General geology and geomorphology of the Emigrant Gulch-Mill Creek area, Park County, Montana
by Wayne Adams Van Voast

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Applied Science
Montana State University

Abstract:
Rocks ranging in age from Precambrian through Late Jurassic are present along the Beartboth Mountain front between Emigrant Gulch and Mill Creek. The Middle Cambrian strata have been intruded by a silllike pluton of dacitic magma which possibly caused upthrusting and warping of the overlying sedimentary sequence. The crystallized magma is concentrated at the point of convergence of the Mill Creek fault zone, the Cooke City zone, and the Deep Creek fault suggesting a cause and effect relationship.' Uplift of the west flank of the Beartooth massif is attributed to range-front movement along the Deep Creek fault, the trace of which is postulated to be buried beneath alluvium and glacial deposits on the valley floor within the map area. Its presence is implied by springs and travertine deposits in the. Chico vicinity and by recent scarps projecting into the map area along the mountain front.

Tertiary sediments on the valley floor at Wanigan were dated as late Miocene - early Pliocene and correlated with similar deposits of that age five miles to the south at White Cliffs.

Wisconsin glacial features cover a pre-Wisconsin topography of considerable relief on the valley floor and include two outwash plains and two piedmont terminal moraines of different ages. Analyses of preservation of these glacial features, weathering of debris, soil profile development, stratigraphic relationships, and physiographic relationships indicate at least two Wisconsin piedmont glacial advances. However, evidence for correlation with "standard" Bull Lake and Pinedale substages is inconclusive.

The post-glacial history of the valley is characterized by recurrent structural movement along the mountain fronts and sporadic downcutting and lateral erosion by the Yellowstone River and its tributaries.

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ABSTRACT

Rocks ranging in age from Precambrian through Late Jurassic are present along the Beartooth Mountain front between Emigrant Gulch and Mill Creek. The Middle Cambrian strata have been intruded by a sill-like pluton of dacitic magma which possibly caused upthrusting and warping of the overlying sedimentary sequence. The crystallized magma is concentrated at the point of convergence of the Mill Creek fault zone, the Cooke City zone, and the Deep Creek fault suggesting a cause and effect relationship.

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GENERAL GEOLOGY AND GEOMORPHOLOGY OF THE EMIGRANT GULCH-MILL CREEK AREA, PARK COUNTY, MONTANA

INTRODUCTION

Geographic Setting

The area of this field study is located along the west flank of the Beartooth Range in the mountains of south-central Montana, part of the northern Rocky Mountain chain. This area includes part of the valley on the east side of the Yellowstone River directly south of the small community of Pray, Montana, about 25 miles south of Livingston. The map area (see figure 3) is bounded by the Yellowstone River on the west, Emigrant Creek on the south, and Mill Creek on the north. The eastern boundary is a hypothetical line paralleling the mountain front and extending from White City to Mill Creek. This line nearly coincides with the saddles between the more subdued ridges and the steep front of the main Beartooth massif.

Previous Investigations

Bedrock geology of the map area was first studied by Iddings and Weed, whose work was published in 1893 in the U. S. Geological Survey's Livingston Folio. Their map and descriptiom of the area is very general. The area was later mapped in more detail by J. T. Wilson (1937) as part of his Ph. D. thesis at Princeton University but this work was never published. However, his map was used in the compilation of the state geologic map of Montana (1955).

Geomorphic studies which included the map area have been published by Weed (1893) and by Horberg (1940). Horberg's work was done in considerably more detail but the most important geomorphic interpretations can be attributed to Weed. Alden (1932) made several trips through the

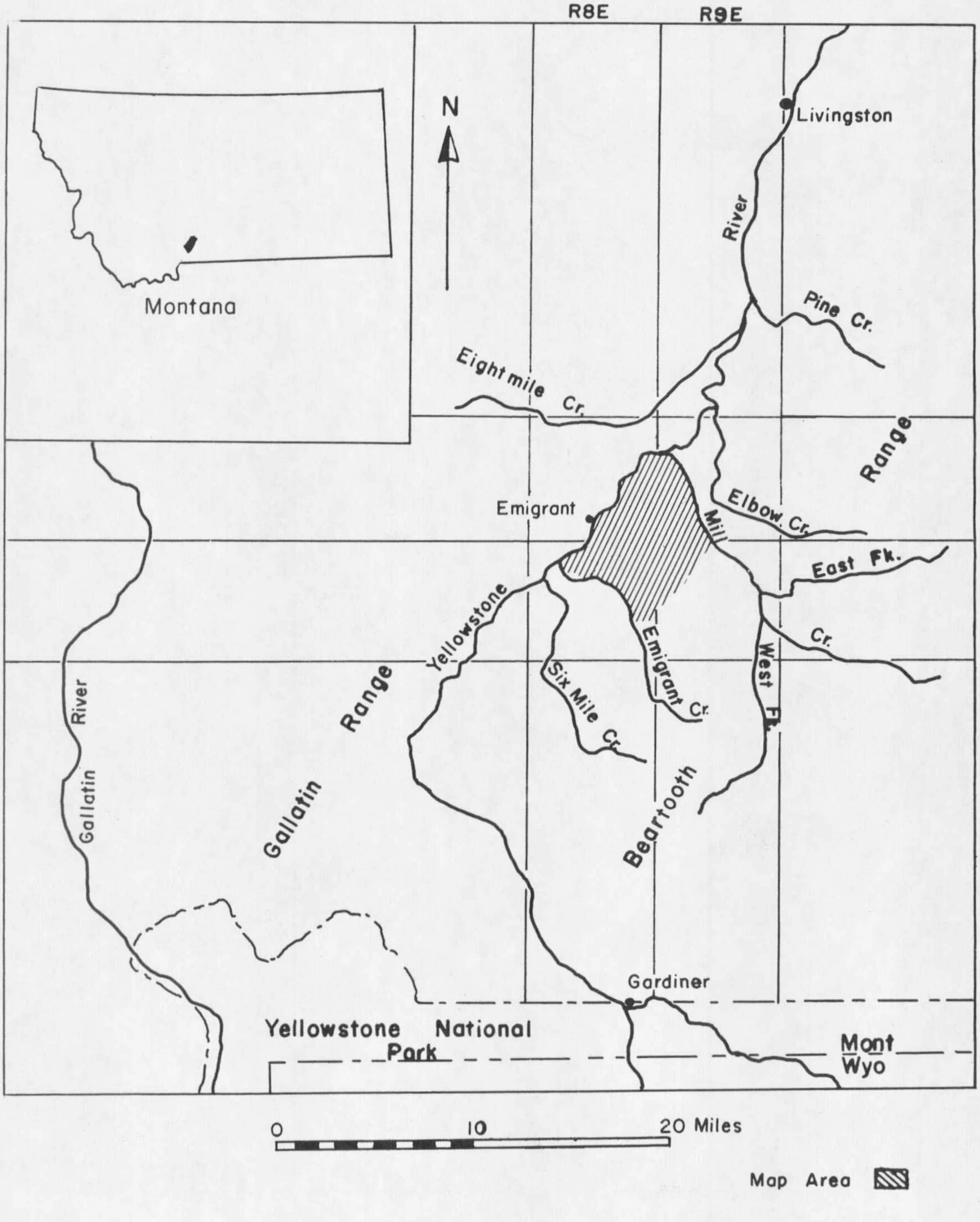


Figure 3. Index Map

area but relied essentially on Weed's work in presenting some interesting suggestions regarding correlation of surfaces on a regional basis.

