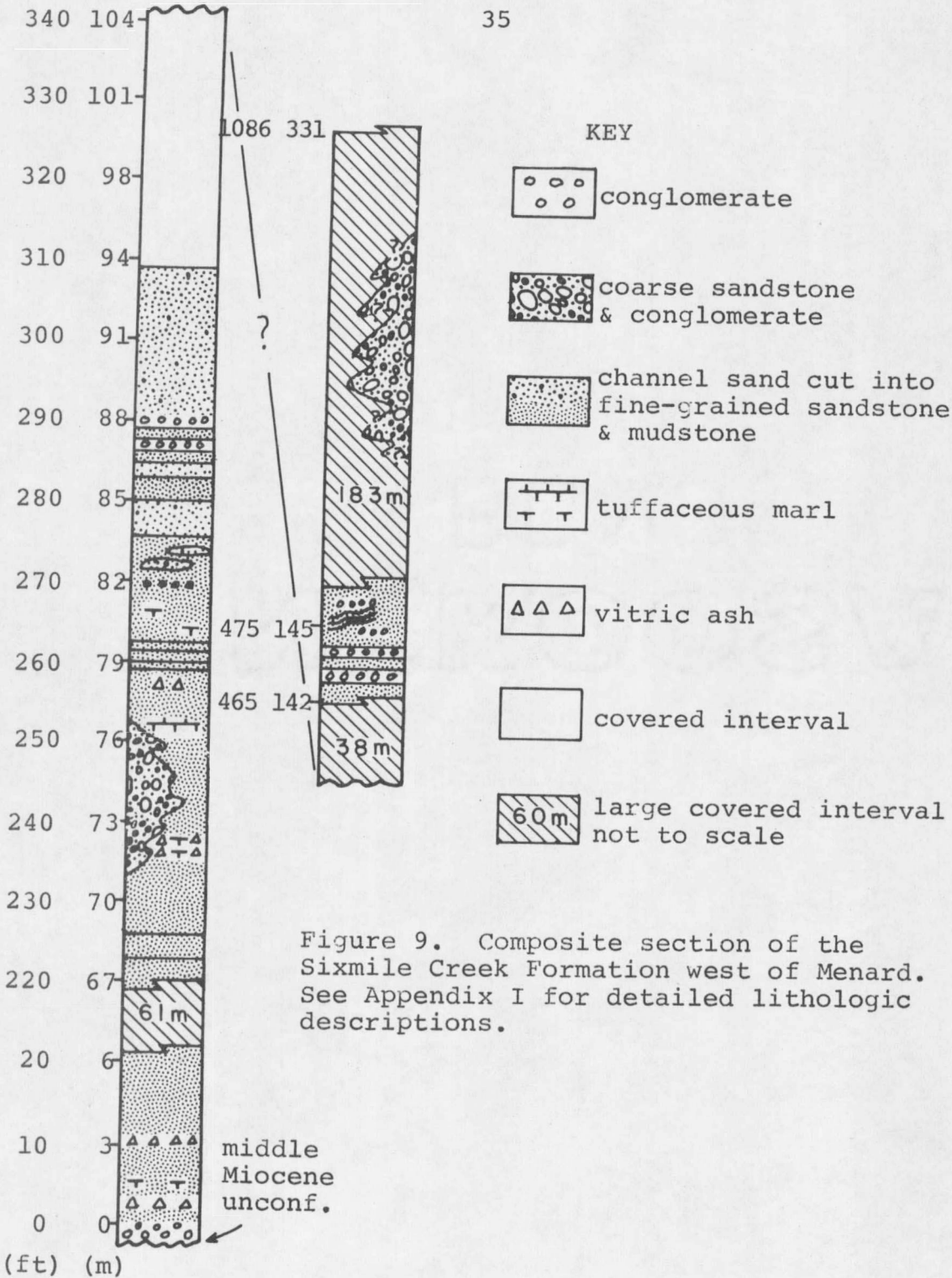


Figure 9. Composite section of the Sixmile Creek Formation west of Menard. See Appendix I for detailed lithologic descriptions.

Exposures observed east and southeast of Menard suggest that Sixmile Creek strata contain much more coarse-grained sandstone and conglomerate and less fine-grained sandstone and mudstone than these percentages indicate.

Lithology, Provenance, and
Mode of Deposition

Cross-Bedded Sandstone and Conglomerate. Cross-bedded sandstone and conglomerate crop out at three different locations: 1) west of Menard; 2) northeastern portion of the map area; and 3) southwestern portion of the map area. At each of these locations, Sixmile Creek strata show fluvial characteristics such as channel forms, cross-bedding, and imbrication. Descriptions and interpretations of the rocks at each location follows directly.

West of Menard (S $\frac{1}{2}$, Sec. 26, T.3N., R.4E.) — In this area, cross-bedded sandstones and conglomerates are typically grayish orange to very pale orange and are porous and loosely packed. Trough and wedge-set cross-bedding and poorly developed imbrication characterize these deposits. Both cross-bedding and imbrication typically have a southward orientation. These deposits are characterized by a channel form appearance (Fig. 10A).

Grain sizes range from silt to cobbles, the latter

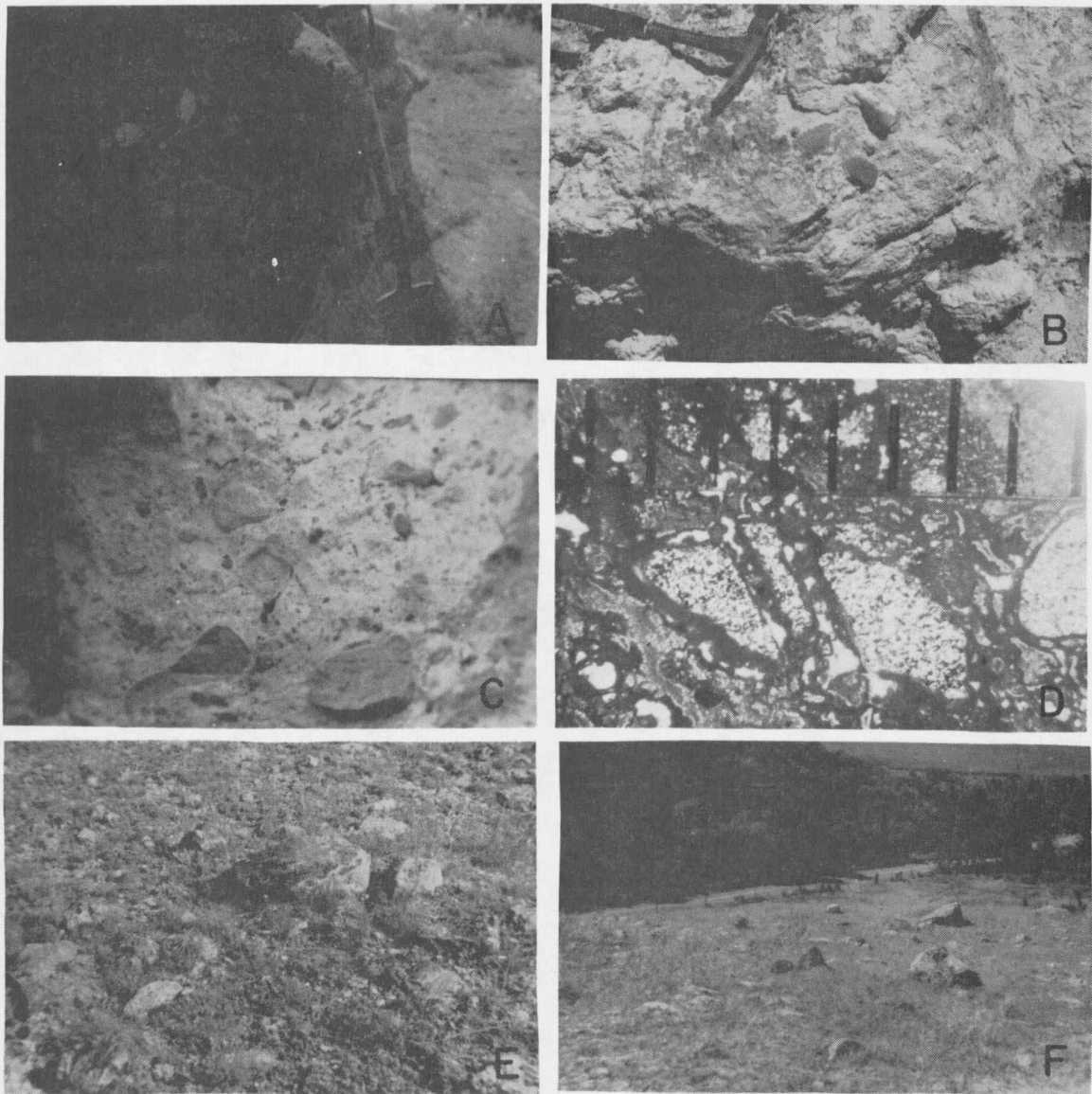


Figure 10. A. Channel form appearance of Sixmile Creek strata west of Menard. B. Large gravel-sized clasts suspended in structureless conglomeratic sandstone. C. View of the matrix-supported conglomerate at the outcrop. D. Thin section of the matrix-supported conglomerate under plane light. Note the split grain and the intervening micrite. Hatched marks are 1 mm apart. E, F. High level unconsolidated mantle material west of Menard and in the northeastern portion of the map area, respectively.

of which are up to 20 cm in diameter. Medium-grained sand to 3 cm diameter gravels are common. Most grains are angular to subangular, although well-rounded clasts do occur. These deposits are poorly to moderately sorted.

The cross-bedded sandstones and conglomerates west of Menard contain 30 to 40% lithic fragments. Metamorphic and andesitic volcanic rock fragments compose 1% and 20% of all the rock fragments, respectively. Paleozoic and Mesozoic clasts constitute the remainder. Quartz makes up 10 to 30% of the deposits, while 5 to 20% is plagioclase and microcline. Mica, heavy minerals, and glass shards occur in subordinate amounts. Most of these rocks fall into the feldspathic litharenite range (Fig. 11).

The volcanic clasts within these deposits were probably derived from the Maudlow basin to the north, where Livingston volcanic and volcanoclastic rocks crop out (Skipp and Peterson, 1965). Plagioclase and microcline observed in these rocks also originated from this area. The nearest outcrop of the Livingston Group is 5 km north of Menard. The proposition of a northern source is also supported by the southward orientation of both cross-bedding and imbricated clasts.

The metamorphic rock fragments were probably derived

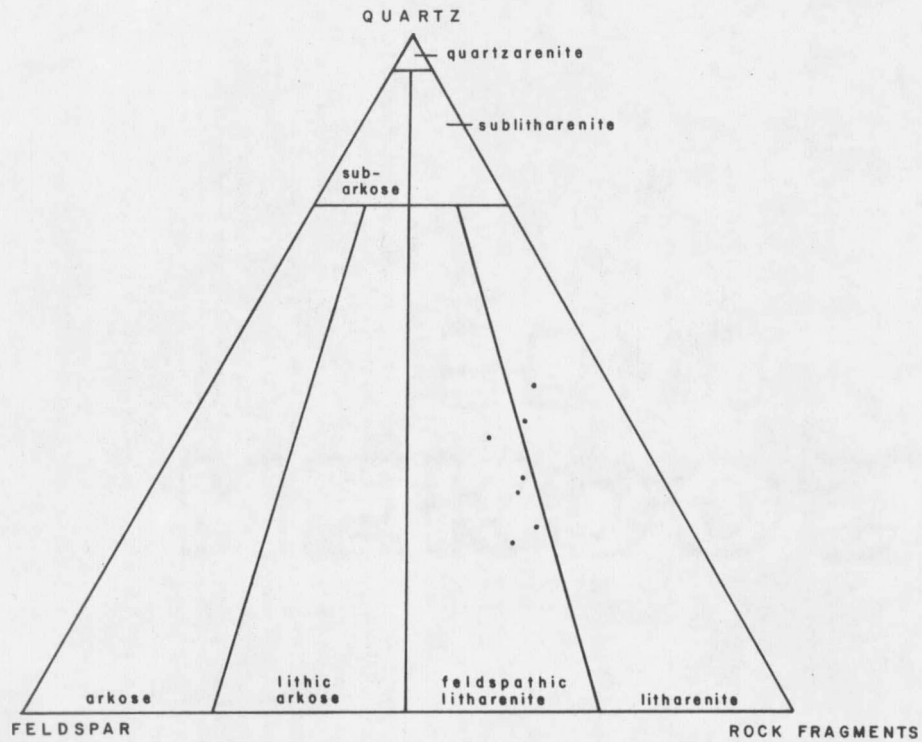


Figure 11. Composition of the cross-bedded sandstones that crop out west of Menard.

from the Precambrian core of the Big Belt Mountains farther north. Whether these metamorphic rock fragments were transported directly from the Big Belt Mountains or were reworked from older Tertiary deposits to the north is uncertain. Upper Paleozoic and Mesozoic clasts observed in these deposits originated in the Horseshoe Hills, because these pre-basin rocks are exposed west of Menard (Plate I).

The presence and orientations of both cross-bedding and imbrication imply that southward flowing fluvial systems transported much of this detritus from the north. The cut and fill channel form, combined with the predominant angularity and poor sorting of these deposits indicate that ephemeral streams rapidly deposited locally derived sediments, presumably in the waning stages of short-lived floods (Fig. 10A). Many of the features observed here compare to those of modern ephemeral streams described by Picard and High (1973).

Northwestern Portion of the Map Area — Coarse imbricated conglomerates are exposed in the ^{western} northeastern part of the map area. The best exposure occurs in a gully just north of Johnson Canyon Road (SE $\frac{1}{4}$, NE $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 3, T.2N., R.5E.), while smaller outcrops occur directly adjacent to this road. Another exposure crops out along the north side of Cox Road

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in the SE $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 9, T.2N., R.5E. Similar rocks probably underlie the hills south of Johnson Canyon Road, but have been covered by younger unconsolidated cobbles.

The conglomerates are very pale orange and are grain-supported. Horizontal bedding occurs in the conglomerates north of Johnson Canyon Road, each bed being 15 to 30 cm thick. Within each bed, very well developed westward imbrication is present. Small sand lenses also occur within this exposure and are 5 to 10 cm wide and 3 to 4 cm thick. Coarse-grained sand to small cobbles are common grain sizes, although silt-sized grains and clasts up to 20 cm in diameter do occur. The clasts are angular to subrounded and are poorly sorted.

Rock fragments compose 30 to 40% of the rock. LaHood arkoses and Paleozoic limestones make up at least 50% of all the lithic fragments observed. Paleozoic sandstones and shales and Tertiary clasts occur in subordinate amounts. Lithologies that represent rocks stratigraphically above the Quadrant Formation were not observed. Quartz composes 10 to 15% of the conglomerate, while plagioclase occurs in amounts up to 10%. Mica and heavy minerals were observed in lesser amounts. The amount of calcite cement varies between exposures, but can compose up to 30% of the

rock.

The composition and westward imbrication of these deposits indicates that they were derived from the Bridger Range. The imbrication, predominant angularity, and the occurrence of detrital clasts of shales and Tertiary rocks suggest that these sediments were rapidly deposited by a westward flowing stream. The size and nature of this stream is unknown. It may have been a distributary channel flowing over an alluvial fan.

Southwestern Portion of the Map Area — In the southwestern part of the map area, in the bluffs adjacent to Dry Creek, very small poorly exposed imbricated sandy cobble conglomerates crop out (N $\frac{1}{2}$, Sec. 34, T.2N., R.4E.; SE $\frac{1}{4}$, Sec. 27, T.2N., R.4E.; NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E.). These conglomerates are semi-consolidated to consolidated, horizontally bedded, and imbricated to the south-southwest.

Coarse-grained sand to gravel-sized clasts predominate, but clasts up to 30 cm in diameter occur. The conglomerates are poorly sorted, and angular to well-rounded grain shapes are common. Rock fragments compose 30 to 45% of the deposit, LaHood arkoses and Paleozoic limestones being the most characteristic. Clasts resembling Quadrant and Morrison sandstones are also common. Tertiary clasts

and Precambrian and Paleozoic shales also occur as detrital material but are rare. Quartz comprises 10 to 20% of the deposits, while feldspars compose 20%. Plagioclase makes up at least 80% of the total feldspar observed; microcline occurs in lesser amounts. Calcite cement may constitute 45% of some of the conglomerates.

A conglomerate bed east of Dry Creek (NE $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E.) contains volcanic rock fragments up to 15 cm in diameter. This outcrop represents the southern-most limit where volcanic rock fragments occur in Tertiary Sixmile Creek strata (Fig. 12).

The conglomerates in the southwestern portion of the map area were derived from a northern source. The presence of andesitic volcanic rock fragments, Quadrant and Morrison sandstone clasts, and southward imbrication support this interpretation.

The conglomerates were deposited by southward flowing fluvial systems, as evidenced by their composition, coarse and rounded nature, and southward imbrication. The nature of these streams is uncertain, but the streams may have nearly followed the present course of Dry Creek.

Structureless to Thickly Bedded Conglomeratic Sandstone. Structureless to thickly bedded conglomeratic

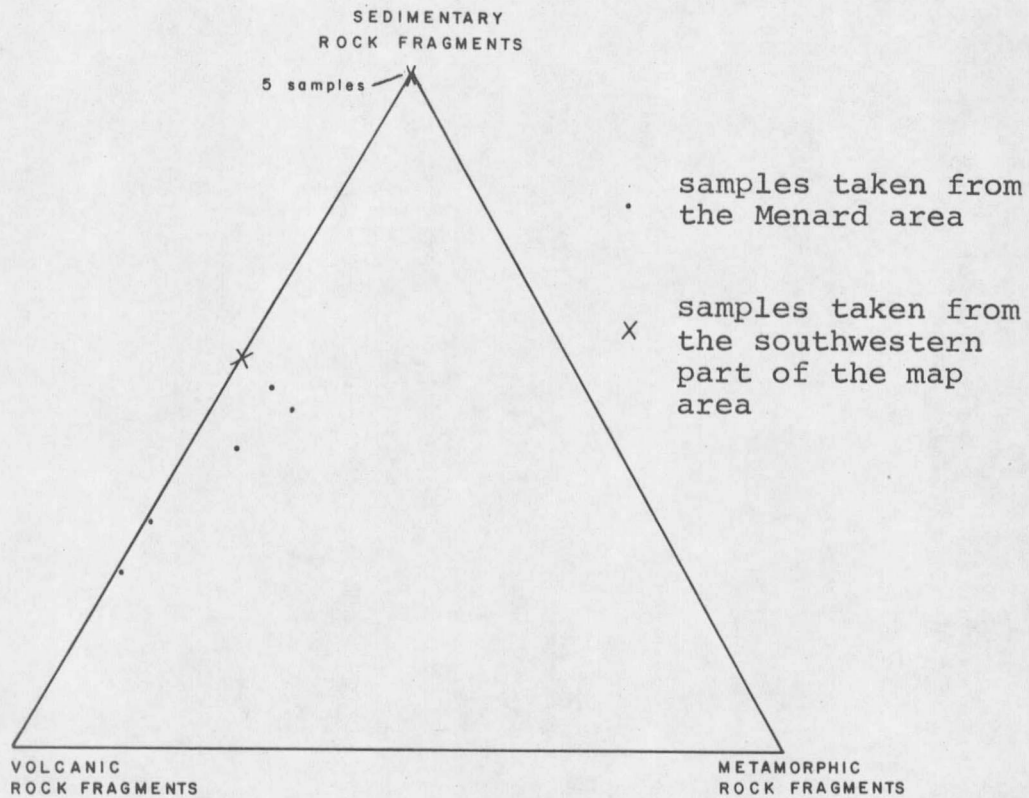


Figure 12. Ternary diagram illustrating the type and proportion of lithic fragments that occur in some of the Sixmile Creek fluvial deposits. The igneous and metamorphic rocks were derived from the Maudlow basin to the north.

sandstones occur throughout the study area. They are best exposed in the central and southern portions of the study area, east of Foster Creek. More discontinuous exposures occur southwest and east of Menard and southeast of Accola (Appendix III).