The most recent work in the area has been done by John Montagne in 1961, '62, and '63. Montagne's research was concentrated on the evidence for high-level pre-Wisconsin glaciation in the valley but the general geology was also noted. The results of his work have not yet been published.

Objectives

The objectives of this study were to construct an accurate geologic map of the area, to describe rock units and structural and geomorphic relationships, and to propose a likely Quaternary through Recent geomorphic history of the area. Other problems considered in this study include the possibility of range front faulting and the age of Tertiary sediments on the valley floor.

Age	Stratigraphic Unit		Approx. Thickness	Character
	Morrison Formation and overlying Mesozoic units not exposed.			
U. Jurassic	Ellis Group	Swift Formation	80'	Calcareous fossiliferous cross-bedded glauconitic sandstone.
		disconformity		
M. Jurassic		Rierdon Formation	95'	Calcareous olive-gray shale overlying thin zone of gray fossiliferous oolitic limestone.
M. Jurassic		Sawtooth Formation	250'	About 160' of dense gray, brown, and yellow shale overlying about 80' of yellow to gray silty and sandy shale.
		disconformity		
Pennsylvanian		Quadrant Formation	115'	Light-yellowish-gray to light-reddish-gray fine-grained quartzite or quartz sandstone.
Pennsylvanian and Mississippian		Amsdem Formation	80'	Non-resistant beds of red shale and siltstone. Interbedded limestone and varicolored shale. Basal sandstone containing fragments of underlying Madison Limestone. Weathers to red soil.
		disconformity		
Mississippian		Mission Canyon Limestone	580'	Light gray siliceous limestone. Chert nodules and lenses commonly parallel to bedding. Generally massive, dense, and devoid of fossils.
		Lodgepole Limestone	400'	Light gray thin-bedded to massive fossiliferous fragmental limestone. Chert nodules and lenses commonly parallel to bedding.
		disconformity		

TABLE I. - Generalized Paleozoic and Mesozoic Stratigraphic Section near Mill Creek

U. Devonian	Three Forks Shale		85'	Thin-bedded orange-brown shales interbedded with gray to orange-gray dolomite. Thin beds of yellow cross-bedded arenaceous dolomite. Salt casts and ripple marks common in some beds.
U. Devonian	Jefferson Limestone		258'	Dark gray to black medium-bedded to massive fine-grained dolomitic limestone. Weathers to medium to dark brown color and gives "petroliferous" odor from fresh fractures. Contains Amphipora and has calcite veinlets in fractures. Solution breccias common in a few zones.
	disconformity			
U. Ordovician	Bighorn Dolomite		80'	Buff to gray massive fine-grained dolomite. Crinoid stems are common. Siliceous stringers cause weathering to "honey-comb-like" rough pitted surface.
	disconformity			
U. Cambrian	Snowy Range Formation	Grove Creek Limestone Member	30'	Medium-bedded buff limestone pebble conglomerate. Well-rounded greenish-coated limestone pebbles with little or no limestone matrix.
		Sage Pebble Conglomerate Member	160'	Medium-bedded to massive flat pebble conglomerate with interbedded gray-green thin-bedded shales. Conglomerate composed of dense limestone pebbles in a crystalline limestone matrix.
		Dry Creek Shale Member	90'	Gray-green and dark green, thin-bedded shales intercalated with a few beds of brown, sandy shales.
	Pilgrim Limestone		202'	Approximately 100 ft. of light gray to buff mottled thick-bedded oolitic crystalline limestone overlying

TABLE I. - (Continued)

			about 100 ft. of gray-green coarse edgewise conglomerate irregularly bedded with intercalated thin beds of gray and green shales.
M. Cambrian	Park Shale	200'	Gray-green fissile micaceous shale. A few thin beds of gray crystalline limestone in the middle of the unit.
	Meagher Limestone	150'	Gray thin-bedded limestone with silty yellow partings. Weathers to yellowish-gray soil. Middle part is most resistant. Yellow silty partings give a mottled appearance.
	Wolsey Shale	110'	Gray-green and maroon fissile micaceous shale with some thin beds of lighter micaceous siltstone. Worm trails and burrows are common.
	Flathead Quartzite	75'	Buff to red medium-to coarse-grained medium-to-thick-bedded cross-bedded quartz sandstone or quartzite. Conglomeratic near base.
	unconformity		
Precambrian (Archean)			Dark green schist with many veins and veinlets of quartz generally parallel to foliation.

TABLE I. - (Continued)

STRATIGRAPHY

Lithologic units in the map area range in age from Precambrian (Archean) to Recent. Formations typical of the interval from Precambrian through Upper Jurassic are exposed along the west side of the Beartooth Range between Emigrant Gulch and Mill Creek. Exposures are generally poor but suffice for field-mapping. The poor exposures make it necessary to draw upon information from other areas for descriptions of Paleozoic and Mesozoic units. Significant thicknesses of Middle Cenozoic and Recent sediments are confined to the area west of the mountain front and are well exposed only along road-cuts and stream channels.

Precambrian

In the map area, Precambrian rocks are exposed mainly along the north side of Emigrant Gulch. A small patch was also mapped in sec. 7, T. 6 S., R. 9 E. in the bottom of Conlin Gulch on the basis of float. Where exposed in Emigrant Gulch the Precambrian consists of dark green to black schist containing many small quartz veins. The quartz veins are randomly distributed and tend to parallel the foliation of the schist. The foliation generally parallels the mountain front striking at about N. 60° E. and dipping steeply to the northwest.