The conglomeratic sandstones are grayish orange to pale yellowish orange and are usually consolidated. These deposits are structureless to thickly bedded, the beds ranging from 15 to 30 cm thick. The grains are randomly oriented and are in contact with each other. Large gravel- and cobble-sized clasts are "suspended" in the sand (Fig. 10B). Some of these deposits are cut by overlying fine-grained well sorted cross-bedded sandstones and conglomerates.

Grain sizes range from silt to small cobbles, the latter of which ranges up to 7 cm in diameter. Medium to coarse sand is the average grain size. The grains are angular to subround and are poorly to moderately sorted.

These deposits are comprised of 25 to 40% lithic fragments. LaHood arkoses and Paleozoic limestones are the most common lithologies observed. Quartz constitutes 10 to 30% of the rocks, while plagioclase and microcline compose up to 25%. Well preserved isotropic glass shards make up

20% of some of the samples. Mica, heavy minerals, and matrix occur in subordinate amounts. Calcite cement occurs in varying amounts.

In the vicinity of Menard, the conglomeratic sandstones are apparently devoid of LaHood arkose lithic fragments. They are also low in feldspar, relative to the deposits southeast of this area (Fig. 13). The deposits in the Menard area also contain a predominance of Mesozoic lithologies, whereas those to the south do not.

The feldspathic litharenites of the southern and central portions of the map area were probably derived from the Bridger Range and the southeastern portion of the Horseshoe Hills. The relatively high feldspar content is thought to reflect the presence of the LaHood Formation in the source areas.

The relatively low feldspar content and the absence of LaHood arkose lithic fragments in the litharenites near Menard probably reflect the absence of arkosic source rocks. The abundant Mesozoic lithologies observed in these deposits can be attributed to the presence of Mesozoic strata west of Menard (Plate I).

The apparent absence of volcanic lithic fragments in all of these deposits indicates that the Maudlow basin did

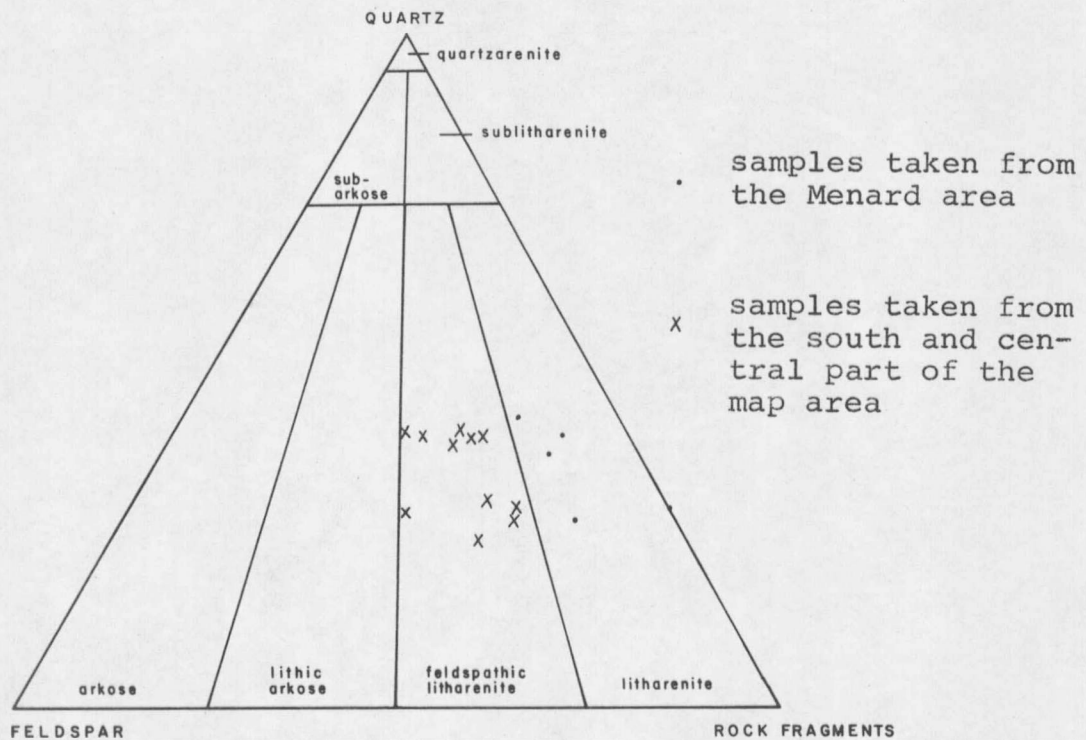


Figure 13. Composition of structureless to thickly bedded conglomeratic sandstones. The slightly higher feldspar content in rocks of the south and central portions of the map area reflects the presence of the LaHood Formation in the source area.

not contribute any detrital material. The Bridger Range and the Horseshoe Hills supplied all of the detritus.

The mode of deposition of the structureless to thickly bedded conglomeratic sandstones is uncertain. Their poor sorting, predominant angularity, high content of well-preserved glass shards, random orientation of grains, and structureless to thickly bedded character imply a short distance of transport and very rapid deposition. The low content of matrix and the grain-to-grain nature of these sandstones indicate that they were deposited in an aqueous medium, rather than a viscous one. Similar deposits in other basins have been attributed to sheetfloods (R. W. Fields, 1978, pers. comm.).

Although sheetfloods and their deposits are not well documented, they have been described by McGee (1897), Davis (1938), Rahn (1967), and Bull (1972) and will be briefly discussed here.

Sheetfloods are one of many alluvial fan processes that operate under arid conditions and have been observed in the southwestern United States (McGee, 1897; Rahn, 1967). They are surges of sediment-laden water that spread from the end of a stream channel onto an alluvial fan. Deposition is initiated by a widening of the flow into

intricately braided shallow bands or sheets and a simultaneous decrease in depth and velocity of flow. Change in the gradient at the end of the channel does not seem to be an influencing factor (Bull, 1972). Depths of water are generally less than 30 cm. Shallow braided distributary channels rapidly fill with sediment and then shift a short distance to another location. The final product is a sheet-like deposit of sand and gravel that is traversed by shallow braided channels (Bull, 1972). One of the striking peculiarities of sheetfloods is the shortness of their flow in distance as well as time. This is because they are fed by local and short-lived downpours of rain and are absorbed by the dry and pervious detrital slopes of the alluvial fan (Davis, 1938).

None of the aforementioned characteristics of the conglomeratic sandstone in the map area, when considered individually, support the proposition of sheetflood origin. But when they are considered together, they do suggest rapid deposition in an aqueous medium, such as in a sheetflood. A fluvial origin may be an alternative explanation, but the lack of grains with preferred orientations and the apparent absence of cross-bedding and channel forms may preclude such a suggestion. Certainly, fluvial systems must have been

associated with these deposits, because the massive conglomeratic sandstones are, at some locations, cut by overlying well sorted cross-bedded sandstones and conglomerates. This relation may further support the idea of a sheetflood origin. As Bull (1972) and Davis (1938) observed, present day sheetflood deposits are traversed by shallow braided channels. These shallow channels may be a modern analogue to these overlying fluvial deposits.

Based on all of these observations, the structureless to thickly bedded conglomeratic sandstones are tentatively believed to represent alluvial fan deposits, deposited principally by sheetfloods. This interpretation corresponds to that of Fields (1979, pers. comm.) and Kuenzi (1974) concerning portions of Sixmile Creek strata in other basins.

Matrix-Supported Conglomerate. One exposure of a matrix-supported conglomerate was found near the northern boundard of the map area in the NW $\frac{1}{4}$, SW $\frac{1}{4}$, SW $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 29, T.3N., R.4E. The rock is grayish orange and is tightly cemented. All of the grains observed in outcrop and in thin-section appear to float in a lime mud matrix and are randomly oriented.

Large detrital clasts up to 18 cm in diameter occur,

although coarse sand to large pebbles are the predominant grain sizes. Many of the grains are subangular to subround, poorly sorted, and randomly mixed.

Rock fragments compose 30% of the deposit, 15% of which are LaHood arkoses. Paleozoic and Mesozoic lithologies are also common, while Livingston volcanic and volcanoclastic rock fragments are rare. Quartz constitutes 10% of the rock, and plagioclase occurs in amounts less than 10%. Micrite and coarse anhedral spar make up 35% and 25% of the sample, respectively. Micrite composes the matrix and also occurs as coatings around grains. Spar has filled pores within the micrite (Figs. 10C, 10D).

The abundance of Precambrian LaHood arkoses and the presence of lower as well as upper Paleozoic lithologies indicate that the Bridger Range supplied the majority of detrital material. Lithic fragments of upper Paleozoic and Mesozoic rocks were probably derived from the Horseshoe Hills. The small amount of volcanic rock fragments observed originated in the Maudlow basin area or were reworked from older Tertiary deposits.

Micrite and spar are probably diagenetic features. Many detrital grains are completely separated or split by the intervening micrite and the pieces can be visually fit

back together. If the grains were broken during or prior to deposition, it seems unlikely that the broken pieces would have remained so close together. Consequently, the micrite is believed to be secondary (Fig. 10D). The coarse anhedral calcite spar occurs as pore-fillings within the micrite. This relationship suggests that the precipitation of spar post-dated that of the micrite.

The CaCO_3 occurs as a supporting framework in the conglomerate and is in excess of that needed for cementation. If the micrite and spar were removed, the grains would collapse through lack of support. Therefore, the CaCO_3 is not just a cement in this deposit, because it is more than a binding agent.

Based on the observations given in the preceding paragraphs, the matrix-supported conglomerate represents a Tertiary caliche soil or calcrete. The following characteristics of this deposit are shared by other ancient as well as modern caliche soils studied by Watts (1978), Steel (1974), Siesser (1973), Gardner (1972), and Brown (1956): 1) matrix-supported character; 2) the predominance of fine-grained lime mud and subordinate amounts of sparry calcite; 3) the detrital material and CaCO_3 are randomly mixed; 4) CaCO_3 occurs in amounts greater than that needed

for cementation; and 5) brecciated or split grains.

There is some disagreement on how the detrital grains in number 5 are broken. But most workers agree that the grains are broken in situ, after deposition, by pedogenic processes (Klappa and Watts, 1979).

The occurrence of a caliche soil within the Sixmile Creek Formation fits in very well with the developing scenario of late Tertiary time; that is, a time of alluvial fan deposition under an arid climate.

Vitric Ash. The best exposures of vitric ash in the Sixmile Creek Formation occur along the southern bluffs east of Foster Creek Road, and in a road cut along Foster Creek Road in the SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 6, T.1N., R.5E. Other less pure ash beds crop out discontinuously west of Menard.

The ash is very light gray and porous and loosely packed. The exposure along Foster Creek Road is 0.9 to 1.5 m thick. Horizontal laminations 2 to 4 mm thick occur in the lower 0.9 m. In the top 0.6 m, climbing ripples were observed. The ash bed overlies a tuffaceous mudstone with an abrupt contact and is in turn, overlain by younger coarse unconsolidated gravels.

Very fresh angular isotropic glass shards constitute 60 to 70% of the ash. Some of the shards are slightly

devitrified around the edges. Detrital grains occur in subordinate amounts. The refractive indices of the ash range from 1.505 ± 0.002 to 1.506 ± 0.002 . This may indicate that the ash is composed of 70% SiO_2 and is, therefore, rhyolitic in composition (George, 1924).

The purity of the ash and the abrupt contact with the underlying mudstone indicate that the ash fell into a very low energy environment, where little detrital material was being reworked. A small pond or stagnant waters on a floodplain may be such a site. The climbing ripples near the top of the exposure imply that some of the ash was reworked, after it was deposited, but not to the extent that it was mixed with other clastic material. The source of the ash is unknown.

Tuffaceous Marls and Mudstones. The tuffaceous marls and mudstones of the Sixmile Creek Formation are similar to those of the Renova Formation. The tuffaceous marls are best exposed west and northwest of Menard. Most of the marls are less than 0.9 m thick and contain more than 50% calcium carbonate. The thinly bedded nature of the marls and the presence of ostracode remains indicate that the marls were deposited in ephemeral ponds or small lakes.

The tuffaceous mudstones are best exposed west of

Menard, although they also occur along Foster Creek Road with the vitric ash. They are much more variable in terms of types of sedimentary structures than those of the Renova Formation. The mudstones are structureless to thickly bedded and are cut into by ephemeral stream channel deposits. They contain discontinuous ripple stratification, root casts, burrows, and algal mounds. The mudstones are thought to represent floodplain and overbank deposits.

Environment of Deposition:
Sixmile Creek Formation

The foregoing descriptions and interpretations of the lithologies indicate that the Sixmile Creek Formation was deposited in a complex of flood-basin and alluvial fan environments. The coarse textures and mode of deposition of many of these deposits suggest that high energy systems predominated during a time of internal drainage and basin-filling. Many of these coarse deposits are products of short-lived floods which developed in response to local but heavy downpours of rain.

In other basins, Sixmile Creek strata were deposited under an arid climate (Kuenzi and Fields, 1971; Kuenzi, 1974; Monroe, 1974). The depositional environments described above support this contention. R. W. Fields (1979,

pers. comm.) believed that during the time of Sixmile Creek deposition, the countryside acquired the general appearance and climate of the present arid southwestern United States.

Age, Fossils, and Correlation

A potassium-argon date was obtained from vitric ash along Foster Creek Road in the SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 6, T.1N., R.5E. (Appendix II). The age is 8.9 ± 0.4 mybp (early Pliocene). The lack of exposure in this area prevents any accurate interpretation concerning the exact stratigraphic position of the ash bed. Because of a localized north-westward dip in the area, the alluvial fan deposits directly to the southeast and northwest are thought to be slightly older and younger, respectively, than the ash.

Sixmile Creek strata exposed west of Menard are thought to be the oldest Sixmile Creek rocks in the map area. This is because most of the Tertiary strata in the map area dip eastward and the rocks west of Menard represent the westernmost occurrence of the Sixmile Creek Formation. The oldest Sixmile Creek equivalent in the Three Forks basin is late Miocene (Dorr, 1956).

The fluvial conglomerates in the northeastern part of the map area are the youngest Sixmile Creek strata exposed in the Dry Creek Valley. Taking into account the

location of the exposure, its steep eastward dip, and the eastward dip of Tertiary strata to the northwest, these deposits probably lie near the top of Sixmile Creek basin-fill sediments. The youngest Sixmile Creek strata found in other basins are of middle Pliocene age (Kuenzi and Fields, 1971; Monroe, 1974).

The age of the fluvial deposits west of Dry Creek in the southwestern portion of the map area is at best uncertain. These conglomerates have been tentatively mapped as part of the Sixmile Creek Formation because of their coarseness. Deposits of this grain size rarely occur in the Renova Formation or its equivalents (Kuenzi and Fields, 1971; Robinson, 1963). The conglomerates are unconformably underlain presumably by the Precambrian LaHood Formation and are overlain by Tertiary spring deposits whose age is also questionable (Cross-section A-A', Plate I). The fluvial conglomerates west of Dry Creek occur at the same elevations as the Sixmile Creek sheetflood deposits to the east, but do not show any tectonic dip. Since these deposits have been assigned to the Sixmile Creek Formation, they are tentatively believed to be late Tertiary in age.

Diagnostic vertebrate fossils were not found. Algal mounds, ostracodes, root casts, and burrows are common in

the tuffaceous marls and mudstones that occur west of Menard.

The age of the ash bed along Foster Creek Road correlates very well with the age of Sixmile Creek equivalents in other parts of the Three Forks basin. Glancy (1964) and Schneider (1970) both found late Miocene and Pliocene vertebrates in their respective study areas. In other basins, Sixmile Creek strata range from late Miocene to middle Pliocene (Fig. 5; Kuenzi and Fields, 1971; Monroe, 1974; Peterson, 1974).

Tertiary Spring Deposits

Stratigraphic Position and Thickness

A formal name has not been assigned to this unit. It lies with angular unconformity on Precambrian and Paleozoic rocks and may also overlie Tertiary Sixmile Creek strata. The spring deposits are underlain by a thin mantle of unconsolidated gravels and also underlie part of the Sixmile Creek Formation. The thickness of this deposit ranges from 0.9 to 24 m. The rocks thicken in wedge-like fashion to the southeast.

Distribution and Topographic Expression

The spring deposits are discontinuously exposed

over a 3.3 to 5 square km area in the southwestern portion of the map area. They are always poorly exposed and are found on the shoulders of steep-walled gullies west of Dry Creek. Small exposures also crop out along the west-facing slopes east of Dry Creek (Plate I). The spring deposits occur as a tabular body blanketing the top of the bench west of Dry Creek. Outcrops are weathered, blocky, and very discontinuous (Appendix III).

Lithology

The spring deposits contain over 50% CaCO_3 and are, therefore, limestones. However, they do contain large detrital clasts which are supported by the CaCO_3 . Grain-supported textures are rare. Three different rock types belong to this map unit, all of which are similar in composition but differ in the proportion of their components.

Conglomeratic Micritic Sparites. Rocks of this type are found over the entire area. They are grayish orange to very pale orange, porous, and have a sugary texture. Exposures are commonly structureless, although irregular wavy beds were observed at one outcrop.

The size of the detrital material ranges from clay-sized particles to cobbles 36 cm in diameter. The clasts

are poorly sorted and are randomly distributed throughout the outcrop. Their shapes range from angular to well rounded.

Rock fragments compose 5 to 30% of the deposit. Precambrian LaHood arkoses and lower Paleozoic lithologies through the Devonian Jefferson Formation occur. Upper Paleozoic and Mesozoic rocks were not observed in any of these deposits. Quartz composes up to 10% of the sample. Plagioclase occurs in trace amounts. Sparry calcite constitutes 40% of the rock whereas micrite ranges from 20 to 30%.

The carbonate matrix of three samples was dissolved in dilute hydrochloric acid. The percentages of dissolved carbonate versus insoluble residue are given in Table 1.

The insoluble residue consists of a fine-grained sand and mud mixture. Of the sand fraction, quartz and plagioclase are common. Mica and heavy minerals occur in subordinate amounts. Silt and clay compose 35 to 40% of the residue.

Sparry Biomicrites. Sparry biomicrites were found at only one location (SW $\frac{1}{4}$, SE $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 22, T.2N., R.4E.). They are very light gray, dense, and porous, although many pores are filled with spar. The rock contains fewer

Table 1

Percent Dissolved Carbonate — Percent Insoluble Residue in Tertiary Spring Deposits. Note that two samples contained detrital limestone clasts. Consequently, the percentage of dissolved carbonate as matrix was mathematically corrected for this.

	Conglomeratic Micritic Sparites			Sparry Biomicrite	Arenacious Biosparite
% insolubles	5.1	5.8	7.0	3.3	34.8
% total dissolved carbonate	94.9	94.2	93.0	96.7	65.2
% detrital carbonate by vol. (visual estimate)	-	-	15	-	10
% detrital carbonate by wt. (ρ of Ls=2.6; % vol÷2.6)	-	-	5.8	-	3.8
% dissolved carbonate as matrix	94.9	94.2	87.2	96.7	61.4

detrital grains than those previously described and bedding was not observed. Detrital grains from clay-size to 8 cm in diameter were noted. The clasts are poorly sorted and angular.

In thin section, 68% of the rock is composed of micrite. Coarse anhedral spar constitutes 30% of the sample, while the remaining 2% consists of quartz sand grains and lower Paleozoic rock fragments. Ostracode shells occur in trace amounts.

One sample of the CaCO_3 matrix was dissolved in dilute hydrochloric acid. The results are tabulated in Table 1. The insoluble residue is composed of a mixture of coarse to fine-grained sand and mud. Much of the sand fraction consists of quartz and plagioclase, while mica and heavy minerals occur in subordinate amounts. Silt and clay compose 40% of the insoluble residue.

Arenaceous Biosparites. Arenaceous biosparites also occur at only one location ($\text{NE}\frac{1}{4}$, $\text{NE}\frac{1}{4}$, Sec. 26, T.2N., R.4E.). They are very pale orange and are grain-supported. Bedding was not observed.

Detrital grains range from clay-sized particles to large cobbles 20 cm in diameter. Sorting is poor and the clasts are angular to well rounded.

Rock fragments compose 25% of the deposit, with Precambrian LaHood through lower Paleozoic lithologies being common. Lithic fragments representing lithologies above the Jefferson Formation were not observed. Quartz grains constitute 10% of the rock, while plagioclase, microcline, and other unidentifiable grains occur in subordinate amounts. Fine-grained sparry cement composes 40% of the rock, while lime mud occurs as coatings around small detrital grains in amounts of 5% or less.

Grains resembling fragments of charophyte algae were also observed in this rock. The shape and structure of these grains are very similar to the charophyte algae shown in the photomicrographs of Horowitz and Potter (1971) and Scholle (1978).

A sample of this rock was dissolved in dilute hydrochloric acid (Table 1). The insoluble residue contains sizes ranging from coarse-grained sand to mud. It is poorly sorted and the grains are angular to subrounded. Quartz and plagioclase dominate the sand fraction, while mica and heavy minerals occur in subordinate amounts. Silt and clay compose greater than 35% of the residue.

Mode of Deposition:
Tertiary Spring Deposits

Verrall (1955) briefly mentioned the occurrence of these rocks and interpreted them as lacustrine and fanglomerate deposits. Their origin is believed to be slightly more complex than this and is discussed below.

A lacustrine origin is valid, in part. The presence of ostracodes and algae support this. But the random occurrence of large detrital clasts throughout most of the rocks complicates this interpretation. A caliche origin may also be considered, but the absence of both brecciated grains and larger amounts of detrital material combined with the occurrence of algae and ostracodes make this interpretation less plausible.

D. L. Smith and J. Montagne (1979, pers. comm.) suggested that these rocks represent spring deposits. The writer agrees with this interpretation and offers the following scenario which best explains the combined occurrences of: 1) charaphyte algae and ostracodes; 2) coarse- to fine-grained detrital material; and 3) large amounts of CaCO_3 .

Carbonate-rich groundwaters flowing through Paleozoic limestones issued from Laramide faults onto a flat erosional surface. Small ponds formed in certain areas on

the surface, producing an ecosystem conducive to the growth of ostracodes and charaphyte algae. Elsewhere, spring waters made their way downslope in very shallow channels. Evaporation initiated the precipitation of CaCO_3 and a carbonate blanket or fan began to form over the entire surface.

Ephemeral streams, generated by brief but heavy rainstorms, spread across the carbonate fan, depositing coarse gravels and cobbles. Fragments of charaphyte algae and ostracodes became intimately mixed with clastic material. As the storms subsided, the ephemeral streams gradually disappeared. Spring activity, however, continued and CaCO_3 precipitation resumed, ultimately binding the clastic and bioclastic detritus.

Thus, continued activity of carbonate-rich spring waters combined with the sporadic occurrences of ephemeral streams produced matrix-supported fanglomerate material composed of conglomeratic limestone.

The small Laramide faults mapped near the northernmost occurrence of the spring deposits were the source from which the springs emanated (Plate I). The composition of the detrital material in the spring deposits corresponds with the outcrops of Precambrian and lower Paleozoic rocks

in the area. Lithologies that represent rocks above the Jefferson Formation were not found. Consequently, the source area of the detrital material and the location of spring activity was located south of the ridge formed by the Jefferson Formation.

Age, Fossils, and Correlation

An exact age for the spring deposits has not been determined. Verrall (1955) tentatively assigned them to an Oligocene age because these deposits and the lacustrine limestones west of Menard (Renova Formation) both contained similar-looking gastropods. R. W. Fields (1979; pers. comm.) stated that gastropods are not good index fossils in the Tertiary rocks of western Montana. Consequently, because of the absence of good index fossils, geomorphic and structural relations were used in this report to discern the age of the spring deposits.

In the southwest portion of the map area, along the west bluffs of Dry Creek (SE $\frac{1}{4}$, Sec. 27, T.2N., R.4E.; N $\frac{1}{2}$, Sec. 34, T.2N., R.4E.), imbricated conglomerates tentatively mapped as part of the Sixmile Creek Formation, underlie the spring deposits. If these conglomerates are part of the Sixmile Creek Formation, they are probably late Tertiary in age. The overlying spring deposits are, then, slightly

younger than these conglomerates (Cross-section A-A', Plate I). It is interesting to note that if these conglomerates are proved to be part of the Renova Formation and early Tertiary in age, the age of the spring deposits may be Oligocene, as postulated by Verrall (1955).

East of Dry Creek, in the NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E., Sixmile Creek strata are characterized by a north-eastward tectonic dip. Approximately 30 m. south of this exposure, in the same gully, spring deposits crop out. If the dip of the Sixmile Creek rocks is projected southwestward, Sixmile Creek strata would overlies the spring deposits. At this location then, the spring deposits appear to be older than part of the Sixmile Creek Formation (Fig. 14). On the basis of the two relations just described, the spring deposits are tentatively believed to be late Tertiary in age, and equivalent, at least in part, to the Sixmile Creek Formation. Further evidence discussed below may help to substantiate this interpretation.

The spring deposits are overlain by a thin veneer of unconsolidated boulders and cobbles (QTof). These mantle deposits represent a separate and younger depositional event than the underlying spring deposits. They rest high above the present drainages and were deposited just prior to the

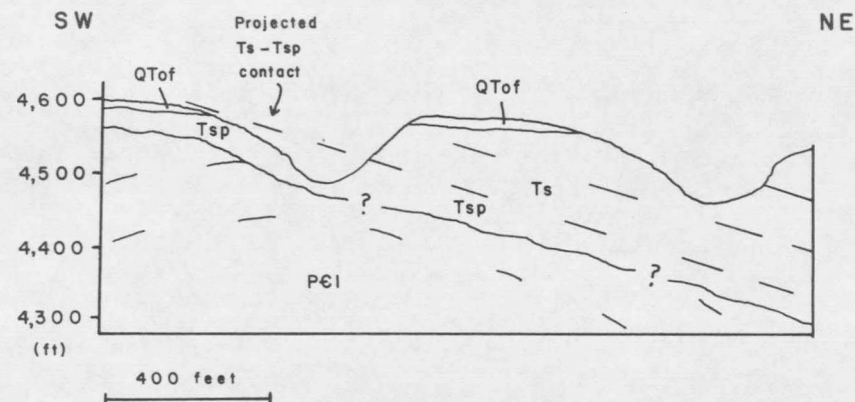


Figure 14. Diagrammatic cross-section through the NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E. Horizontal and vertical scales are only approximate. The relation shown here indicates that the spring deposits are older than Sixmile Creek strata. QTof= high level pediment gravels; Ts= Sixmile Creek Formation; Tsp= spring deposits; Pcl= LaHood Formation.

initiation of the last canyon-cutting episode. Canyon-cutting began less than 4.2 mybp (Peterson, 1974). Therefore, the mantle deposits are late Pliocene or early Quaternary in age, and since they overlie the spring deposits, the latter must be slightly older (Cross-section A-A', Plate I).

Tertiary spring deposits also dip gently to the east. Whether the dip is structural or depositional is a question that will be addressed later. But if the dip is projected far enough to the east, it does project under Sixmile Creek deposits (Cross-section A-A', Plate I). There is no evidence, however, that reveals the extent of the spring deposits in the subsurface.

Although correlation of these deposits is very difficult without the presence of index fossils or good exposures, similar-looking deposits in the Nixon Gulch area in the Horseshoe Hills have been observed by Spahn (1967) and D. L. Smith (1979, pers. comm.). Whether or not they are contemporaneous with these deposits is uncertain. Both of the carbonate-rich deposits occur on bench-like surfaces high above the present drainages and may represent a time of increased spring activity in the Horseshoe Hills sometime during the late Tertiary.

QUATERNARY OR TERTIARY DEPOSITS

Distribution, Stratigraphic Position, and Thickness

Quaternary or Tertiary deposits consist of a thin mantle of unconsolidated gravels, cobbles, and boulders that blanket the entire area. They characteristically occur at elevations above the present drainages. The mantle material lies on erosion surfaces which, in turn, overlie and, in part, truncate older Tertiary basin-fill deposits. The mantle material is covered by younger alluvial fan deposits near the Bridger Range. Elsewhere, it is exposed or disrupted by cultivation.

The exact thickness of the Quaternary or Tertiary mantle material is unknown. Map data indicate that they are very thin compared to the underlying Tertiary rocks. In most areas, they do not exceed 1.5 m. However, in a quarry in the north-central part of the area (SW $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 5, T.2N., R.5E.), 4.6 m of unconsolidated gravels and cobbles are exposed. The lower contact was not observed.

Lithology and Mode of Deposition

Gravels and cobbles are the common grain sizes, although sizes ranging from small pebbles to large boulders measuring 1.8 m in diameter do occur. The clasts range from angular to well rounded and they are typically unsorted

(Figs. 10E, 10F).

Composition of the clasts in the mantle material varies upon location. In the Menard area, upper Paleozoic and Mesozoic clasts are common. Volcanic rock fragments also occur but are rare. In the southwestern portion of the map area, LaHood arkose clasts and lithic fragments from the lower Paleozoic section predominate, although coarse lithic sandstone clasts resembling the Kootenai Formation are present. LaHood arkose clasts and rock fragments that represent rocks of the Paleozoic section below and including the Quadrant Formation are common in the mantle material of the central, southern, and eastern part of the map area. Here, lithologies that represent rocks above the Quadrant Formation have not been found. Metamorphic amphibolite clasts are very rare.

Most of the mantle material was derived from the adjacent Bridger Range and Horseshoe Hills. Bridger Range material is more extensive than that of the Horseshoe Hills and is present as far west as Dry Creek.

Although both source areas are composed of the same pre-basin rocks, detritus from one of the areas can be distinguished from the other by the following characteristics: 1) the presence of LaHood arkosic lithic fragments

that contain pink feldspar grains. The occurrence of these clasts indicate Bridger Range material. Only the LaHood Formation in the Bridger Range contains arkoses with pink feldspar grains (A. Bonnet, 1979, pers. comm.; J. Montagne, 1979, pers. comm.). 2) The presence of LaHood arkoses in the northern part of the map area. This occurrence also indicates a Bridger Range source because the LaHood Formation does not crop out in the Horseshoe Hills in the vicinity of Menard. 3) The presence of Kootenai and other Mesozoic lithic fragments. The occurrence of these lithologies in the mantle gravels indicates that they were shed from the Horseshoe Hills. Mesozoic rocks crop out at very low elevations on the east side of the Bridger Range, and, therefore, could not have been transported in a westward direction to the map area.

This blanket of unconsolidated mantle material probably owes its origin to a number of processes that formed large coarse-grained alluvial fans. Crude imbrication observed in the deposits that are exposed in a small quarry in the north-central part of the area indicate that some of this detritus was deposited by fluvial activity. However, it is difficult to imagine fluvial processes transporting some of the large boulders that do occur. The

proposition of a debris-flow origin seems to be more plausible. The absence of morainal forms and striated boulders may preclude the idea that glacial activity deposited these deposits. It is possible that some of the unconsolidated gravels and cobbles were weathered out of underlying Tertiary strata. But because many of the clasts in the mantle material are much coarser than the lithic fragments of the Tertiary deposits, the Quaternary or Tertiary mantle material is thought to represent a separate and younger depositional event.

Environment of Deposition: Quaternary or Tertiary Deposits

The predominant coarseness of this deposit indicates that high energy systems were more important during latest Pliocene and early Quaternary time than during late Tertiary time. Debris-flows may have also been more frequent than during the late Tertiary. Robinson (1963) attributed similar coarse-grained deposits in the Three Forks area to the onset of the more humid climate of the Pleistocene.

Age and Correlation

The mantle gravels overlies late Tertiary Sixmile Creek strata and occur at elevations high above the present drainages. This observation suggests that these gravels are

younger than the Sixmile Creek Formation, but predate the present erosion cycle. Previous workers have attributed the coarse-grained nature to a humid climate, a Quaternary phenomenon. Thus, these scientists have assigned similar deposits to an early Quaternary age (Robinson, 1963; Kuenzi and Fields, 1971).

Peterson (1974) dated the inception of the present erosion cycle as being soon after 4.2 mybp. Inasmuch as some of these gravels in the Dry Creek Valley occur up to 60 m (200 ft.) above the present drainages, they probably were deposited before the initiation of canyon-cutting. Therefore, some of these deposits may be very late Pliocene. It should be noted that some of the gravels and cobbles in the central part of the map area and on the lower benches south of Menard may represent middle or even late Quaternary deposition. Only those deposits that occur at the highest elevations are probably very late Tertiary in age. Accordingly, the symbol used to designate the mantle material has a "QT" prefix (Plate I).

Robinson (1963) and Schneider (1970) both described high level unconsolidated gravels and cobbles in the Three Forks and Madison Bluffs areas, respectively. All of these high level sediments were deposited at the climax of basin-

filling and during basin excavation in very late Tertiary and early Quaternary time.

QUATERNARY DEPOSITS

Introduction

Quaternary deposits consist of unconsolidated sands, gravels, and boulders which overlie older basin-fill sediments. Three mappable units were differentiated: 1) imbricated old alluvium that occurs 24 to 30 m above the present drainages (Qoa); 2) coarse cobbles and boulders that occupy present drainages (Qf); and 3) recent stream alluvium (Qal). Loess also occurs sporadically throughout the study area, but was not mapped.

Old Alluvium

Distribution, Stratigraphic Position, and Thickness

Only one exposure of this lithology (Qoa) and texture was found. It occurs along the southern bluffs in the SE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 7, T.2N., R.5E., and unconformably overlies Tertiary Sixmile Creek deposits. These gravels and cobbles are overlain by a thin veneer of loess and its thickness ranges from 0 to 4.5 m.

Lithology and Mode of Deposition

The old alluvium is grain-supported and is unconsolidated. It has no bedding, but is characterized by westward imbricated clasts.

The largest clast observed is 13 cm in diameter, while the smallest grains are silt-sized. Common grain sizes range from coarse sand to small cobbles. Most of the grains are subrounded to well rounded and poorly sorted.

A wide variety of lithic types occur in this deposit and compose 40% of the sediments. Of the rock fragments, 30% are igneous (andesites and basalts), 30% are sedimentary (Precambrian LaHood arkoses and Paleozoic limestones), and 40% are metamorphic (schists, gneisses, and amphibolites). Quartz composes 30% of the deposit and plagioclase and orthoclase make up 20%. Biotite, muscovite, and heavy minerals occur in subordinate amounts.

The old alluvium may represent sediments deposited by an ancestral westward flowing East Gallatin River that moved into the southern margin of the Dry Creek Valley during basin excavation. The volcanic rock fragments may have originated from the volcanic rocks of the Gallatin Range or in the Rocky Canyon area where rocks of the Livingston Group crop out. The sedimentary and metamorphic clasts were probably derived from the west flank of the Bridger Range, south of Ross Pass, although some could have originated in the Gallatin Range. The composition, therefore, indicates that the old alluvium was derived from a

southern and southeastern source.

Cobbles and Boulders

Distribution, Topographic Expression, and Stratigraphic Position

Unconsolidated coarse cobbles and boulders blanket the east flank of the Dry Creek Valley along the front of the Bridger Range. They display a prominent lobate, hummocky topography and occupy modern stream channels (Fig. 15A; Plate I).

Lithology and Mode of Deposition

Small boulders are the common grain size observed in this deposit, although boulders with diameters as large as 1.2 m occur. They are angular to subrounded and are poorly sorted.

Precambrian LaHood arkoses compose 90 to 95% of the boulders, while the remaining 5 to 10% consists of Paleozoic limestones. There is a noticeable change in composition between this unit, which occupies modern stream channels, and the high level cap gravels, cobbles, and boulders (QTof), which occur on the tops of the adjacent hills. The latter is composed of LaHood arkoses as well as Paleozoic lithic fragments, whereas in this deposit,

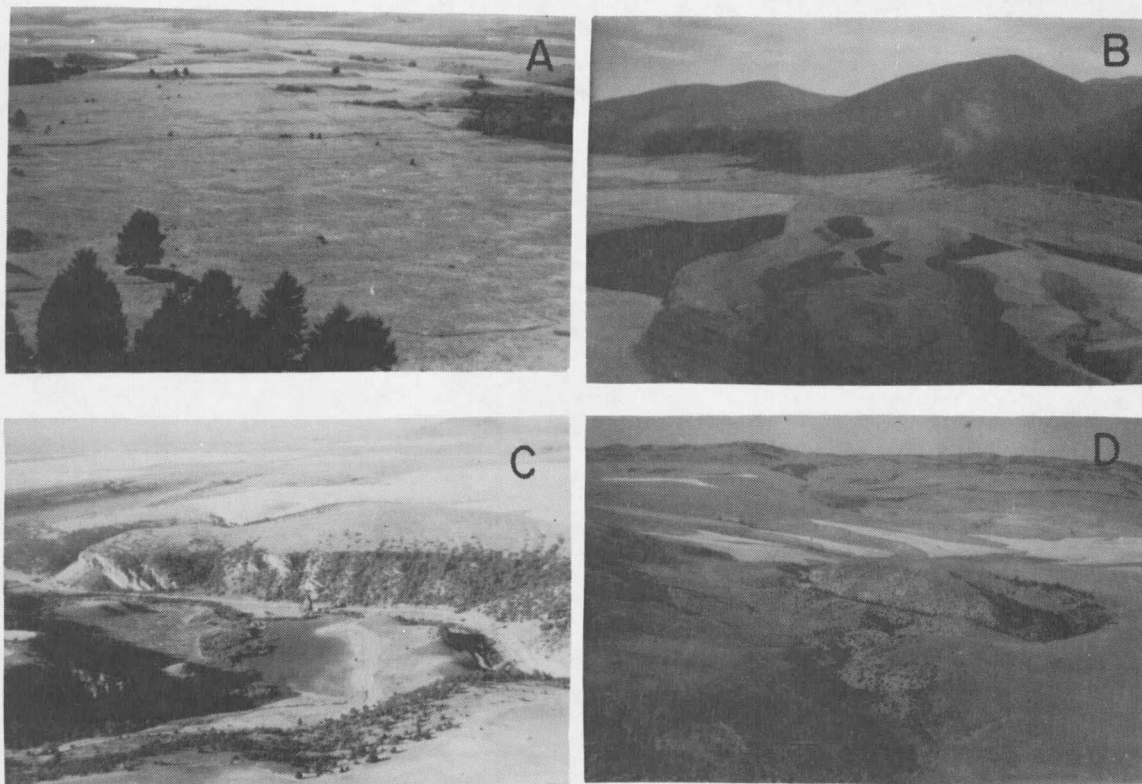


Figure 15. A. Looking west at hummocky topography near the mouth of Mill Canyon. B. Flat-bottomed channels projecting toward the mouth of North Cottonwood Canyon in the Bridger Range. Many of these channels are devoid of perennial streams. C,D. Canyons of Dry Creek and Chipmunk Creek, respectively. Both are cut in resistant Paleozoic rocks.