Although no radiogenic age determinations have been made on the metamorphic rocks in the map area, an age of 2420 m.y. was determined from K - Ar analysis of biotite in phyllite from Jardine, about 20 miles from Emigrant, on the southwest corner of the Beartooth massif by Bruno Gilletti (oral communication, William J. McMannis, 1963). This age may be similar to that of the Precambrian schist in the map area and indicates that the metamorphic rocks of the western Beartooth Mountains are pre-Belt in age.

Cambrian

Cambrian stratigraphic units in the thesis area were mapped as Є$_{fw}$ - Middle Cambrian Flathead Quartzite and Wolsey Shale, Є$_{m}$ - Middle Cambrian Meagher Limestone, and as Є$_{u}$ - Middle Cambrian Park Shale and Upper Cambrian Pilgrim Limestone and Snowy Range Formation. The Cambrian section approaches 1000 feet in thickness in the map area. Each unit is discussed below.

Flathead Quartzite

The oldest Cambrian unit in the map area is the Flathead Quartzite which unconformably overlies Precambrian metamorphic rock. The only exposure of this contact found in the area is on the ridge along the north side of Emigrant Gulch. At this contact the angular discordance between the Flathead and the Precambrian schist is as great as 80°. The Flathead is present along the bottom of Conlin Gulch and in sec. 3, T. 6 S., R. 9 E. on the south side of Mill Creek Canyon. All exposures of Flathead in the map area consist of a buff to red medium-to coarse-grained quartzite. Cross-bedding is prominant in some zones. Thin lenses of conglomerate containing subrounded quartz pebbles also characterize the unit. Where exposed near the map area and studied by other workers, the Flathead Quartzite generally consists of 50 to 125 feet of quartz sandstone and quartzite with a characteristic buff and red mottling which is independent of bedding planes. A basal arkosic and somewhat conglomeratic zone with a varying thickness is found in some areas.

The thickness of the Flathead was not measured but appears to be about 75 feet on the north side of Conlin Gulch. This is the only place where what is believed to be a full thickness is present in the map area. This thickness agrees with that measured by Richards (1957) near Livingston and that reported by J. T. Wilson (unpublished Ph. D. thesis, Princeton U., 1937) near the mouth of Mill Creek. The Flathead was deposited on an irregular Precambrian surface so local variations in thickness are common (Lochman-Balk, 1956, p. 593).

At most places in the map area, the Flathead is closely associated with Tertiary dacite porphyry which has intruded along the Cambrian-Precambrian contact. Contact metamorphism has baked the quartzite to a dark red to black extremely brittle material in some places. In other places along the contact the quartzite has been bleached to a medium gray and the iron oxide has accumulated along fractures.

Wolsey Shale

Although the Wolsey Shale is present at several places in the map area it crops out only at one location in a road-cut about one-quarter mile south of Chico Hot Springs. About 40 feet of the unit is exposed in fault contact with Devonian Jefferson Limestone and intrusive contact with Tertiary dacite porphyry. At this outcrop the Wolsey consists of gray-green and maroon fissile micaceous shale with some thin beds of micaceous siltstone. No trilobite fragments were found although they are common in the Wolsey in adjacent areas. Worm trails and burrows which characterize the

Wolsey in other areas are very common in this exposure.

Wherever the Wolsey is present in the map area it is closely associated with porphyritic intrusive rock. Contact metamorphism has considerably altered the character of the shale near the contact with the porphyry. Such a contact is exposed just upstream from the mouth of Mill Creek Canyon (see figure 4.) where the originally green micaceous shale has been metamorphosed to a dark gray to black siliceous hornfels. The bedding plane fissility of the shale for as much as two inches from the contact has almost completely disappeared. Also, this two-inch-thick metamorphosed zone contains a few scattered porphyroblasts of quartz and is extensively iron-stained along fractures. The hornfels has retained much of the original mica and does not contain any metamorphic minerals.

The contact between the Wolsey Shale and the underlying Flathead Quartzite is poorly exposed in the map area. Near Livingston (Richards, 1957) and in the Garnet Mountain Quadrangle west of the map area (McMannis and Chadwick, in press) the top of the Flathead grades into the base of the Wolsey and the contact is placed above the highest prominent sandstone or quartzite ledge. Isopach maps (Hanson, 1952) indicate that the Wolsey Shale should be about 110 feet thick in the map area. This agrees reasonably with the thickness of 105 feet measured by Richards (1957) near Livingston.

Meagher Limestone

The Meagher Limestone is Middle Cambrian in age and conformably overlies the Wolsey Shale. The contact is not exposed in the map area but is

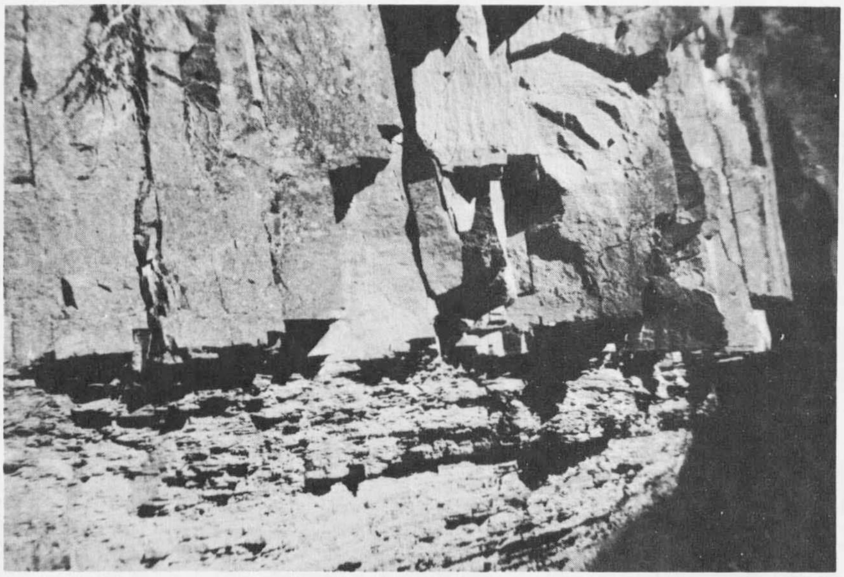


Figure 4. Tertiary intrusive over Wolsey Shale near mouth of Mill Creek Canyon.

generally chosen as the bottom of the lowest ledge-forming limestone in the gradational zone between the two formations as in the Garnet Mountain Quadrangle (McMannis and Chadwick, in press) and near Livingston (Richards, 1957). In the map area the Meagher crops out as a dark gray thin-bedded limestone with yellow silty partings which give a mottled appearance. The rock weathers to a yellowish-gray soil. Like the other Cambrian units in the map area, the limestone is intruded by dacite porphyry. No effects of contact metamorphism were found but the rock is extremely fractured near the intrusive contact. The thickness of the Meagher Limestone was not measured in the map area but the unit is about 150 feet thick on the East Fork of Mill Creek (W. J. McMannis, personal communication, 1964). This agrees well with the isopach thickness shown by Hanson (1952). In other areas between the Gallatin Range and Cooke City, the Meagher Limestone varies considerably in thickness. Generally there is a rapid thinning to the northeast. At Garnet Mountain in the Gallatin Range, the thickness is 449 feet (McMannis and Chadwick, in press) whereas east of the map area, near Cooke City, it is 116 feet (Hanson, 1952).

Park Shale

The Park Shale is not exposed in the map area but was mapped on the basis of float and the covered interval between outcrops of the underlying Meagher Limestone and the overlying Pilgrim Limestone. Because the Park is not exposed and contacts could not be precisely determined, its thickness was not measured. An approximate thickness of about 200 feet, interpolated from an isopach (Hanson, 1952) seems to be about right. McMannis and Chadwick (in press) measured 217 feet of Park Shale in the northeast corner of the Garnet Mountain Quadrangle and Richards (1957) reports a thickness of 380 feet near Livingston. The discrepancies in thicknesses can probably be attributed to the use of different criteria for the choice of contacts.

Where exposed in the areas mentioned above, the Park Shale consists of gray-green and maroon micaceous fissile shale with interbedded calcareous siltstone and fine sandstone. The Park is much like the Wolsey except that it is less micaceous. Near the top of the unit are thin interbedded limestones and yellow calcareous shales. Near the base of the Park are a few thin beds of glauconitic limestone and limestone-pebble conglomerate (McMannis and Chadwick, in press). In the map area, only a few scattered pieces of gray-green shale in a greenish soil could be found in the Park covered interval.

Pilgrim Limestone

Between Conlin Gulch and Mill Creek in the map area, the more resistant upper part of the Pilgrim Limestone is quite well exposed in the saddles between the lower, more subdued ridges and the steep front of the Beartooth Range. The Pilgrim Limestone is the lowest unit of the Upper Cambrian sequence and conformably overlies the Middle Cambrian Park Shale. According to Dorf and Lochman (1940), the Pilgrim has a uniform lithology throughout the region and consists of two distinct units. The upper unit is about 100 feet thick and consists of thick-bedded oolitic gray to buff mottled crystalline limestone. The lower unit is also about 100 feet thick and consists of gray-green coarse edgewise flat-pebble conglomerate and gray-green shale. In the map area, the upper unit is generally well exposed and provides an excellent marker unit for field mapping. The lower unit is not exposed except in a logging-road cut in sec. 7, T. 6 S., R. 9 E. on the north side of Conlin Gulch.

Snowy Range Formation

In the map area the Snowy Range Formation is very poorly exposed. It was mapped on the basis of float. The Snowy Range Formation is subdivided into three members as described by Lochman-Balk (1956). The lowest member is the Dry Creek Shale Member which overlies the Pilgrim Limestone conformably and consists of intercalated fissile shales, black, gray and green sandy shales, tan to pink fine-grained calcareous dolomitic and pure sandstones, thin-to medium-bedded buff siltstones, and red to purple arenaceous limestones. The top of the unit is generally placed at the base of a columnar limestone which forms the base of the overlying Sage Pebble Conglomerate Member. The Dry Creek Shale has a reported thickness of 80 to 95 feet in the Beartooth Range.

The Sage Pebble Conglomerate Member overlies the Dry Creek Shale conformably and in the Mill Creek area consists of medium-bedded to massive flat limestone-pebble conglomerate with interbedded gray-green shales (Lochman-Balk, 1956; Dorf and Lochman, 1940). The conglomerate is composed of dense limestone pebbles in a crystalline limestone matrix. Minor lithologic zones within the unit are a columnar algal limestone near the base, thin brachiopod lenses about 20 feet above, and a limestone-pebble conglomerate ledge near the middle. The type locality for the Sage Pebble Conglomerate Member is the south slope of Castle Rock which is a few miles east of the map area at the mouth of the East Fork of Mill Creek. At the type locality the unit is 160 feet thick.

The Grove Creek Member is the youngest member of the Snowy Range Formation and represents the uppermost beds of the Cambrian sequence in the map area. The Grove Creek was originally described as a formation (Dorf and Lochman, 1940) but was later included as the upper member of the Snowy Range Formation (Lochman-Balk, 1956). The Grove Creek consists of 0 to 50 feet of thick-bedded limestone-pebble conglomerates, thin shales, and limestones. The lower part of the member is composed of thick-bedded limestone-pebble conglomerate interbedded with a few thin shales and gray limestones. The upper part consists of platy arenaceous dolomite, limy siltstones, and pure limestones intercalated with varying amounts of shale (Lochman-Balk, 1956).

Ordovician

Bighorn Dolomite

The Bighorn Dolomite first assigned to the Upper Ordovician by Darton (1904, p. 28), disconformably overlies the Grove Creek Member of the Snowy Range Formation. Lower and Middle Ordovician strata are absent. The Bighorn is very poorly exposed in the map area and was mapped on the basis of float and a few scattered ledges. Where exposed the unit is a buff fine to medium-grained differentially crystalline dolomite containing abundant crinoid stems. No other fossils were seen in the Bighorn of the map area. The weathered surface in some places shows a rough, "honeycomb-like" character. No thickness could be determined but isopachs (Richards and Nieschmidt, 1957) indicate a thickness of about 80 feet in the map area. The Bighorn is generally much thicker to the south and east but has been partially removed by post-Ordovician - pre-Devonian erosion (Richards and Nieschmidt, 1957).

The Bighorn of the map area is probably the lower unit of the Bighorn Dolomite which attains thicknesses of over 400 feet in north-central Wyoming. This lower unit is described by Richards and Nieschmidt (1957) as a massive cliff-forming dolomite which is somewhat mottled yellowish-gray to pale orange, is microcrystalline to coarsely crystalline, and contains abundant fragments of crinoid stems, orthocone cephalopods, and some brachiopods and corals.

Devonian

Silurian and Early and Middle Devonian time is represented by an unconformity in the map area, Late Devonian stratigraphic units present in the map area are the Jefferson Limestone and the overlying Three Forks Shale. Because of the paucity of exposures the two units were mapped together. (D_u).

Jefferson Limestone

The Jefferson Limestone overlies the Bighorn Dolomite disconformably in the map area. Parts of the Jefferson are well exposed between Emigrant Gulch and Mill Creek but not well enough for a stratigraphic study. Outcrops show a dark gray to black medium-bedded to massive fine-grained dolomitic limestone. The Jefferson is generally weathered to a medium to dark brown color and gives a "petroliferous" odor from fresh fractures. Solution breccias and Amphipora are common in some zones. An excellent exposure of the solution breccias can be seen in a road-cut between Chico Hot Springs and Old Chico in sec. 12, T. 6 S., R. 8 E. No thickness of the unit was measured in the map area.