Paleozoic rocks are very rare.

The hummocky topography and large boulders suggest that debris-flows deposited these rocks. The restricted composition represented in this deposit indicates that the debris-flows originated in the proximity of the LaHood Formation. The lobate form of this deposit is delineated by the contour lines on the Belgrade quadrangle (Plate I). The locations of the lobate forms imply that the debris-flows originated in Mill and North Cottonwood Canyons.

Recent Stream Alluvium and Loess

These deposits occur throughout the area but were not studied in detail. Stream alluvium (Qal) has been produced by the present streams and is confined to the present day stream channels.

Loess deposits occur sporadically throughout the area and consist of well-sorted calcareous silt. An eolian origin is assumed.

Environment of Deposition: Quaternary Deposits

The presence of the old alluvium and the debris-flow deposits support the well-documented proposition that Quaternary time was dominated by a moist, humid climate. The coarse-grained and well-rounded nature of the old

alluvium as well as its composition suggest that these sediments were transported by a through flowing stream, possibly an ancestral East Gallatin River. Further, much water must have been available to generate the large extensive debris-flows that blanket the east flank of the valley. Deposits similar to these are not characteristic of the Sixmile Creek Formation.

Age

The old alluvium (Qoa) is late Quaternary (Pinedale) in age or older. This statement is based on the following lines of reasoning. Present drainages acquired their present elevations by Pinedale time (J. Montagne, 1979, pers. comm.). Further, at some localities, Pinedale features are simultaneously identified with two or more levels of activity (J. Montagne, 1979, pers. comm.). Since the old alluvium (Qoa) occurs at 24 to 30 m above the present drainages, it is thought to be Pinedale or pre-Pinedale in age. The fact that these deposits unconformably overlies Sixmile Creek strata indicates that they are younger than late Tertiary.

Conversely, the debris-flow deposits (Qf) are thought to be Pinedale or younger, because they occupy present drainages. Very large conifers which have grown

on this deposit are very straight. They do not appear to be bent or deformed by mass movement. Therefore, the debris-flow deposits are probably older than 200 years (?).

STRUCTURE

Introduction

The Dry Creek Valley and surrounding areas are located near the eastern margin of the Montana Disturbed Belt. Intricate folds and faults generated by Laramide compressional forces characterize pre-basin rocks exposed in the Horseshoe Hills, Bridger Range, and Maudlow basin. Similar compressional features probably underlie younger Cenozoic basin-fill deposits in the Dry Creek Valley.

Tensional forces and subsequent basin formation followed the compressional forces of the Laramide orogeny. The map area was downdropped relative to the Bridger Range along a high angle normal fault or fault zone that separates these two areas. Tertiary strata in the Dry Creek Valley typically dip northeastward into the Bridger Range front, indicating that this area continued to be downdropped through most of Tertiary time.

Laramide Structures

All pre-Tertiary sedimentary rocks in the area are structurally conformable, showing that no large-scale deformation occurred from late Precambrian through late Cretaceous time. The compressional structural features observed west and just east of Dry Creek are a series of

Laramide folds and associates steep vertical and strike-slip faults. Thrust faults were not observed in the area, but do occur farther west in the Horseshoe Hills (Verrall, 1955).

All of the folds exposed in the map area occur west of Dry Creek and strike to the northeast. The anticline and syncline northwest of Menard are overturned and asymmetrical to the east, respectively. Both of the folds are partially buried by the Tertiary basin-fill. The anticline in the southwestern corner of the map area is broad and is characterized by moderate dips on both limbs (Plate I).

Steep vertical faults apparently of "Laramide age" cut Paleozoic rocks west of Dry Creek. These faults have locally steepened the dips of the rocks that they intrude. Some of these faults may have served as the conduits through which Tertiary carbonate-rich spring waters emanated.

A northward-trending left-lateral strike-slip fault occurs in the vicinity of Accola. Its trace is approximately 2.5 km long and it cuts most of the lower Paleozoic section. Drag can be observed by noting the change in the strike and dip of the Paleozoic rocks as they approach the fault from the west. The west side of this fault is broken into five segments by northwest trending normal faults.

These faults intersect the strike-slip fault and probably originated from movement along it (Plate I; Verrall, 1955).

Further discussion of Laramide features in this area is beyond the scope of this report. For further information the reader is referred to the works of Verrall (1955), Klemme (1949), and McMannis (1955) which concern the pre-basin geology of the Horseshoe Hills, Maudlow basin, and the Bridger Range, respectively.

Cenozoic Structures

Attitudes

A general northeastward dip toward the Bridger Range typifies Tertiary strata of the Dry Creek Valley. Tertiary rocks, then, should become younger toward the east. The dips range from 2 to 33 degrees and their structural orientation is probably due to movement along the Bridger Range front fault. Strata west of Menard and north of Johnson Canyon Road best show this tectonic dip.

In the southern bluffs area, near the lower reaches of Foster Creek (NW $\frac{1}{4}$, Sec. 7, T.2N., R.5E.; SW $\frac{1}{4}$, Sec. 6, T.2N., R.5E.), Tertiary Sixmile Creek strata dip from 6 to 8 degrees to the northwest. If the dips were depositional, the dip direction should be southward,

toward the center of the basin, instead of toward the Horseshoe Hills. Consequently, these dips are believed to be tectonic in origin.

The structural orientation of these rocks is thought to be caused by a small fault in the $S\frac{1}{2}$, $NW\frac{1}{4}$, Sec. 7, T.2N., R.5E. Although displacement could not be calculated, the northwest side of the fault is believed to be upthrown (Cross-section D-D', Plate I).

Tertiary spring deposits dip very gently to the east-southeast. West of Dry Creek, dips were calculated by the three point method and average 2 degrees. East of Dry Creek, the dips of the spring sediments range from 5 to 9 degrees. These were measured in the field.

These dips may be, in part, depositional, because they are very small and are dipping basinward. But the dips east of Dry Creek are believed to have also been tectonically influenced. In the $SW\frac{1}{4}$, $NE\frac{1}{4}$, $NE\frac{1}{4}$, $NE\frac{1}{4}$, Sec. 26, T.2N., R.4E., a fluvial deposit (Sixmile Creek Formation), which is imbricated to the southwest, dips at 13 degrees to the northeast. This is undoubtedly a tectonic dip. If the dip is projected to the southwest, this fluvial deposit would cover spring deposits which are exposed in the same gully (Fig. 14). This projection suggests that the fluvial

deposits are younger than the spring deposits. If deformation affected the younger fluvial deposit, it should have also influenced the underlying spring deposits. Why the tectonic tilt is better expressed in the younger deposit is uncertain.

Observable Faults

Bridger Range Front Fault. The Bridger Range front fault was mapped at the break in slope along the west flank of the Bridger Range. Its presence is suspected because of the following occurrences: 1) the predominant northwestward dip of Tertiary strata; 2) the trends of the triangular facets on the range front cut across the internal structures of the range and mark an abrupt change in slope from the Quaternary fans to the Precambrian rocks of the mountains (McMannis, 1955); and 3) absence of pre-Tertiary outcrops west of the range front. This latter occurrence indicates that older bedrock lies at depth, below the basin-fill materials (McMannis, 1955).

A fault zone, rather than a single fault, is interpreted to occur west of the range front. This interpretation is based on gravity data that indicate that Cenozoic basin-fill strata do not exceed a thickness of

914 m (3000 ft.) in the Dry Creek Valley, and the thickest portion of basin-fill sediments occurs in the center of the area (Fig. 17; Davis and others, 1965). However, if the dipping conglomerate north of Johnson Canyon Road (SE $\frac{1}{4}$, NE $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 3, T.2N., R.5E.) is projected directly into the fault at the range front, a relatively deep trough is produced directly adjacent to the Bridger Range (Fig. 16). This contrasts with the interpretation from gravity data.

To account for this discrepancy, a buried fault zone is proposed for the area west of the range front. The fault zone is believed to have brought the more dense pre-basin rocks closer to the surface in stair-step fashion (Cross-section B-B', Plate I). This interpretation accounts for the fact that the gravity anomalies become less negative in value toward the Bridger Range. The exact amount of cumulative displacement is unknown, but may be in the order of 900 m (3000 ft.) (Pardee, 1950).

The conglomerate (Sixmile Creek Formation) north of Johnson Canyon Road is the youngest deposit observed that is offset by the Bridger Fault zone. Recent fault scarps have not been observed along the range front. Therefore, movement along the Bridger Fault zone may have ceased by late Pliocene or early Quaternary time.

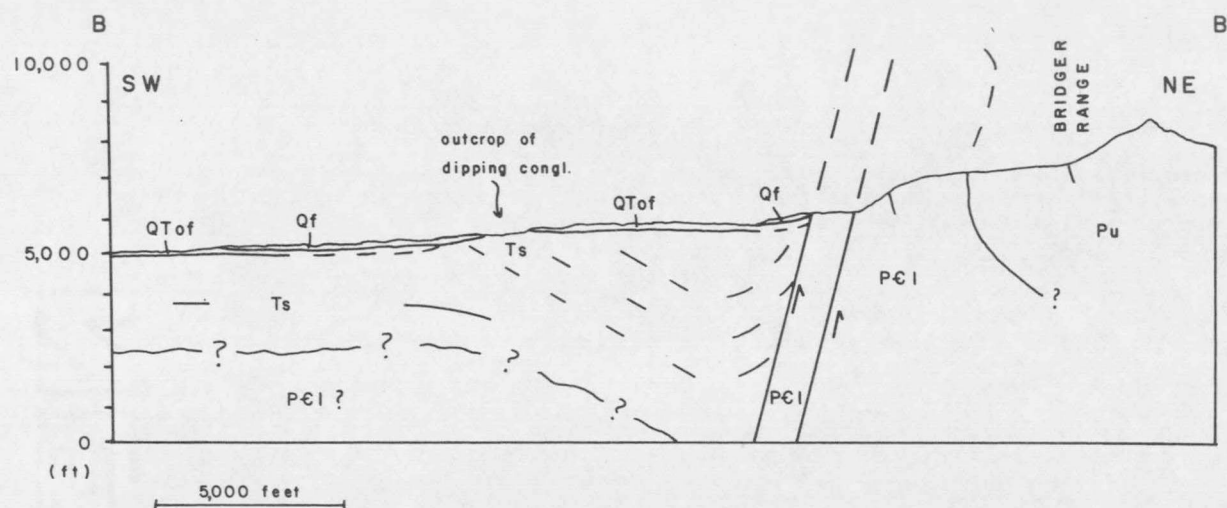


Figure 16. Diagrammatic cross-section through the northeast portion of the map area. It is the same line of section as B-B', Plate I. The deep trough produced adjacent to the range contrasts with evidence from gravity data. Compare this section with B-B', Plate I. Qf= fan material; QTof= old pediment gravels; Ts= Sixmile Creek Formation; Pu= Paleozoic undifferentiated; P&I= LaHood Formation.

Small Faults. A small northeast-trending fault was mapped in the southern bluffs area ($S\frac{1}{2}$, $NW\frac{1}{4}$, Sec. 7, T.2N., R.5E.). It displaces Tertiary Sixmile Creek strata but is apparently buried by younger late Cenozoic (QTof) gravels. On the northwest side of the fault trace, Tertiary rocks consisting of ash beds dip to the northwest. On the southeast side, Tertiary sheetflood deposits are horizontal (Cross-section D-D', Plate I).

The origin of this fault is uncertain. It may be due to a breaking up of the incompetent Tertiary rocks in response to movement along the Bridger Fault zone. Younger late Cenozoic (QTof) gravels do not appear to be offset by this fault. Therefore, faulting apparently stopped prior to the deposition of these gravels.

Smaller unmappable faults with minimal displacement and fractures occur in fine-grained Sixmile Creek strata in the Menard area. They occur along the Dry Creek Road southeast of Menard ($SE\frac{1}{4}$, $SE\frac{1}{4}$, $NW\frac{1}{4}$, Sec. 36, T.3N., R.4E.) and just north of Menard Road, 2.5 km west of Menard ($SW\frac{1}{4}$, $SW\frac{1}{4}$, $SE\frac{1}{4}$, Sec. 26, T.3N., R.4E.).

Along the Dry Creek Road, 0.3 to 0.6 m of displacement occurs in the east trending vertical faults. Overlying gravels (QTof) do not appear to be cut by these

faults, and, therefore, post-date the time of faulting.

Many of these small faults and fractures in the fine-grained Tertiary rocks are filled by clastic dikes. The clastic dikes are commonly 5 to 7 cm wide and are nearly vertical in orientation. The dike material is vertically bedded and consists of the same sediment that composes the intruded rock. The clastic dikes are thought to occupy pre-existing fractures, the material having been forced in from below by hydrostatic pressure or by the weight of overlying strata.

Inferred Fault

The east-west trace of the Willow Creek Fault occurs approximately 4 km south of the southern bluffs of the Dry Creek Valley. Its location has been delineated by gravity data (Plate I; Fig. 17; Davis and others, 1965). Hackett and others (1960) documented Cenozoic displacement along this fault in the Camp Creek Hills to the southwest; the north side was upthrown. If surface evidence exists in the Dry Creek Valley that suggests Cenozoic displacement along the Willow Creek Fault, it has not been recognized.

GEOMORPHOLOGY

Introduction

Landforms of the Dry Creek Valley are a result of many complex, interrelated events. They record episodes of basin-filling and subsequent basin excavation under the alternating arid-humid conditions of Cenozoic time. Brief descriptions of some of these features follow directly. More conceptual aspects, such as paleotopography, are discussed later.

Streams

Master Streams

The East Gallatin River is the largest stream in the eastern part of the Three Forks basin. Its northwestward trend brings it within 2.5 km of the Dry Creek Valley. The river flows in many winding meanders on a very broad, flat floodplain which slopes gently to the north.

Dry Creek is the master stream in the map area. Its southward flow carries it to the East Gallatin River. It meanders in a wide valley that is interrupted by a steep-walled canyon in the vicinity of Accola. Dry Creek is nearly 1.8 to 2 m wide and the approximate channel gradient is 11.4 m/km (60 ft./mi.).

Tributaries

All of the perennial tributaries in the Dry Creek Valley originate in the Bridger Range or the eastern part of the map area and are maintained by springs. Since the Bridger Range is higher and retains more snow than the Horseshoe Hills, this relation is to be expected. It is interesting to note that Foster Creek and Reynolds Creek both originate from within the Dry Creek Valley. Springs maintain both of these streams throughout the year. The upper reaches of Bear Creek are also characterized by spring activity.

Pass, Mill, Quagle, Bear, and North Cottonwood Creeks are perennial tributaries that originate from within the Bridger Range. Other water courses in the area are dry for most of the year. All of the tributaries intersect Dry Creek or the East Gallatin River with dendritic pattern.

Only the larger perennial tributaries that originate in the Bridger Range (Pass, Mill, Quagle, Bear, and North Cottonwood Creeks) flow in flat-bottom valleys and channels (Fig. 15B). These small valleys or channels seem much wider than what the present stream would require. They may have been cut during the Quaternary when the climate was more humid and the streams were discharging more water. Further,

some of the flat-bottom channels that radiate from the mouths of Mill and North Cottonwood Canyons are completely devoid of any perennial stream (these channels are located in Secs. 3, 10, 22, and 27, T.2N., R.5E.). It is conceivable that some of these channels were cut by outwash streams discharging from melting glaciers in the Bridger Range. Since then, the discharge of these streams has decreased, if not ceased completely.

Smaller tributaries throughout the rest of the map area have cut V-shaped valleys, some with relief of over 30 m (100 ft.).

Superimposed Streams

Present drainages in the Dry Creek Valley probably developed as consequent streams on soft Cenozoic deposits. But some local stream features have more complex histories.

In the vicinity of Accola (Secs. 1, 2, 11, 12, T.2N., R.4E.) and just south of Menard (Secs. 35 and 36, T.3N., R.4E.), Dry Creek and the tributaries of Chipmunk Creek, Pass Creek, and some unnamed drainages flow through narrow hardrock canyons without regard for structure (Figs. 15C, 15D). All of these streams flow oblique or nearly perpendicular to the strike of folded and faulted pre-basin rocks. The nearby soft and nonresistant Cenozoic

rocks seem to offer far easier paths.

Because there is no evidence of local Quaternary uplift, the streams were most likely superimposed from a continuous cover of nonresistant Cenozoic sediments. The elevation of the nearby Cenozoic rocks suggests that such a blanket may well have reached elevations of 1463 m (4800 ft.); adequate to account for a now nonexistent late Cenozoic covermass. Other accounts of a high late Cenozoic covermass and subsequent superposition or antecedence have been described by previous workers in other parts of the Three Forks basin as well as other basins (Robinson, 1963; Mifflin, 1963; Peterson, 1974; Aram, 1979).

Peterson (1974) dated the inception of canyon-cutting at slightly less than 4.2 mybp. Recent alluvial fans inside the Jefferson Canyon contain Glacier Peak volcanic ash. This relationship suggests that the Jefferson Canyon acquired its present depth by approximately 11,000 ybp (J. Montagne, 1979, pers. comm.). It seems logical, as Peterson (1974) stated, that canyon-cutting was a regional event and that all of the canyons of southwestern Montana were cut penecontemporaneously.

Glaciation

The west flank of the Bridger Range was glaciated,

although detailed studies have not been conducted to determine how many glacial advances are represented. From a cursory look at the Belgrade and Sedan quadrangles, Mill and North Cottonwood Canyons stand out as relatively wide U-shaped canyons with cirque-like features at their heads. McMannis (1955) and Schrunk (1976) stated that morainal material occurs within both of the canyons, and from the air, the writer has observed arcuate ridges traversing both canyons. However, the hummocky topography that occurs at the mouths of the canyons should not be mistaken for terminal moraines. This is part of the debris-flow deposit (Qf) that is composed of 90 to 95% LaHood cobbles and boulders. If this material was deposited by glacial ice, it should contain a much higher percentage of Paleozoic lithologies, because Paleozoic rocks crop out in the central portion of the range, where the glaciers originated.