On the East Fork of Mill Creek, McMannis (1962) measured the Jefferson Limestone and reported a thickness of about 260 feet. The upper 85 feet consists of medium-to coarse-grained light-colored massive dolomite. According to McMannis (1962, p. 8) this upper part is almost invariably separated from the lower more heterogeneous part by a solution breccia and/or shaly dolomite zone of varying thickness. The lower part is medium-bedded and contains shale, limestone, dolomite, and several solution breccia zones. There is generally a little more limestone and less dolomite near the base.

Three Forks Shale

The Three Forks Shale overlies the Jefferson Limestone conformably and consists of thin-bedded orange-brown shale interbedded with gray to orange-gray dolomite. The Three Forks is very poorly exposed in the map area except in a road-cut between Chico Hot Springs and Old Chico in sec. 12, T. 6 S., R. 8 E. The exposure consists of thin-bedded orange-brown shale, interbedded gray to orange-gray dolomite, and some thin beds of yellow cross-bedded arenaceous dolomite. The formation was mapped on the basis of scattered pieces of float in the covered interval above the more resistant Jefferson Limestone and below the ledges of the Lodgepole Limestone.

The nearest measured section is that of McMannis (1962) on the East Fork of Mill Creek. His columnar section shows about 80 feet of orange-colored dolomite with a thin zone of orange-brown dolomitic shale near the base.

Mississippian

Mississippian stratigraphic units of the map area are the Lodgepole and Mission Canyon limestones, comprising the Madison Group and having a combined thickness of about 1000 feet. Because of poor exposures, the two formations were mapped as a single unit (M_{mu}).

Lodgepole Limestone

The Lodgepole Limestone is Early Mississippian in age and overlies the Three Forks Shale with erosional unconformity. The Lodgepole is well exposed in some places in the map area but most of the good outcrops are near an igneous intrusive body. Contact metamorphism and/or hydrothermal activity which may have been related to faulting have considerably altered the character of the limestone at these exposures. For example, a ridge of Lodgepole in sec. 12, T. 6 S., R. 8 E., is composed of very siliceous extremely brecciated limestone. A large deposit of travertine is exposed on the southwest end of the ridge about a quarter of a mile from the hot springs at Chico. Elsewhere in the map area the Lodgepole shows similar but less extreme alteration. Where no hydrothermal and/or contact metamorphism has occurred, scattered ledge show a thin-bedded medium- to coarse-grained gray-brown fossil fragmental limestone containing abundant brachiopods and an occasional Syringopora. Chert nodules are present in some zones and are oriented more or less parallel to bedding.

McMannis (1964, personal communication) found a thin black silt-shale zone at the base of the Lodgepole Limestone on the East Fork of Mill Creek and reports that this zone is also present in the Gallatin Range. It is probably the same shale unit described by Sandberg (1963, p. 17) as having a thickness of about 12 feet in the western Beartooth Range and consisting of, "dark-gray to black carbonaceous dolomitic quartzose shale and light olive-gray, yellowish-brown, yellowish-gray, and dark gray dolomitic siltstone that grade to very shaly and very silty dolomite".

A columnar section (Roberts, 1961) of the Madison Group in the lower canyon of the Yellowstone River near Livingston includes 575 feet of Lodgepole Limestone. This section shows three distinct parts of the unit: A lower part about 200 feet thick composed of limestone and dolomite in which chert zones are common, a middle part composed of more than 300 feet of silty limestone and dolomite and fragmental limestone, and an upper part consisting of about 50 feet of dolomite.

Mission Canyon Limestone

The Mission Canyon Limestone is Early Mississippian in age and conformably overlies the Lodgepole Limestone. An abrupt change from the thin beds of the upper Lodgepole to the massive beds of the lower Mission Canyon is the basis for determining the contact between the two units. In the map area, the Mission Canyon Limestone is well exposed as scattered ledges in some places but outcrops are not sufficiently continuous for stratigraphic study. Where exposed the unit is a light to dark brownish-gray massive dense limestone. The limestone is dolomitic in most exposures and is very siliceous near contacts with dacite porphyry intrusives. Irregular chert nodules oriented parallel to bedding are abundent in some zones. No fossils were found in the Mission Canyon in the map area.

A columnar section of the Madison Group near Livingston (Roberts, 1961, p. 295) shows the Mission Canyon Limestone sub-divided into two parts. The lower part is 330 feet thick and consists mainly of dolomite and dolomitic limestone. Zones containing abundant chert nodules are present near the middle of this part. The upper part is 325 feet thick and consists mostly of limestone and dolomitic limestone. There are some zones containing chert nodules and stringers and there are a few thin zones of silty limestone and silty dolomitic limestone in the upper 100 feet.

Mississippian and Pennsylvanian

Beds overlying the Mission Canyon Limestone of Mississippian age and underlying the Quadrant Formation of Pennsylvanian age comprise the Amsden Formation. The Amsden was mapped as a distinct stratigraphic unit (M_a) in this study.

Amsden Formation

The Amsden Formation is probably latest Mississippian and earliest Pennsylvanian in age (Williams, 1948) and is exposed at only one place in the map area. This outcrop is in the southwest part of sec. 6, T. 6 S., R. 9 E. on the north side of the mouth of Conlin Gulch. The Amsden consists of non-resistant beds of red shale and siltstone with interbedded limestone and varicolored shale. The formation weathers to a red soil.

The Amsden is also present in sec. 5, T. 6 S., R. 9 E. but is not exposed. At this location it was mapped on the basis of a red soil stratigraphically beneath ledges of the Quadrant Formation. The width of the red soil zone and dip of the Quadrant indicates a thickness of 75 to 100 feet for the Amsden.

On Cinnabar Mountain, about 25 miles south of the map area, C. W. Wilson (1934) measured 161 feet of Amsden. At that location the formation consists of fine-grained white to gray thin-to thick-bedded limestone with interbedded yellow, green, and red shale and massive white to buff fine-grained sandstone. The basal part is medium-grained white to red sandstone which contains abundant fragments of the underlying Mission Canyon Limestone. Most workers feel that this irregular contact between the Amsden and the Mission Canyon represents deposition on a rough karst topography which developed on the Mission Canyon prior to Amsden deposition.

Pennsylvanian

Quadrant Formation

The Quadrant Formation is Pennsylvanian in age (Henbest, 1954, p. 53) and conformably overlies the Amsden Formation. The Quadrant, mapped as P_q, is well exposed in sec. 5, T. 6 S., R. 9 E. and is present under a covered interval at the mouth of Conlin Gulch. It is absent elsewhere in the map area. The one good exposure consists of light-yellowish-gray to light-reddish gray fine-to medium-grained locally quartzitic cross-bedded quartz sandstone. This description is consistent with general lithologies reported by workers in other areas although McMannis and Chadwick (in press) report that the lower part of the formation contains yellow-brown and gray dolomite interbedded with quartz sandstone in the Garnet Mountain Quadrangle. Some fragments of dolomite were found near the base of the Quadrant in the map area so probably this interval is present but not exposed. Interpolation between a thickness of 130 feet on Cinnabar Mountain (C.W. Wilson, 1934) and a thickness of 100 feet near Livingston (Richards, 1957) suggests a thickness of about 115 feet for the Quadrant Formation in the map area.

Jurassic

The Jurassic Ellis Group is exposed in the map area and comprises the Sawtooth, Rierdon, and Swift formations. Each formation was mapped separately as J_s, Jr, and J_{sw}, respectively. The only place in the map area where Jurassic strata are present is on a low ridge parallel to the mountain front directly west of Conlin Gulch in sec. 6, T. 6 S., R. 9 E. Exposures of the formations are small and field descriptions are limited.

Sawtooth Formation

The Sawtooth Formation is Middle Jurassic in age (Imlay, 1952, p. 948) and is the basal unit of the Ellis Group. It is represented by a covered interval north of the mouth of Conlin Gulch and was mapped on the basis of scattered fragments of dense gray and yellow limestone and shale in the soil.

The Sawtooth Formation is equivalent to the Piper Formation which is 240 feet thick near Livingston (Richards, 1957) and overlies the Quadrant Formation disconformably. Near Livingston, the Piper consists of a thin basal sandstone and conglomerate overlain by a thick shale and limestone interval. The conglomerate contains angular chert pebbles as much as one inch in diameter in a yellowish-gray calcareous sandstone matrix. The limestone is gray, platy, and dense and is fossiliferous near the top of the formation. The shales are gray, yellow, green, and red and include some silty zones.

Rierdon Formation

The Rierdon Formation is Middle and Late Jurassic in age (Imlay, 1952,

p. 968) and is the middle unit of the Ellis Group. The Rierdon rests conformably on the Sawtooth Formation. A few thick ledges of the unit are exposed directly north of the mouth of Conlin Gulch and consist of very oolitic gray-brown limestone. These ledges are characterized by large travertine filled fractures which may suggest hydrothermal activity. The thickness of the Rierdon Formation was not measured in the map area but Richards (1957) reports 95 feet of Rierdon consisting of gray oolitic somewhat cross-bedded ledge-forming limestone and olive-gray shale and siltstone near Livingston.

Swift Formation

The upper unit of the Ellis Group is the Swift Formation, of Late Jurassic age (Imlay, 1952, p. 968). It disconformably overlies the Rierdon Formation. The Swift is the youngest Mesozoic unit exposed in the map area and the only exposure is between Conlin Gulch and Mill Creek, near the center of sec. 6, T. 6 S., R. 9 E. This outcrop consists of medium- to coarse-grained thin-bedded light gray to tan cross-bedded calcareous glauconitic fossiliferous sandstone that weather to a yellow gray color. This description is similar to those of lithologies reported by workers in nearby areas. Thickness of the Swift Formation could not be measured in the map area because contacts are not exposed but Richards (1957) reports a thickness of 80 feet for the unit near Livingston.

Uppermost Jurassic and Cretaceous

Scattered fragments of the Morrison Formation (Upper Jurassic) and the Kootenai Formation (Lower Cretaceous) are present in Quaternary glacial till directly north of the mouth of Conlin Gulch. These formations may be present at depth in the map area and are now covered by glacial deposits. Because they are not exposed and were not mapped, they will not be discussed in this paper.

Tertiary

Only two exposures of Tertiary sediments are present in the map area. One is a small poorly exposed patch about 400 feet above the valley floor between the mouths of Conlin Gulch and Davis Gulch; the other is an excellent exposure along a highway-cut directly north of the Wanigan in the northwest corner of sec. 3, T. 6 S., R. 8 E. (see figure 5.). At this second location the deposit consists of white to light tan poorly bedded siliceous

Figure 5. Vertebrate fossil locale near Wanigan.

siltstone and claystone. The sediments are highly tuffaceous, contain some small fragments of basic extrusive (aphanitic) and intrusive igneous rock, and are very non-resistant. A thickness of about 80 feet of this deposit is exposed beneath a sharp contact with overlying glacial till (see figure 3.). The base is not exposed.

Vertebrate fossils collected at this location have been identified as late Miocene - early Pliocene in age (Dr. Bryan Patterson and Dr. Morris Skinner, personal communication, 1963). Among these were: (1) Camelid: incisor and fragmentary premaxilla, incomplete posterior cervical, and incomplete anterior dorsal and (2) Later three toed horse: fragments of forelimb, distal end of scapula, distal end of humerus, incomplete proximal end of radius, distal portion of 3rd metacarpal with proximal phalanx, and fragment of lateral metacarpal. Because the specimens are so well preserved, further work by paleontologists at this locality might yield a much more complete fauna.

The late Miocene - early Pliocene date for this deposit correlates with the age assigned to Tertiary sediments exposed at the White Cliffs, several miles south of the Wanigan, (Horberg, 1940, p. 285). A general description of that section as measured by Montagne (personal communication, 1963) is as follows:

	Pleistocene (?) gravel.
24 feet	Light tan siltstone with some layers of very tuffaceous material. Sharp contact with overlying gravel.
12.6 feet	Tan siltstone as above but with thin greenish clayey zones.

	54.5 feet	Massive tan siltstone with some small shell fragments, possibly gastropods,
	16.8 feet	Massive tan poorly bedded siliceous claystone. Small shell fragments common.
	27.8 feet	Massive greenish siltstone. Many small shell fragments, possibly gastropods.
	38.8 feet	Light tan poorly bedded massive siliceous claystone. Highly tuffaceous. Bottom not exposed.
total	174.5 feet	

The gravel overlying the late Miocene - early Pliocene sediments at the White Cliffs contains boulders up to 2½ feet in diameter and is poorly sorted. The larger boulders are mostly of various volcanic lithologies but pieces of Precambrian granitic and Tertiary sedimentary rock are also present. A few cobbles resembling lithologies of the Precambrian Belt series were also found. The gravel is about 125 feet thick and is overlain by olivine basalt. The gravel and basalt overlie probable early Pliocene sediments and underlie Pleistocene glacial debris so must be Pliocene and/or Pleistocene in age.