There is no evidence to suggest that glaciers ever flowed into the Dry Creek Valley from the Bridger Range. But certain features along the east flank of the map area are, at least, indirect consequences of glaciation, and they are summarized below.

The association of debris-flow material with the glaciated Mill and North Cottonwood Canyons may be more than

just a fortuitous circumstance. Both canyons may have been undercut and oversteepened by glacial erosion, thus forming unstable slopes. If the unstable slopes were developed under the moist conditions of the Quaternary climate and within the interbedded argillites and arkoses of the LaHood Formation, some kind of mass movement would have been inevitable.

As mentioned earlier, some of the flat-bottom channels which radiate from both Mill and North Cottonwood Canyons are presently devoid of perennial streams (Secs. 3, 10, 22, and 27, T.2N., R.5E.). All of these channels project toward the mouths of the glaciated canyons. This coincidence suggests that large streams originating from melting glaciers in the mountains flowed through the Dry Creek Valley exploiting these channels. Since the close of Quaternary time, the climate has become semi-arid (Robinson, 1963) and the discharge of many of the streams has decreased if not ceased completely (Fig. 15B).

(The widespread high-level gravels (QTof) in the central and southern parts of the map area have been incised by Recent streams, producing up to 30 m (100 ft.) of relief in many places. The debris which comprises this material is coarse, in contrast to the sediments that are presently

being transported. Perhaps the high-level deposits in this area were deposited as large aggrading fans built during Pleistocene glaciations in the Bridger Range. This would account for the occurrence of Bridger Range detritus as far west as Dry Creek.

The above occurrences, when considered together, indicate a humid climate. Even if these features were not produced directly from outwash streams or from glacial ice, they do reflect humid conditions; a Quaternary characteristic.

Paleotopography and the Development of the Present Topography

Directly following basin formation, an early Tertiary topography of mature relief developed in the Dry Creek Valley. It was formed by through-flowing streams under a humid climate and was very similar to the present topography (Lange and others, 1980; Robinson, 1963).

By late Tertiary time, the area was filled with debris shed from adjacent highlands, and much of the early Tertiary topography was ultimately buried. A late Tertiary surface of low relief developed on these sediments and was bordered by the high peaks of the Bridger Range and Horseshoe Hills. The development of the present topography

is intimately related to the history of dissection of this surface by fluvial systems. Presumably, this dissection occurred under a climate that alternated between humid and semi-arid conditions (Robinson, 1963). This dissection has also partially exhumed the early Tertiary surface.

Early Tertiary Surface

Only west of Menard and in the southwestern portion of the map area along Dry Creek can the early Tertiary surface be detected. It is completely buried beneath basin-fill sediments east of these areas.

West of Menard, many of the hills and ridges of Paleozoic and Mesozoic strata are partially exhumed from a Tertiary covermass and represent a mature early Tertiary topography. The contact of Tertiary and pre-basin rocks follows the contour of the present hills. Further, some of the Tertiary conglomerates southwest of Menard contain lithologies exclusively from the hill directly above. These occurrences indicate that the hills are being exhumed. Relief of the early Tertiary topography in this area was probably greater than 122 m (400 ft.; Cross-section E-E', Plate I).

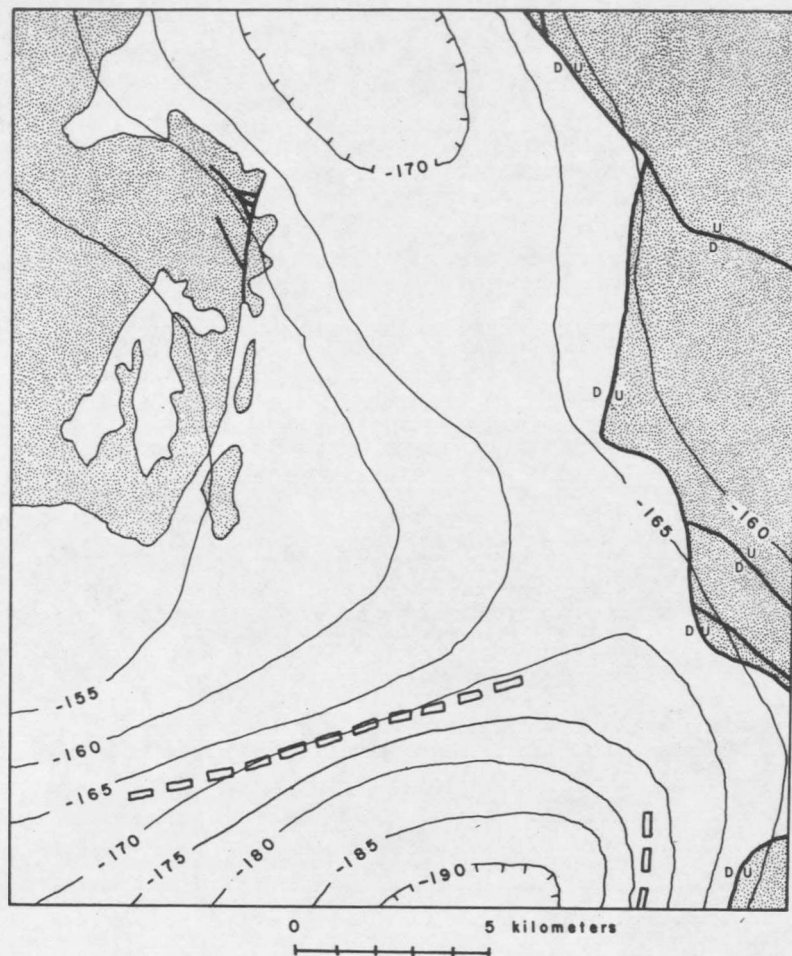
In the southwestern portion of the map area, east of Dry Creek (Secs. 13, 24, and 26, T.2N., R.4E.), the LaHood

Formation crops out to the north and south, but is covered by basin-fill deposits in the intervening area (Plate I). This occurrence suggests that a depression has been cut into the LaHood Formation.

Gravity data of Davis and others (1965) and Burfeind (1967) give a general view of the basin configuration. In the northern part of the Dry Creek Valley, a relatively high negative anomaly suggests that a depression within the pre-Tertiary rocks occurs. Whether or not this depression is related to faulting along the Bridger Range front is unknown (Davis and others, 1965; Burfeind, 1967). This depression is probably not more than 914 m (3000 ft.) deep (Fig. 17; Davis and others, 1965).

South of this depression, gravity data indicate that pre-Tertiary rocks rise to form a low eastward-trending ridge. This ridge represents an eastward plunging anticline whose eastern end has been truncated by the Bridger Fault (Davis and others, 1965). Whether or not this anticline is the same as the one mapped in the southwestern corner of the area is uncertain. Their trends appear to be slightly different (Fig. 17; Plate I).

South of the ridge, one of the deepest depressions in the Three Forks basin occurs. Gravity gradients suggest



KEY

-  basin deposits
-  pre-basin rocks
-  contact; approx. located
-  fault; approx. located
-  concealed fault zone (interp. from gravity data)
-  gravity contour; gravity contour interval is 5 milligals
-  gravity contour enclosing area of low gravity

Figure 17. Gravity map of the Dry Creek Valley area (modified from Davis and others, 1965).

that the depression is bounded by steep slopes on the east and north. Its depth is estimated to be about 1524 m (5000 ft.). The eastern side of this depression is apparently a concealed part of the Bridger Fault system. The steep northern side may represent the eastward-trending Willow Creek Fault zone (Fig. 17; Davis and others, 1965).

Late Tertiary Surface

Most of the highest benches and hills covered by unconsolidated mantle gravels (QTof) are remnants of the late Tertiary surface. These benches are best observed west of Menard, on the east flank of the Dry Creek Valley, and in the southwestern portion of the map area.

West of Menard. West of Menard, in Sections 26 and 35, T.2N., R.4E., three distinct bench levels occur in stair-step fashion. Each level slopes to the southeast and each is developed on and truncates Tertiary basin-fill deposits. The surfaces are capped by mantle material (Fig. 18A; Cross-section C-C', Plate I).

These benches are pediments, as evidenced by the truncated nature of the underlying Tertiary rocks. Details concerning their genesis are very limited. Presumably, they were cut by sheetflow or by streams.

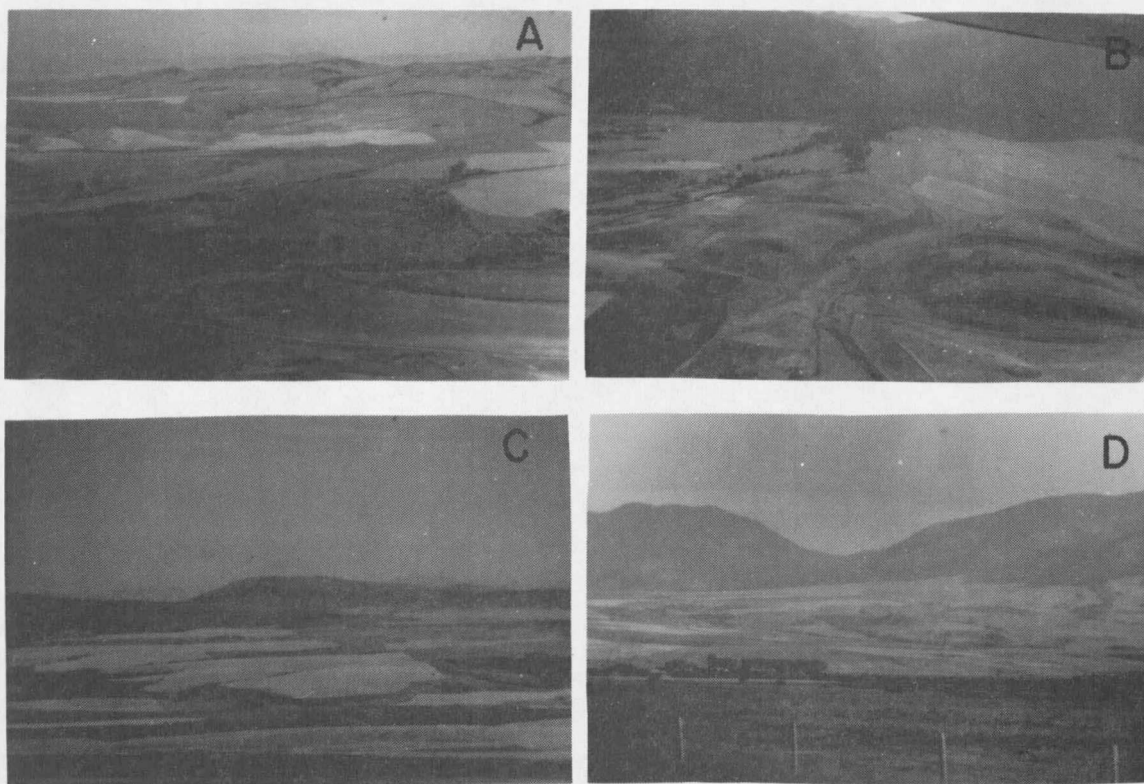


Figure 18. A. High surface west of Menard. Dry Creek is flowing from right to left in foreground. B. Westward-trending hills near the mouth of Mill Canyon (looking east). C. Pediment in the southwestern portion of the map area. D. Looking northeast at the Dry Creek Valley and the Bridger Range. The East Gallatin River has efficiently excavated the basin to the south, leaving a partial cross-sectional view of the late Tertiary surface.

The highest surface stands 73 m (240 ft.) above the present channel of Dry Creek, and represents part of the late Tertiary surface that developed at the climax of basin-filling. Peterson (1974) stated that the present erosion cycle began soon after 4.2 mybp. Therefore, this surface is 4.2 mybp or slightly older. The two lower surfaces and their respective cap gravels (QTof) are probably Quaternary in age and were established during basin excavation.

East Flank of the Dry Creek Valley. Westward and southwestward trending hills radiate from the mouths of Mill and North Cottonwood Canyons, respectively (Fig. 18B; Plate I). They stand 37 to 85 m (120 to 280 ft.) above the nearby drainages and their altitudes range from 1585 to 1737 m (5200 to 5700 ft.). Sixmile Creek rocks are exposed in two of these hills and it is assumed that similar deposits underlie the others.

All of these hills are blanketed by a thin veneer of unconsolidated gravels, cobbles, and boulders (QTof). Just north of Johnson Canyon Road, these deposits lie on a surface which truncates the eastward-dipping conglomerate of the Sixmile Creek Formation (Fig. 19).

This pediment relation probably occurs in the other hills, too, because they are blanketed by these cap gravels

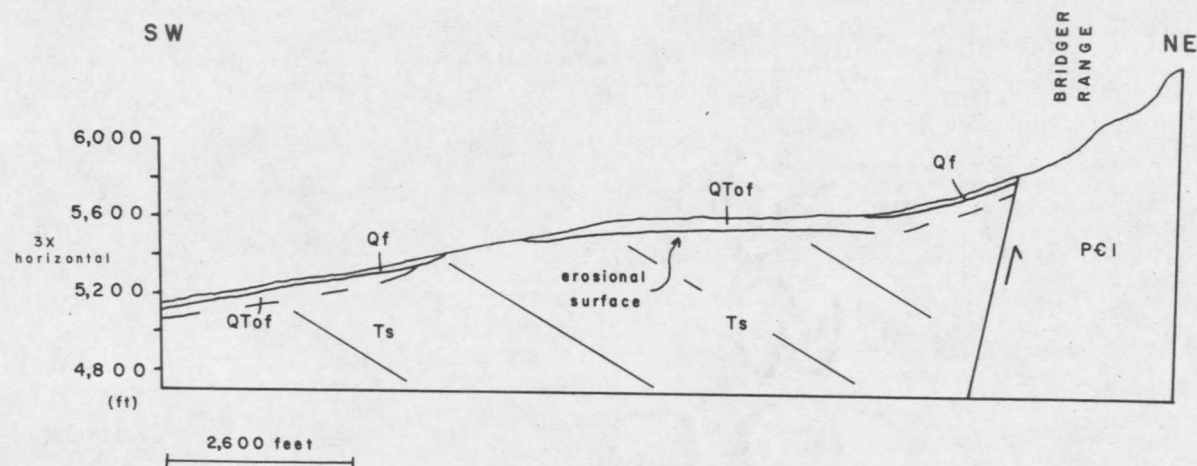


Figure 19. Diagrammatic cross-section through the $N\frac{1}{2}$, Sec. 3, T.2N., R.5E. Vertical and horizontal scales are only approximate. Note that Sixmile Creek strata are truncated by the erosional surface. Qf= fan deposits; QTof= old pediment gravels; Ts= Sixmile Creek Formation; PCl= LaHood Formation.

and are presumably underlain by late Tertiary Sixmile Creek strata. These surfaces probably represent part of the late Tertiary surface which has since been dissected by Recent streams.

Southwestern Portion of the Map Area. In the southwestern portion of the map area, in Sections 15, 22, 23, and 27, T.2N., R.4E., a high, flat to slightly undulating surface slopes to the southeast (Fig. 18C). In actuality, two surfaces occur here; a younger late Tertiary surface lying on and paralleling the slope of a lower, older surface (Fig. 20). These surfaces are approximately 61 m (200 ft.) above the present elevation of Dry Creek and have an average altitude of 1433 m (4700 ft.).

Older Surface — The contact between the pre-basin rocks and the Tertiary spring deposits is not only an angular unconformity, but is also an erosional surface on which the spring sediments were deposited. This pediment truncates underlying pre-basin rocks and possibly Sixmile Creek strata, and slopes gently to the southeast.

The age of this older surface is uncertain. Because it truncates pre-basin rocks and Laramide folds, it must post-date the Laramide orogeny. The surface must pre-date the late Tertiary spring deposits, since the latter overlies

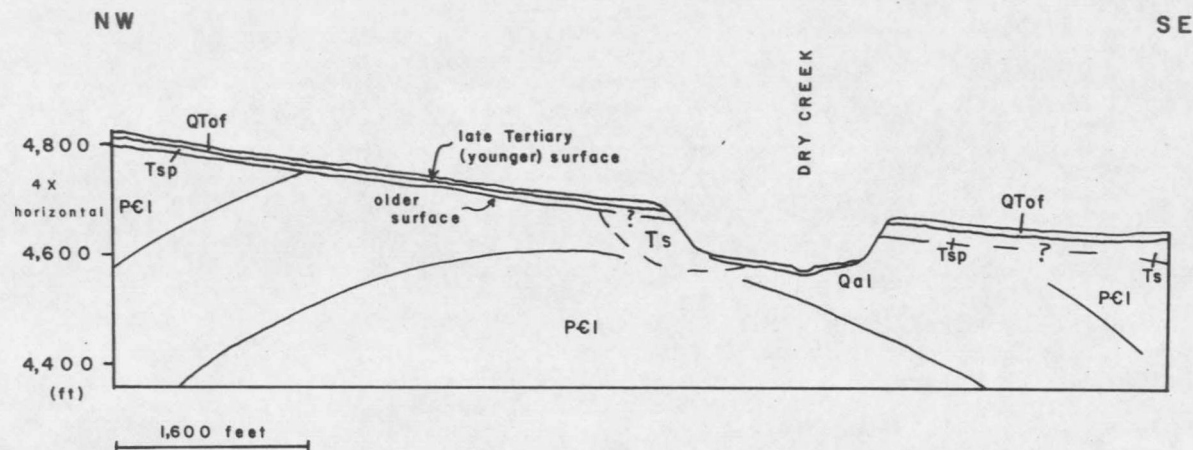


Figure 20. Diagrammatic cross-section through the southwestern portion of the map area. Vertical and horizontal scales are only approximate. Note the two erosion surfaces. Whether the older surface truncates or is cut into by the Sixmile Creek Formation west of Dry Creek is uncertain. Qal= Recent alluvium; QTof= old pediment gravels; Tsp= spring deposits; Ts= Sixmile Creek Formation; PCl= LaHood Formation.

the surface. Therefore, this surface formed sometime during the Tertiary.

A more exact age for this surface could be given if the relationship between the surface and the underlying Sixmile Creek conglomerates west of Dry Creek (NE $\frac{1}{4}$, Sec. 34, T.2N., R.4E.) could be determined. It is unknown whether the conglomerates are truncated by the surface or are cut into it (Fig. 20).

Younger Surface — The contact between the unconsolidated mantle of cobbles and boulders (QTof) and the underlying late Tertiary spring deposits in the southwestern part of the map area is thought to be the younger erosion surface. It seems to have exploited the slope of the underlying older surface (Fig. 20). This surface is thought to be equivalent to the highest bench west of Menard and part of the late Tertiary surface.

Summary. The late Tertiary surface developed at the culmination of basin-filling, just prior to the initiation of superposition and the onset of the present erosional cycle. It was a surface of relatively low relief, the surrounding Bridger Range and Horseshoe Hills being partially buried in their own debris.

By viewing the entire Dry Creek Valley from the

south, one can easily envision this surface and also the elevation to which the Dry Creek Valley was filled with debris. The East Gallatin River and its tributaries have efficiently excavated the basin to the south, leaving a partial cross-sectional view of the late Tertiary surface and the underlying basin-fill deposits (Fig. 18D).

Present Topography

The Dry Creek Valley probably acquired its present form by late Quaternary (Pinedale) time. As previously mentioned, Glacier Peak volcanic ash (~11,000 ybp) occurs within alluvial fan deposits inside the Jefferson Canyon (J. Montagne, 1979, pers. comm.). This relation indicates that the canyon had already been cut to its present depth by this time. Since canyon cutting was a regional event (Peterson, 1974), it seems logical to assume that Dry Creek and its tributaries acquired their present elevations at this time also.

In Davisian terms, the Dry Creek Valley is presently in the mature stage of erosion. The drainages are integrated; the divides are sharp; and the landscape is generally in slope. It is interesting to note that the Dry Creek Valley stands approximately 152 to 305 m (500 to 1000 ft.) higher than the basin floor to the south. The increase in

elevation is first noticed at the southern bluffs and it gradually increases to the north (Plate I).

In conjunction with J. Montagne (1979, pers. comm.), the writer suggests three processes which, alone or together, may have produced this pronounced elevation difference. They are as follows: 1) increased deposition of basin-fill debris to the north, thus "piling" sediments to a greater elevation; 2) tectonic uplift of the study area, relative to the basin floor to the south; and 3) lack of erosion: erosional agents in the Dry Creek Valley have not been as efficient as those to the south in excavating the basin.

Increased Deposition. In theory, increased deposition in an area could cause it to attain a higher elevation than adjacent areas. But it is difficult to visualize this happening in the absence of tectonic influences.

Gravity data indicate that basin-fill deposits are actually thinner in the Dry Creek Valley relative to those to the south. Davis and others (1965) found a gravity high in the southern part of the Dry Creek Valley, suggesting that basin-fill sediments are less than 914 m (3000 ft.) thick. Directly south of the Dry Creek Valley, the largest gravity low in the Three Forks basin occurs. This depression is filled with at least 1524 m (5000 ft.) of basin-fill

sediments (Davis and others, 1965). This latter area is 183 m (600 ft.) lower topographically than the Dry Creek Valley. In effect, then, gravity data negate the assumption that increased deposition in the Dry Creek Valley is responsible for its present elevation.

Tectonic Influences. The presence of the eastward trending Willow Creek Fault was identified by Davis and others (1965) with the aid of gravity data. It occurs just south of the Dry Creek Valley (Fig. 17; Plate I). Davis and others (1965) calculated 610 m (2000 ft.) of vertical offset along this fault; the north side having been upthrown.

Although gravity data indicate that there has been Cenozoic movement along this fault, there is no surface evidence in the immediate area to suggest that this is so. If there is, it has not been recognized. Therefore, whether or not structural movements produced the present elevation difference of the area is uncertain.

Lack of Erosion. The largest and probably most efficient erosional agent in the eastern part of the Three Forks basin is the East Gallatin River. It flows along the southernmost front of the Bridger Range and migrates to the

northwest towards the Dry Creek Valley before joining the West Gallatin River. The East Gallatin River comes within one kilometer of the southern bluffs of the Dry Creek Valley.

Unlike the East Gallatin River, Dry Creek and its tributaries are much smaller and probably less efficient streams in terms of erosional power. The suggestion, then, is that after the development of the East Gallatin River and the rest of the Missouri drainage during the early Quaternary (Robinson, 1961), the East Gallatin River excavated a vast, but unknown amount of Cenozoic fill. But since its path has not yet crossed into the Dry Creek Valley, the Cenozoic sediments have been left as a temporary remnant of an old basin floor (the late Tertiary surface). Similar remnants also occur along the east and southern margins of the Three Forks basin. The Story Hills are an example.

The lack of erosion seems to best explain the elevation difference between the Dry Creek Valley and the area to the south. However, it is certainly possible that movement along the Willow Creek Fault partially influenced this occurrence.

Basin-Filling

In the Dry Creek Valley, basin-filling began in

Oligocene time with the deposition of the Renova Formation. Unfortunately, little is known about the extent of its occurrence or the extent of its removal during the middle Miocene hiatus. It presumably partially filled the mature early Tertiary topography.

Late Tertiary basin-filling probably began in the late Miocene (?) with the deposition of the Sixmile Creek Formation. Ephemeral streams and sheetfloods may have initially confined deposition to the depression that is delineated by gravity data in the northern part of the area (Fig. 17). As deposition continued, the depression was progressively filled and the area of deposition was gradually expanded, first westward into the Menard area, where the oldest Sixmile Creek rocks presently crop out. By early Pliocene time, sediments lapped southward, ultimately burying the bedrock ridge there (Fig. 17).

In other parts of the Three Forks basin, and in other basins, late Tertiary basin-filling ended by middle Pliocene time (Robinson, 1961; Schneider, 1970; Kuenzi and Fields, 1971; Monroe, 1974). Although this cannot be confirmed in the Dry Creek Valley, Sixmile Creek deposition here is assumed to have ceased by the middle Pliocene, since it seems to have been a regional event. A late Tertiary

surface was developed and subsequently overlain unconformably by high level late Pliocene or early Quaternary gravels (QTof). The modern erosional cycle and canyon-cutting began soon after.

The total volume of Tertiary rocks removed during the present erosion period is unknown. The highest preserved basin-fill deposit in the entire area is the north-eastward dipping conglomerate north of Johnson Canyon Road, which occurs at an altitude of 1680 m (5500 ft.). This is 274 to 305 m (900 to 1000 ft.) above the present channel of Dry Creek.

Late Cenozoic basin-fill deposits probably did not exceed the elevation of the Precambrian LaHood-Paleozoic Flathead contact in the Bridger Range. This interpretation is supported by the fact that LaHood arkose fragments occur in all of the Cenozoic deposits near the Bridger Range. This occurrence suggests that the LaHood Formation was always at least partially exposed during Cenozoic time. It should be noted that the elevation of this contact changed through time as sporadic uplifts raised the Bridger Range relative to the basin floor.

In the Horseshoe Hills, west of Menard, Tertiary deposits occur at an altitude of 1585 m (5200 ft.). In the

southwestern portion of the map area, Tertiary spring deposits occur up to 1524 m (5000 ft.). Comparison of these elevations with that of the conglomerate north of Johnson Canyon Road indicates that the Dry Creek Valley was filled asymmetrically, the sediments attaining a higher elevation adjacent to the Bridger Range. This occurrence is probably related to movement along the Bridger Fault zone (Cross-section F-F', Plate I).

Paleodrainage

Although the Dry Creek Valley was characterized by internal drainage and basin-filling during most of Tertiary time, a southward paleoslope probably existed at least during late Tertiary time. The presence of the southward imbricated fluvial conglomerates of the Sixmile Creek Formation supports this interpretation.

The southward paleoslope of the map area contrasts with the supposed eastward paleoslope proposed for the basin floor to the south. McMannis (1955), Robinson (1963), Mifflin (1963), and Schneider (1970) have presented evidence that suggests that an eastward flowing drainage system developed in the major part of the Three Forks basin in Paleocene time and lasted well into the Pliocene. E. F. Griffith and S. G. Custer (1979, pers. comm.) recently found

granitic rocks, presumably derived from the Tobacco Root Mountains to the west, that weathered out of the late Tertiary rocks of the Story Hills, northeast of Bozeman. This discovery further strengthens the proposition for a Tertiary eastward drainage.

Although there is strong evidence to support the proposition of eastward drainage during Tertiary time, Glancy (1964) presented evidence which contradicts this idea. He found westward imbricated conglomerates in the Story Hills which contained lithologies that were possibly derived from the Crazy Mountains to the east. To date, his discovery has not been refuted or confirmed.

Perhaps Glancy (1964) found the remnant of a small westward flowing tributary, which drained the highlands to the east. This tributary may have ultimately emptied into the master eastward flowing system. Although this suggestion may explain the westward-oriented imbrication, it does not satisfactorily account for the presence of Crazy Mountain lithologies.

Where the eastward flowing drainage left the Three Forks basin is a matter of speculation. Schneider (1970) suggested that the low passes in the Bridger Range (Flathead Pass and Ross Pass) served as the drainage outlets.

If a major drainage did escape through Flathead Pass, it must have passed through the map area. However, it has been demonstrated that a southward paleoslope developed in the Dry Creek Valley, at least during late Tertiary time. Consequently, a large stream flowing northeastward across a southward sloping area would not be expected.

It cannot be determined whether or not a drainage escaped through Ross Pass. Assuming that basin-fill sediments did not bury the Precambrian LaHood-Paleozoic Flathead contact, the problem may be approached as follows: if it could be proved that the lower Flathead contact was higher than the highest point within the pass, an eastward gradient through the pass could be substantiated (Fig. 21). In actuality, complex folding and faulting in both Ross Pass and Flathead Pass prevent any reconstruction of this kind.

The Rocky Canyon area east of Bozeman should also be considered as a possible Tertiary drainage outlet. The elevation differences between the nearest basin-fill sediments and the pre-basin rocks in the canyon area are not much different from those observed between the Dry Creek Valley deposits and the passes of the Bridger Range. As mentioned previously, granitic rocks presumably derived

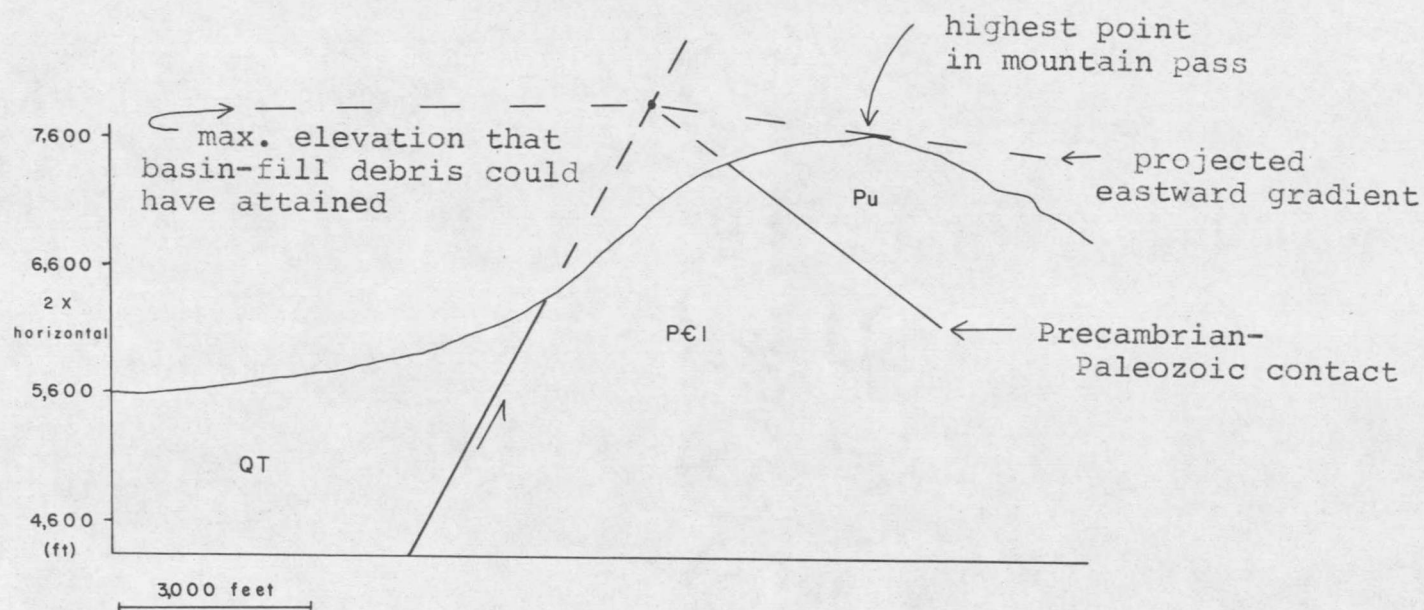


Figure 21. Diagrammatic cross-section through a hypothetical low pass in the Bridger Range. Scales are only approximate. If it could be proved that basin-fill deposits reached an elevation higher than the highest point in the pass, then an eastward gradient through the range could be demonstrated. QT= basin-fill deposits; Pu= Paleozoic undifferentiated; PcI= LaHood Formation.

from the Tobacco Root Range were found in float associated with late Tertiary basin-fill deposits of the Story Hills, 6 km west of the canyon (E. F. Griffith and S. G. Custer, 1979, pers. comm.). This recent find and its proximity to Rocky Canyon is the strongest evidence to date for eastward drainage through the Rocky Canyon area.

By late Pliocene or early Quaternary time, the entire region began to rise, with the greatest uplift occurring in the mountain ranges to the south. The late Tertiary surface in the major part of the Three Forks basin acquired a northwesterly slope on which a consequent drainage system formed. The newly developed Missouri system soon captured the remaining eastward flowing streams, and the development of the present topography was underway (Robinson, 1961). An axis of this late Cenozoic regional uplift must have been located just south of the Dry Creek Valley, since the map area has retained its southward slope, which was established in Tertiary time.

CENOZOIC HISTORY

By integrating the interpretations discussed in the previous pages, the Cenozoic history of the Dry Creek Valley can be outlined:

1. Compressional forces of the Laramide orogeny continued to deform and uplift pre-Cenozoic strata during Paleocene time. Orogenic forces were accompanied by through-flowing drainage systems maintained by a moist, warm climate. These fluvial systems evacuated most of the debris shed from adjacent uplands (Robinson, 1963).

2. Normal faulting accompanied with dissection of the landscape by through-flowing drainages delineated the Three Forks basin and the Dry Creek Valley. A mature erosional topography developed under the humid conditions of early Eocene time (Robinson, 1963).

3. By middle or late Eocene time, the climate became less humid. The Three Forks basin and the Dry Creek Valley were no longer being flushed by large through-flowing streams. Rather, internal drainage and basin-filling ensued (Lange and others, 1980; Robinson, 1963). Scant exposures of Oligocene Renova strata west of Menard indicate that a succession of lacustrine and floodplain sediments partially filled the early Tertiary topography.

4. Renova sediments continued to fill the Dry

Creek Valley until middle Miocene (?) time. By this time, deposition ceased because the climate became humid enough to maintain through-flowing drainage nets (Fields, 1972). An unknown amount of Renova material was removed.

5. By late Miocene (?) time, the climate became arid again; more arid and less equable than Oligocene time (Lange and others, 1980). Basin-filling resumed with the deposition of the Sixmile Creek Formation. An alternating pond and flood-basin environment was established in the northwestern corner of the map area. Southward-flowing ephemeral streams deposited detritus derived from the north. Locally derived clastic material shed from the hills to the south was intimately mixed with the flood-basin deposits. Once again, the early Tertiary topography was gradually buried. Sporadic uplifts of the Bridger Range repeatedly tilted the basin-fill strata eastward. A pediment may have been cut in the southwestern portion of the map area.

6. Coarse angular detrital material from the Bridger Range and the Horseshoe Hills, combined with volcanic ash and mud, was continually transported by ephemeral run-off (mainly sheetfloods) and deposited as alluvial fans. A caliche soil formed in the northern part of the map area, while southward-flowing streams may have developed

in the west-central portion of the Dry Creek Valley. These streams probably followed a course similar to that of Dry Creek. Carbonate-rich spring waters accompanied with ephemeral run-off deposited conglomeratic limestones as carbonate fans, which eventually covered the erosional surface in the southwestern portion of the map area.

7. Sixmile Creek sediments continued to accumulate into Pliocene time. They gradually onlapped in all directions across older rocks. By middle (?) Pliocene time the Dry Creek Valley was filled to the point where all but the higher peaks of the early Tertiary topography were buried. The last movements along the Bridger Fault occurred at this time. The Sixmile Creek landscape is thought to have acquired the appearance of the present arid southwestern United States.

8. Basin-filling ceased by middle or late (?) Pliocene time. Consequent streams developed on the late Tertiary surface, while the climate was becoming more humid. Perennial streams and, in part, debris-flows transported coarse debris (QTof) across the late Tertiary surface. Concurrent regional uplift tilted the major part of the Three Forks basin northward, subsequently forming the ancestral Missouri drainage (Robinson, 1961). The Dry Creek

Valley retained its southward slope.

9. A change in stream regimen occurred in late Pliocene or early Quaternary time (Peterson, 1974). Dry Creek and some of its tributaries were superimposed through the high Tertiary covermass onto underlying resistant pre-basin rocks. Basin excavation and the present erosion cycle had now begun. A stair-step succession of erosion surfaces was established in the Menard area, recording the progressive downcutting of Dry Creek. Remnants of the late Tertiary surface became isolated by the continued erosion of adjacent streams, and the early Tertiary surface was gradually exhumed. A meander bend of an ancestral East Gallatin River migrated into the southern bluffs area, depositing gravels derived from a southern source.

10. Glaciation in the Bridger Range created perennial run-off which deposited some of the coarse gravels (QTof) as alluvial fans in the central and southern portions of the map area. By late Wisconsin (Pinedale) time, the present topography was established. Some of the tributary channels along the east flank of the Dry Creek Valley were occupied by relatively large streams which drained the glaciated Bridger Range. Soon after glaciation, debris-flows flowed out of the glaciated canyons of the Bridger

Range and into the Dry Creek Valley, partially filling modern tributary channels.

11. Presently, the Dry Creek Valley stands as a remnant of an old basin floor, while dissection continues.

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APPENDICES

APPENDIX I

MEASURED SECTION DESCRIPTIONS

MEASURED SECTION DESCRIPTIONS

Four sections of Tertiary rock were measured west of Menard. Together, they form the composite section illustrated in Figure Ia. Stratigraphic correlation is based merely on geometric projection and is considered to be only tentative. Note the large covered intervals which separate the sections.

Each section was measured using a Jacob staff and tape measure. Samples were taken at significant changes in lithology. Fossils diagnostic of age were not found.