At the Tertiary exposure in sec. 3, T. 6 S., R. 8 E. the gravel and basalt described above are not present. Instead, the Tertiary sediments are overlain by glacial till (see figure 6). The White Cliffs are only a few miles from this exposure so it seems likely that the younger gravel and the basalt were once present in the map area and were removed by erosion before glaciation occurred. The fact that the gravel and the basalt at the White Cliffs have been preserved whereas those north of the Wanigan were removed can probably be attributed to the respective locations.

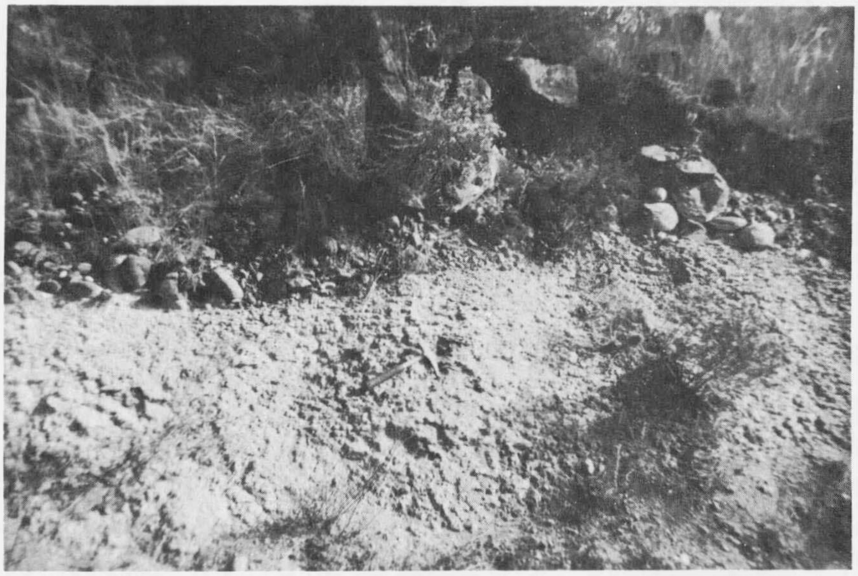


Figure 6. Glacial till over Tertiary sediments near Wanigan.

The area north of the Wanigan is relatively near to the mouth of Emigrant Gulch where stream erosion might have been considerable whereas the White Cliffs are somewhat isolated from the mouths of any major gulches.

Quaternary

Considerable quantities of unconsolidated Quaternary material are present in the map area. No attempt was made to differentiate Pleistocene and Recent deposits in mapping but their ages and origins will be discussed later in this paper under the heading of geomorphic history. Quaternary deposits mapped during this study include glacial till (Q_{g_1} and Q_{g_2}), glacial outwash (Q_{ow}), and other alluvial deposits (Q_{al}).

Glacial Deposits

In the map area, glacial till may be as much as 200 feet thick in some places and consists of unconsolidated unsorted unstratified coarse debris. The coarse fraction is characterized by boulders generally less than one foot in diameter. However, many erratics as much as 30 feet in diameter are present in the map area (see figure 7). Most of these larger boulders are granitic Precambrian rocks. The lithologies comprising most of the glacial till include various types of volcanic rock, much Precambrian schist and gneiss, and a few scattered fragments of Tertiary sedimentary rock. The composition of the till remains fairly heterogeneous near the center of the valley but near the mountain front the composition definitely includes high percentages of local bedrock material. For

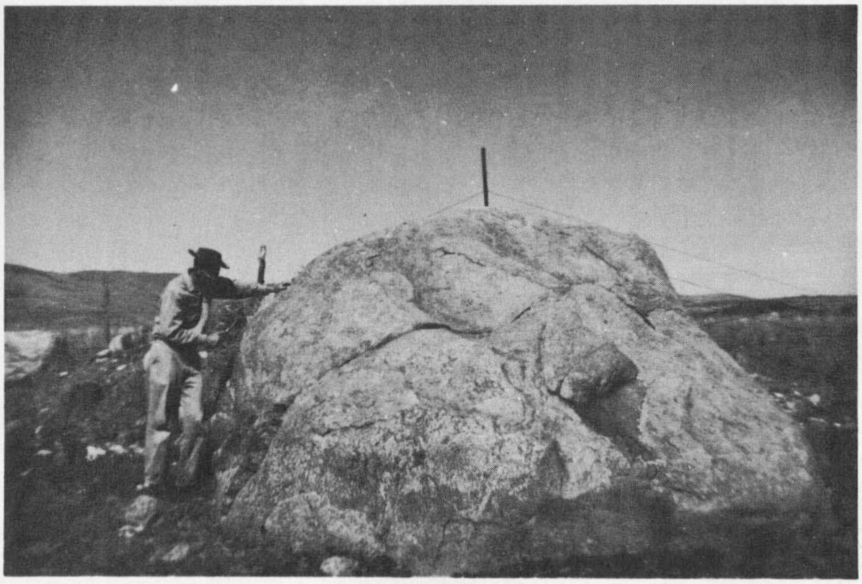


Figure 7. Large erratic near the mouth of Emigrant Gulch.

example, near the mouth of Emigrant Gulch the till is composed mostly of locally derived intrusive rock, volcanic breccia, and green schist. Further north along the mountain front, between Chico and Mill Creek, the till contains a high percentage of dacite porphyry and Paleozoic and Mesozoic sedimentary rock. The coarse fraction predominates over the matrix in most of the map area; however, near the terminus of glacial deposits north of the mouth of Mill Creek a silty to fine sandy matrix appears to comprise the greater volume.

Glaciofluvial Deposits

Two outwash plains, which will be discussed in detail later in this paper, are present in the upper Yellowstone Valley. Glaciofluvial deposits comprising these surfaces consist of subrounded to rounded pebbles and cobbles in a silty to sandy matrix. In cross-section the outwash material shows a poorly developed but distinct bedding with numerous sand and silt lenses. In some places a slight imbrication to the north is present in the coarse fraction. Lithologically there appears to be no difference between the outwash and morainal deposits.

Other Alluvial Deposits

Quaternary deposits other than glacial till and outwash are present at several places in the map area. They will, because of their geomorphic implications, be described later in this paper in the discussion of geomorphic problems of the upper Yellowstone Valley.