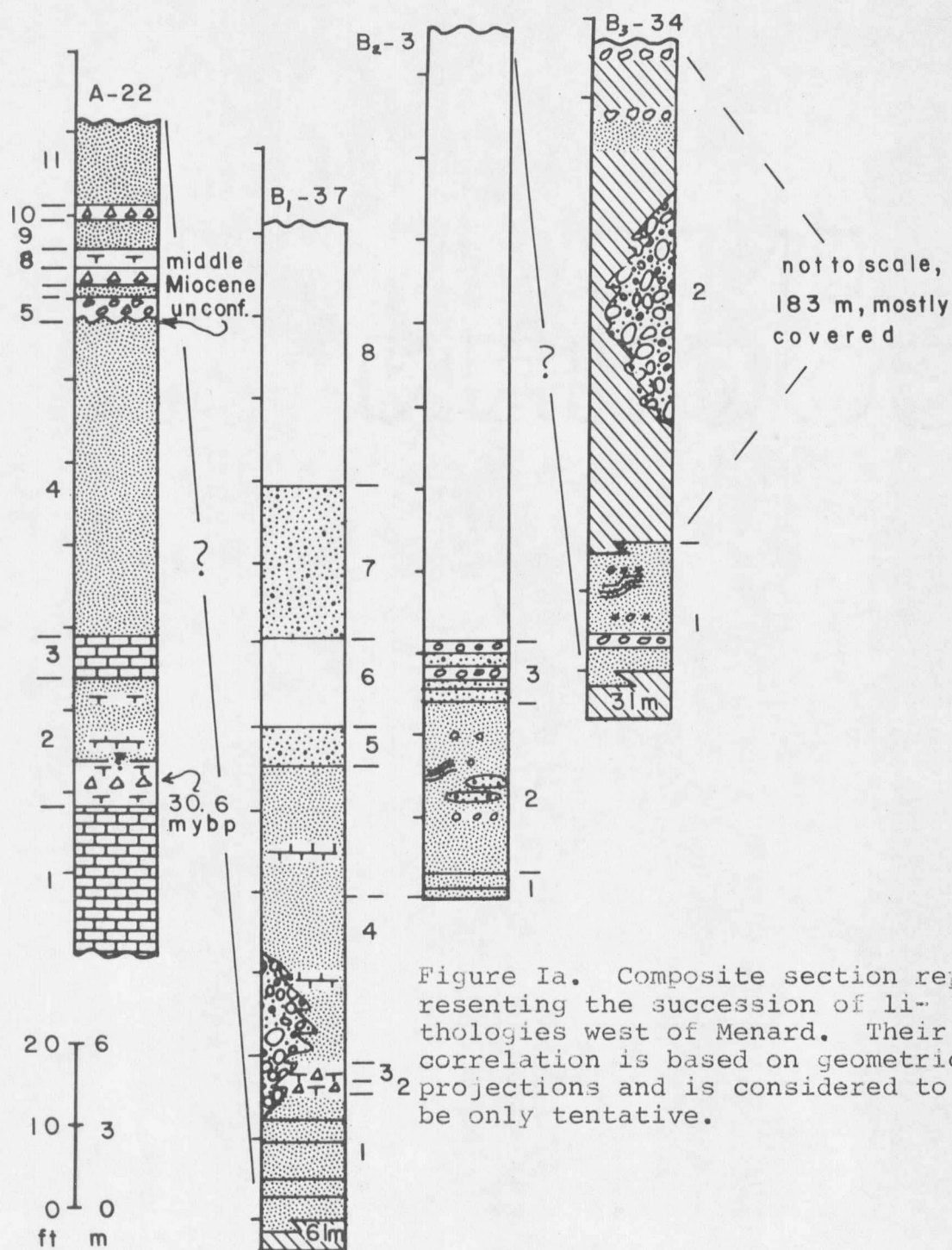
SECTION B₃-34. Located 0.8 km (0.5 mi.) northwest of Menard, just north of Menard Road (NE $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 35, T.3N., R.4E.). The top of this section occurs in the SE $\frac{1}{4}$, NW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 25, T.3N., R.4E.

Sixmile Creek Formation

ft m

2. Covered; although very small and discontinuous exposures of very coarse channel cobble conglomerates and tuffaceous mudstones do occur. The exposures are usually less than 0.6m (2 ft.) thick. Volcanic and Mesozoic lithic fragments are common. Coarse-grained structureless conglomeratic sandstones that crop out east of Menard may be intercalated with these deposits. 602 183

1. Tuffaceous mudstone. Grayish orange (10YR 7/4) and massive to structureless. Climbing ripples are common but very discontinuous. Root casts and burrow fillings are also common. Pebbly conglomerate stringers and small lenses of cross-stratified fine-grained sandstones sporadically occur throughout this unit.



KEY TO FIGURE 1a.



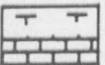
conglomerate



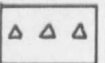
conglomeratic sandstone



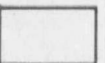
medium to coarse grained channel sandstone

thickly bedded to structureless fine-grained
ripple laminated sandstone and mudstone

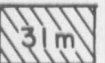
limestone and tuffaceous marl



vitric ash



covered interval



covered interval not to scale

7

correlates to lithologic description in
measured section

	ft	m
Volcanic and Mesozoic rock fragments are common.	15	4.6
Total thickness of section B ₃ -34.	617	187.6

SECTION B₂-3. Located 1.6 km (1 mi.) northwest of Menard in a gully just north of Menard Road (SW $\frac{1}{4}$, SW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 26, T.3N., R.4E.).

Sixmile Creek Formation

4. Covered; overlain by pediment gravels . . .	75	22.9
3. Tuffaceous lithic sandstone. Pale yellowish brown (10YR 6/2), cross-stratified, and fine to medium grained. Contains andesitic lithic fragments. Pebbly conglomerate stringers occur throughout the unit . . .	7	2.1
2. Tuffaceous mudstone which is complexly interbedded with cross-stratified channel sandstones, sandy pebble conglomerates and pebbly conglomerate stringers. The mudstones are very paleorange (10YR 8/2), massive, and contain discontinuous ripple laminations. Burrow fillings and root casts are common. Clastic dikes intrude this unit. The channel sandstones and conglomerates contain volcanic rock fragments	22	6.7
1. Tuffaceous mudstone. Grayish orange (10YR 7/4), thickly bedded, and noncalcareous. Similar to overlying mudstones except that this unit is more clayey. Cut into by clastic dikes	3	0.9
Total thickness of section B ₂ -3	107	32.6

SECTION B₁-37. Located in a channel 0.8 km (0.5 mi.) west of Menard (SW $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 35, T.3N., R.4E.).

Sixmile Creek Formation	ft	m
8. Covered; overlain by pediment gravels . . .	31	9.4
7. Fine-grained tuffaceous sandstone. Grayish orange pink (5YR 7/2), friable, structureless, and calcareous . . .	18	5.5
6. Covered	10	3.0
5. Fine-grained tuffaceous sandstone. Grayish orange pink (5YR 7/2), friable, structureless, and calcareous . . .	4	1.2
4. Tuffaceous mudstone. Very pale orange (10YR 8/2) to light gray (N8), structureless, blocky, and slightly calcareous. Contains thin beds of tuffaceous marl. This deposit is probably interbedded with the coarse cobble conglomerate which crops out approximately 402 m (1320 ft.) downstream from this location. This conglomerate contains large angular clasts of Madison limestone	38	11.6
3. Tuffaceous mudstone. White (N9) to pale orange (10YR 8/2) and structureless. Similar to the overlying unit except that it is more calcareous, indurated, and resistant.	3	0.9
2. Vitric lithic tuff. Grayish orange (10YR 7/4), structureless, and very calcareous. Glass shards compose 50% of the rock	2	0.6
1. Tuffaceous mudstone. Grayish orange (10YR 7/4) and thickly bedded. Each bed is structureless and blocky. The rock is porous and noncalcareous. Contains up to 40%		

	ft	m
glass shards.	15	4.5
Total thickness of section B ₁ -37.	121	36.6

SECTION A-22. Located on the west face of a north-northwest trending ridge northwest of Menard (NW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 27, T.3N., R.4E.).

Renova and Sixmile Creek Formations

Sixmile Creek Formation

- | | | |
|---|---|-----|
| 11. Silty tuffaceous mudstone. Pale orange (10YR 8/2), structureless, blocky, and slightly calcareous. Burrow fillings and root casts are very common. Glass shards compose up to 30% of the rock. Overlain by pediment gravels | 9 | 2.7 |
| 10. Vitric lithic tuff. Grayish orange (10YR 7/4), thinly bedded to massive, and blocky. Glass shards compose up to 50% of the rock | 1 | 0.3 |
| 9. Silty tuffaceous mudstone. Very pale orange (10YR 8/2), structureless, and blocky. Burrow fillings and root casts are common. Slightly calcareous. | 6 | 1.8 |
| 8. Tuffaceous marl. Very light gray (N8), thinly bedded, and micritic. Ostracodes and gastropods compose 5% of the rock, while detrital material comprises 20 to 30%. Reacts vigorously with dilute HCl | 2 | 0.6 |
| 7. Vitric lithic tuff. Very light gray (N8), structureless calcareous, and loosely packed. Contains 40 to 50% glass shards and 30 to 40% detrital | | |

	ft	m
material. Ostracode shell fragments occur in very small amounts	2	0.6
6. Silty tuffaceous mudstone. Very pale orange (10YR 8/2), structureless, and noncalcareous. Composed of 40% detrital material and 30% glass shards.	2	0.6
5. Tuffaceous pebbly conglomerate. Very pale orange (10YR 8/2) and structure- less. Largest clast is 3.5 cm in diameter. Grain-supported texture. Most of the clasts are Tertiary rock fragments	3	0.9

Unconformity ?

Renova Formation

4. Silty tuffaceous mudstone. Grayish orange (10YR 7/4), thinly bedded to massive, and calcareous. Detrital material and glass shards both compose 45% of the rock	38	11.6
3. Tuffaceous marl. Very light gray (N8), thinly bedded, and chalky. Ostracode remains compose 20% of the rock; very clayey.	5	1.5
2. Vitric ash and tuffaceous marl. This unit is overlain by and possibly inter- bedded with a light gray (N7) tuffa- ceous siltstone. The ash bed is inter- calated with the thinly bedded tuffa- ceous marl. The siltstone is tuffaceous, structureless, and blocky. The marl contains Ostracodes and gastropods. . . .	18	5.5
1. Fine-grained limestone and marl. White (N9) to very light gray (N8), thinly bedded, dense, and chalky. Ostracode		

	ft	m
and gastropod shell fragments are common. The base is covered by alluvium . .	16	4.9
Total thickness of section A-22	102	31.0

Approximate thickness of composite section:

B ₃ -34	617	187.6
covered interval.	102	31.0
B ₁ -37 & B ₂ -3 (Fig. 1a).	147	44.8
covered interval.	200	61.0
A-22.	<u>102</u>	<u>31.0</u>
Approximate thickness	1168	355.4

APPENDIX II

POTASSIUM-ARGON AGE DATES

POTASSIUM-ARGON AGE DATES

Age Dates Within the Dry Creek Valley

Sample A-22-2

Location: 2.5 km (1.6 mi.) northwest of Menard near the base of the small northwest trending ridge (45°58'N, 111°13'W; NW¼, NE¼, SW¼, NE¼, Sec. 27, T.3N., R.4E., Belgrade quadrangle).

Formation: Renova.

Rock type: Vitric ash interbedded with tuffaceous marls.

Collected by: Gary C. Hughes, Montana State University.

Dated by: Geochron Laboratories Division; Krueger Enterprises, Inc., Cambridge, MA.

Age: 30.6 ± 1.2 mybp

Material analyzed: Glass shards.

Analytical data: $K^{40} = 5.017$ ppm; $Ar^{40*} = 0.009057$ ppm;
 $Ar^{40*}/K^{40} = 0.001805$.

Sample FC-2

Location: 0.8 km (0.5 mi.) north on Foster Creek Road, from its intersection with Dry Creek Road. Road cut exposes ash bed (45°51'47"N, 111°9'20"W; NE¼, SW¼, SW¼, Sec. 6, T.1N., R.5E., Belgrade quadrangle).

Formation: Sixmile Creek.

Rock type: Vitric ash; overlies pale orange tuffaceous mudstone.

Collected by: Gary C. Hughes, Montana State University.

Dated by: Geochron Laboratories Division, Krueger Enterprises, Inc., Cambridge, MA.

Age: 8.9 ± 0.4 mybp

Material analyzed: Glass shards.

Analytical data: $K^{40}=6.413$ ppm; $Ar^{40}* = 0.003360$ ppm;
 $Ar^{40}*/K^{40}=0.000524$.

Age Dates of Tertiary Rocks Outside of the Dry Creek Valley

Sample SS-1

Location: 6.4 km (4 mi.) west of highway 10N; 2.8 km (1.75 mi.) east of Shoddy Springs. Sample taken along south side of road ($45^{\circ}56'52''N$, $111^{\circ}40'50''W$; $NE\frac{1}{4}$, $NE\frac{1}{4}$, $NE\frac{1}{4}$, Sec. 11, T.2N., R.1W., Three Forks quadrangle).

Formation: Climbing Arrow (Renova equivalent).

Rock type: Devitrified lithic tuff.

Collected by: Gary C. Hughes, Montana State University.

Dated by: Geochron Laboratories Division, Krueger Enterprises, Inc., Cambridge, MA.

Age: 50.4 ± 2.1 mybp

Material analyzed: Feldspar crystal concentrate.

Analytical data: $K^{40}=3.788$ ppm; $Ar^{40}* = 0.01133$ ppm;
 $Ar^{40}*/K^{40}=0.002990$.

Sample YV-2

Location: 0.8 km (0.5 mi.) north of Wan-i-Gans cabins on old highway in the Yellowstone Valley (Paradise Valley). Exposure is part of the White Cliffs ($45^{\circ}17'51''N$, $110^{\circ}49'31''W$; $SW\frac{1}{4}$, $NW\frac{1}{4}$, $NE\frac{1}{4}$, $SE\frac{1}{4}$, Sec. 23, T.6S., R.7E., Fridley Peak quadrangle).

Formation: Unnamed.

Rock type: Vitric ash.

Collected by: Gary C. Hughes, Montana State University.

Dated by: Geochron Laboratories Division, Krueger Enterprises, Inc., Cambridge, MA.

Age: 17.1 ± 0.7 mybp

Material analyzed: Glass shards.

Analytical data: $K^{40} = 6.051$ ppm; $Ar^{40*} = 0.006065$ ppm;
 $Ar^{40*}/K^{40} = 0.001002$.

* NOTE: Ar^{40*} refers to radiogenic Ar^{40} .

APPENDIX III

LOCATIONS OF EXPOSURES

LOCATIONS OF EXPOSURES

Tertiary Renova Formation:

NW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 27, T.3N., R.4E.
(Measured section A-22)

Tertiary Sixmile Creek Formation:

Ephemeral stream channel, floodplain-overbank, and lacustrine deposits--

SW $\frac{1}{4}$, SW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 26, T.3N., R.4E.
SW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 26, T.3N., R.4E.
NW $\frac{1}{4}$, SE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 35, T.3N., R.4E.
SW $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 35, T.3N., R.4E.

Other fluvial deposits (southwestern portion of map area)--

NW $\frac{1}{4}$, SW $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 34, T.2N., R.4E.
NW $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 34, T.2N., R.4E.
SE $\frac{1}{4}$, SE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 27, T.2N., R.4E.
NE $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E.

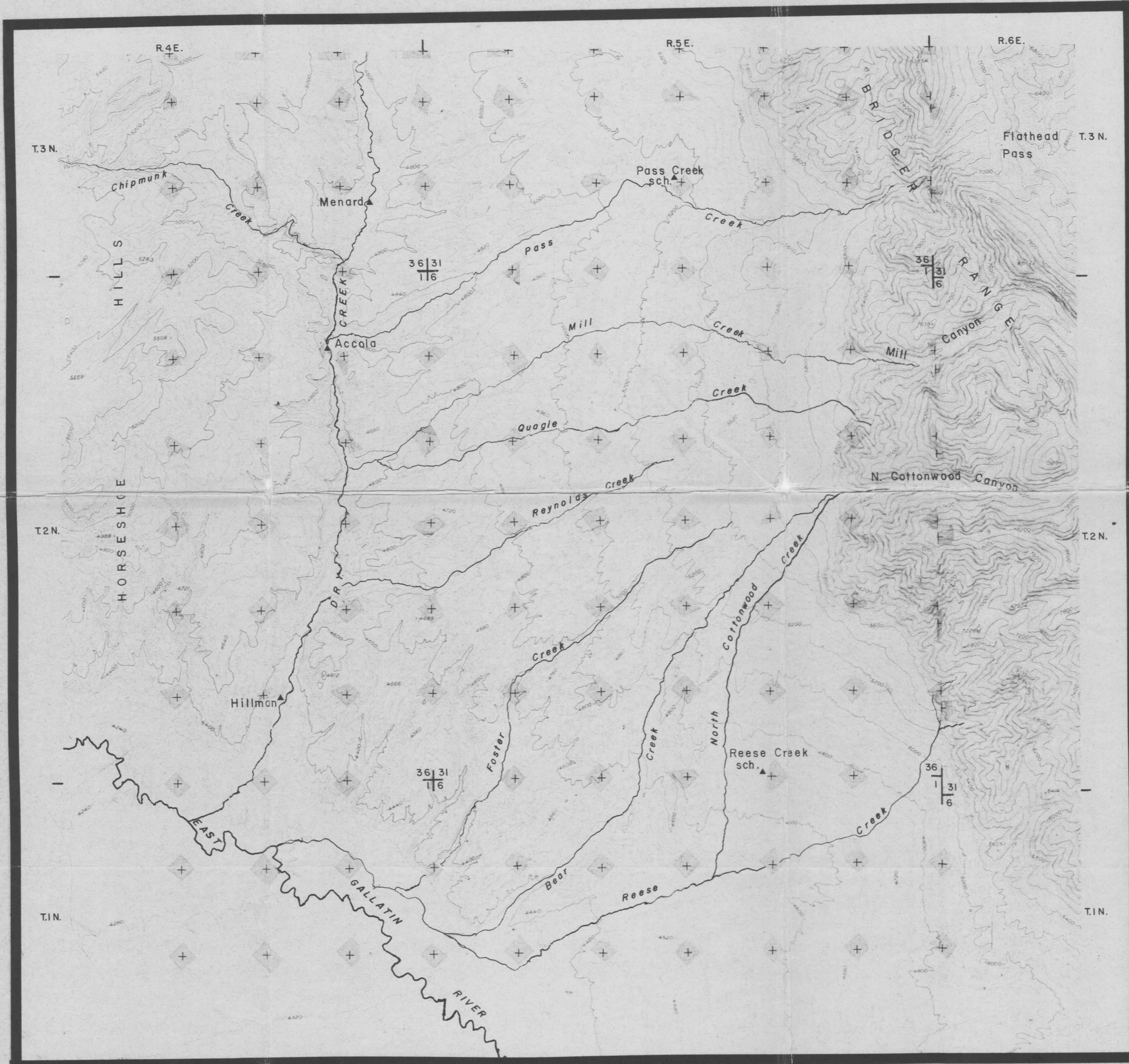
Sheetflood (?) deposits--

NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 7, T.1N., R.5E.
S $\frac{1}{2}$, NW $\frac{1}{4}$, Sec. 7, T.1N., R.5E.
SE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 6, T.1N., R.4E.
NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 36, T.2N., R.4E.
SW $\frac{1}{4}$, NW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 12, T.2N., R.4E.
E $\frac{1}{2}$, SE $\frac{1}{4}$, Sec. 28, T.2N., R.5E.
NE $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 32, T.2N., R.5E.

Tertiary Spring Deposits:

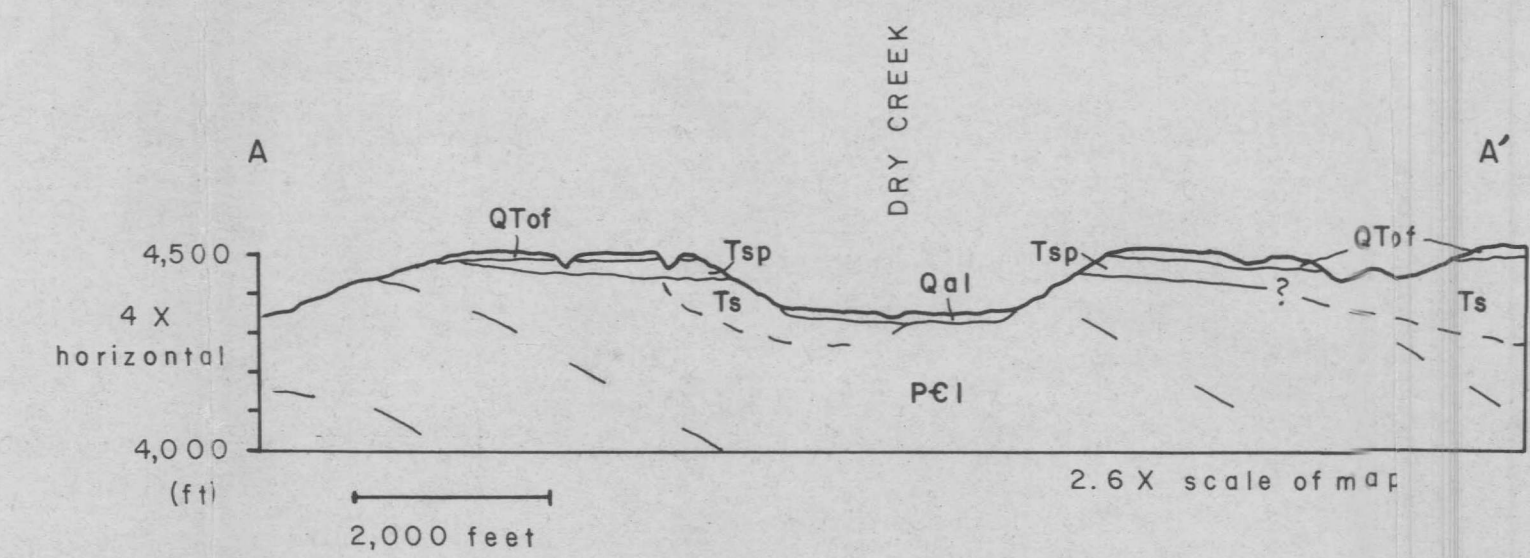
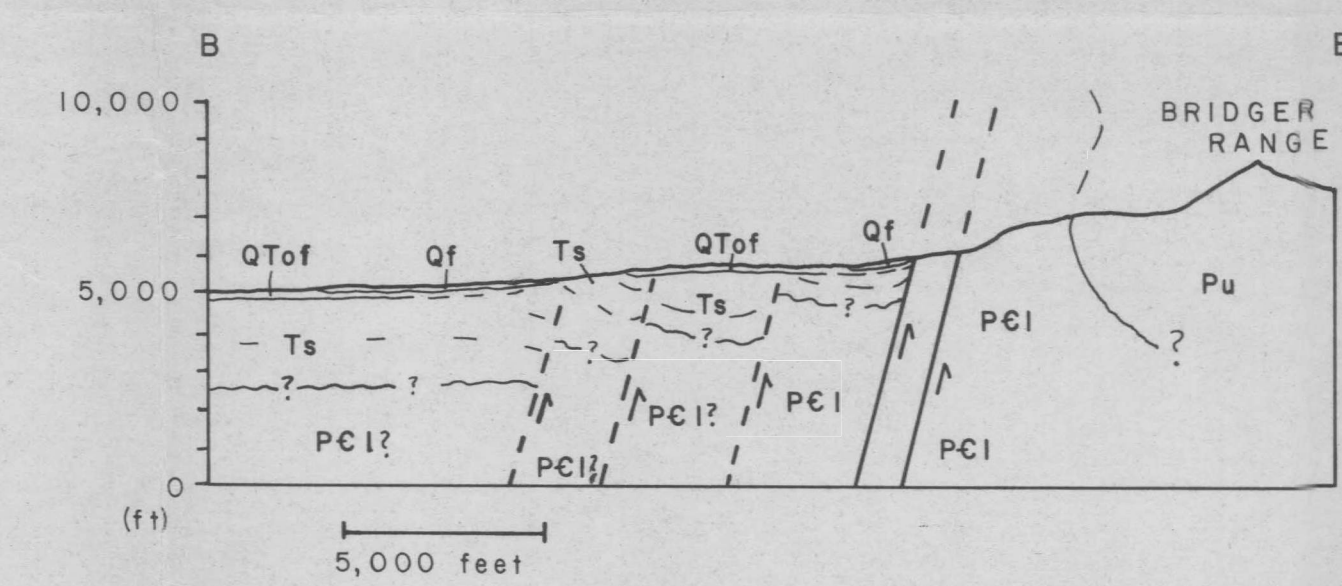
NE $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E.
SE $\frac{1}{4}$, NW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E.
NW $\frac{1}{4}$, NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 26, T.2N., R.4E. (Best exposure)
NW $\frac{1}{4}$, SE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 27, T.2N., R.4E.
SW $\frac{1}{4}$, NW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 34, T.2N., R.4E.
NE $\frac{1}{4}$, NW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 22, T.2N., R.4E.
NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 27, T.2N., R.4E.
NW $\frac{1}{4}$, Sec. 23, T.2N., R.4E.

TOPOGRAPHIC MAP OF THE
DRY CREEK VALLEY

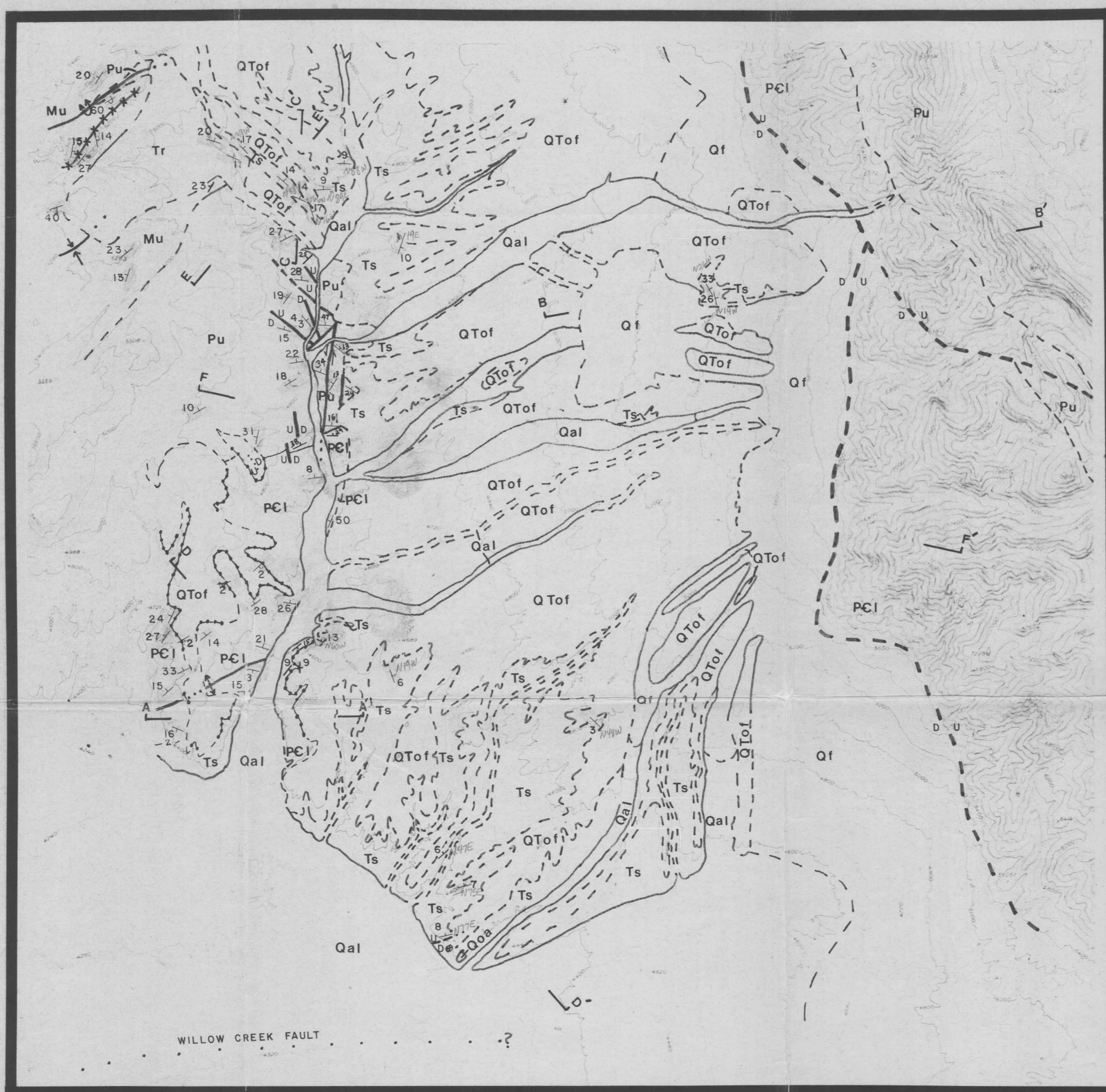
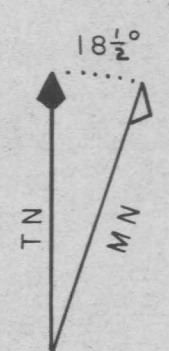


GEOLOGIC MAP OF THE DRY CREEK VALLEY
GALLATIN COUNTY, MONTANA

by
Gary C. Hughes



GEOLOGIC MAP OF THE
DRY CREEK VALLEY

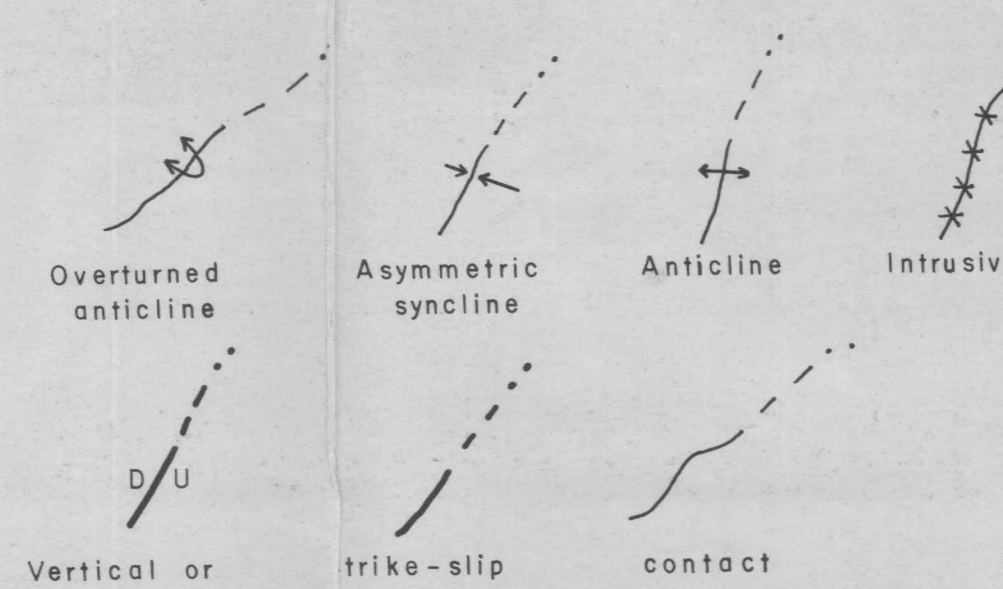


SCALE 1/62,500
5,000 0 5,000 10,000 15,000 FEET
CONTOUR INTERVAL 40 FEET

Pre-basin geology compiled, in part, from
McMannis (1955), Verrill (1955), and
Hockett and others (1960).

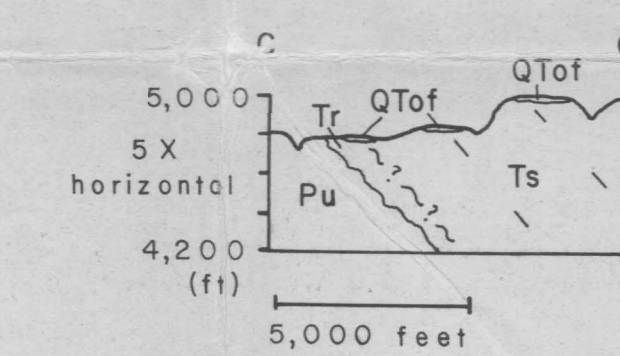
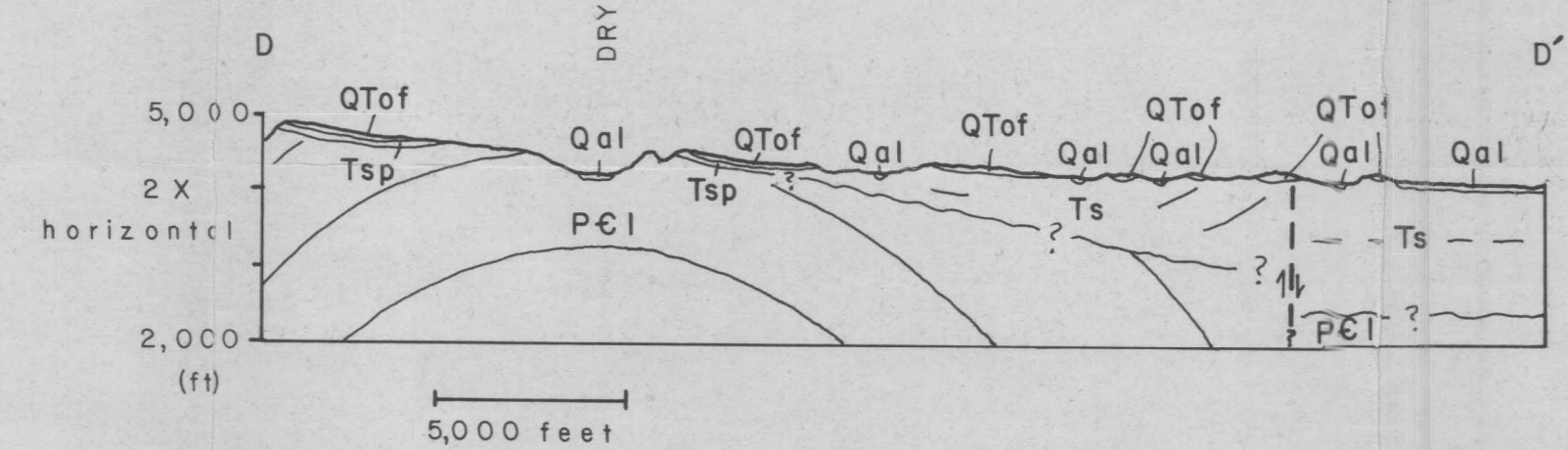
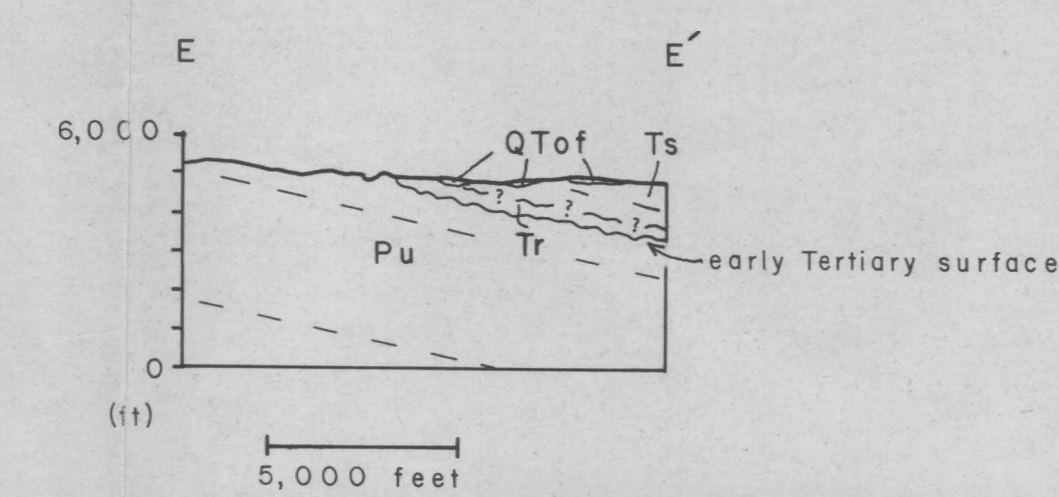
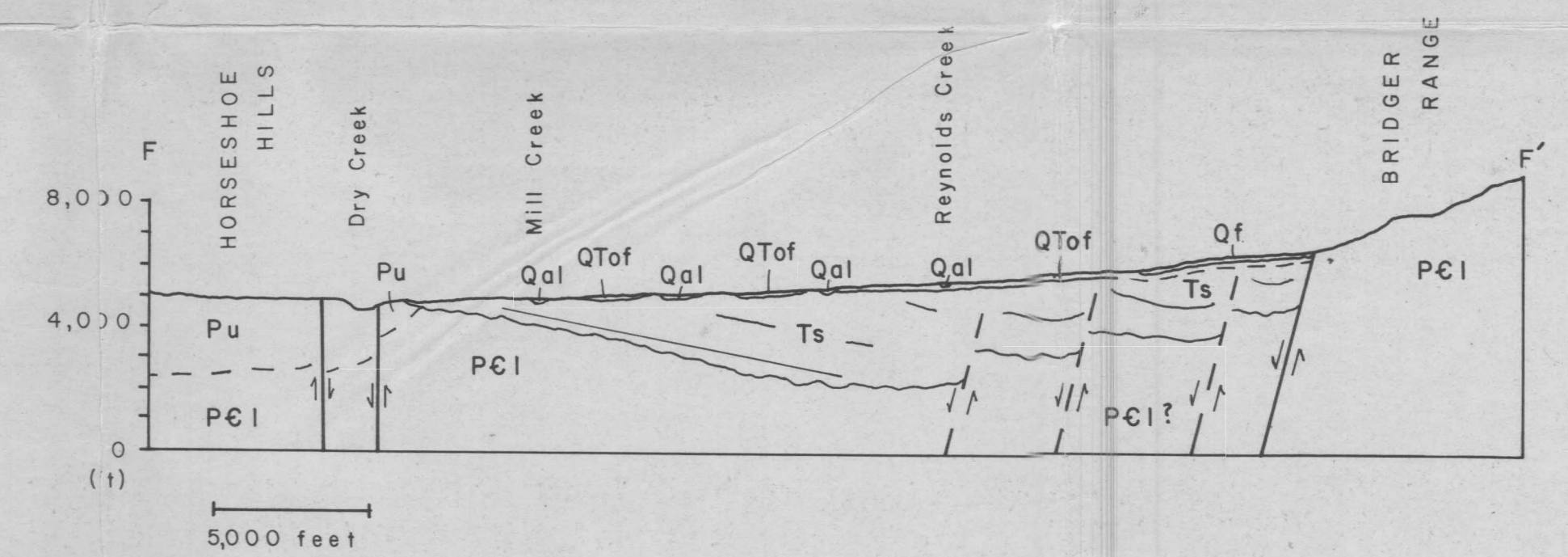
EXPLANATION

- Qal Recent stream alluvium
- Qf Debris-flow and alluvial fan deposits
- Qoa Old alluvium
- QTof Old fan and pediment gravels
- Ts Sixmile Creek Formation
- Tsp Spring deposits
- Tr Renova Formation
- Mu Mesozoic undifferentiated
- Pu Paleozoic undifferentiated
- PCl LaHood Formation



Axes of folds, faults, and contacts are dashed where approximated; dotted where concealed.

location of cross-section



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