TECTONIC SETTING

A discussion of the regional tectonic setting may be pertinent to interpretations within the map area which includes part of the northwest corner of the South Snowy block of the Beartooth Range and a considerable area on the floor of the upper Yellowstone Valley. The valley is bounded on the west by the Gallatin Range and on the east by the Beartooth massif. Northwest- and northeast-trending faults and associated folds are the dominant structural features in the Gallatin and Beartooth ranges and in nearby areas (see figure 8).

Most of the Gallatin Range is covered by a thick sequence of volcanic material which has not been significantly affected by Laramide compressional deformation. These volcanics are mostly breccias and flows that accumulated on an erosional surface with local relief of as much as 3000 feet (McMannis, personal communication, 1964). They are probably present under Tertiary and Recent sediments of most, if not all, of the upper Yellowstone Valley. Although the age of these breccias and flows is not precisely determined, they are similar in most respects to and may correlate with the early basic breccias of early middle Eocene age (Dorf, 1960) in Yellowstone National Park.

Bordering the north end of the upper Yellowstone Valley is a positive structural area of Precambrian, Paleozoic, and Mesozoic rocks through which the Yellowstone River has cut a narrow canyon. West of the canyon, in the Canyon Mountain area, the Paleozoic and Mesozoic strata are deformed by northwest-trending folds and low angle thrust faults. East of the canyon in the northwest corner of the Beartooth massif, the structures are mostly

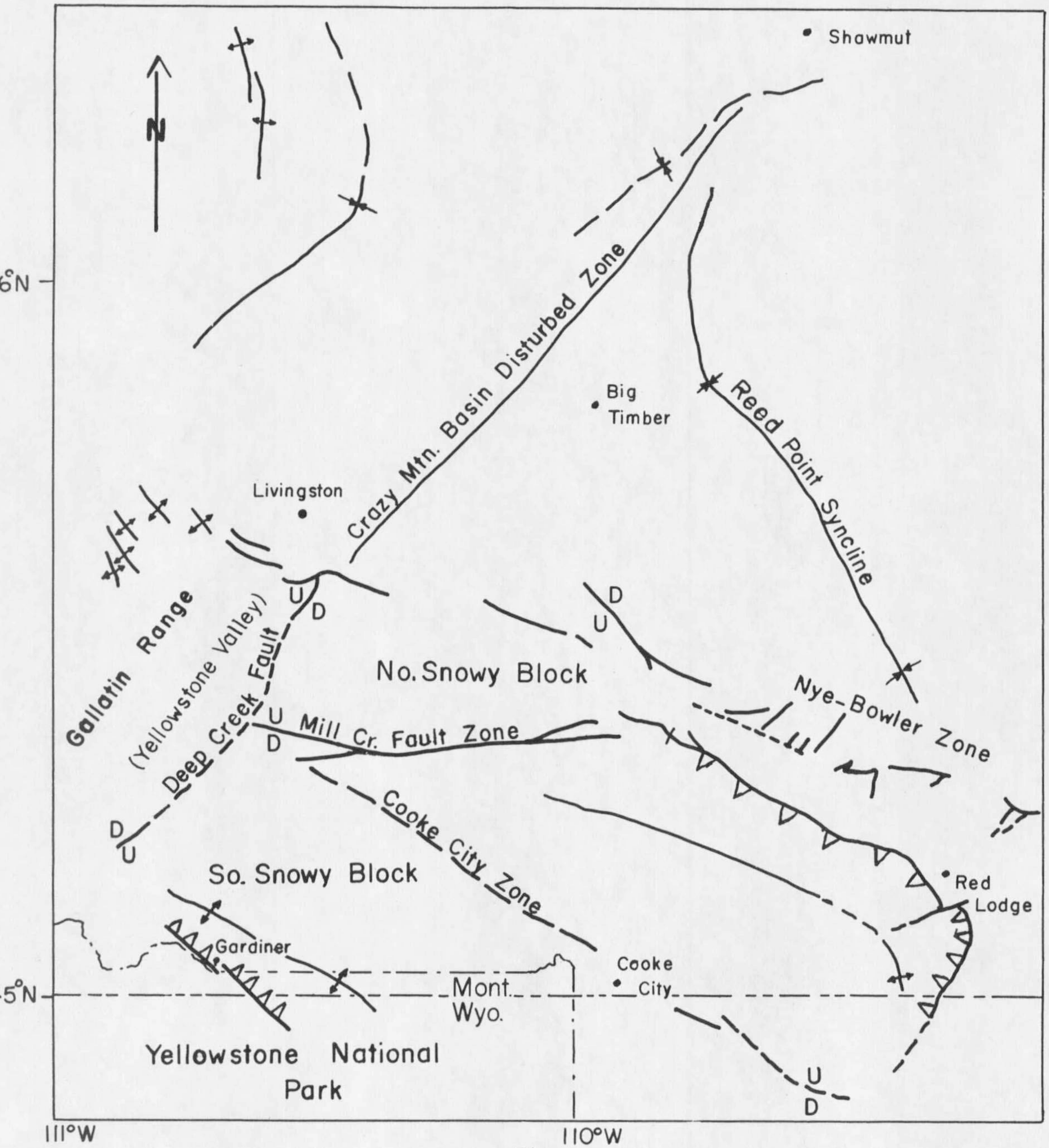


Figure 8.
Major Tectonic Features of the Beartooth Range and Adjacent Areas

northwest- and northeast-trending high angle faults. These faults separate the Beartooth uplift from the Crazy Mountain syncline (see figure 8), a northwest-trending complex structural basin.

The Beartooth Range was uplifted along faults having northeast and northwest trends. Movement along one of these, the Deep Creek fault, which was first described by Lammers (1937), has produced much of the structural and topographic relief between the Beartooth block and the upper Yellowstone Valley. Expressions of recent movement on this fault can be seen where en echelon scarps cut alluvial fans emanating from the mountain front. These recent scarps are present in many places including the fans of Deep Creek and Barney Creek near the north end of the valley, and in alluvium near the mouth of Yankee Jim Canyon at the south end of the valley. At the north end of the upper Yellowstone Valley, the Deep Creek fault loses its identity in a structurally complex area between Canyon Mountain and the northwest corner of the Beartooth massif. The high angle faults along the northwest corner of the Beartooth massif as opposed to the low angle thrusts of the Canyon Mountain area suggest that the Beartooth block was already topographically higher than the Canyon Mountain area when Laramide compression began (W. J. McMannis, personal communication, 1964). Because the Deep Creek fault appears to separate these two differing structural areas, it may pre-date the structures within them. This concept agrees with that of Richards (1957) who suggests that the Deep Creek fault has been offset by one of the northwest-trending high angle reverse faults. A northeast-trending disturbed zone north of Livingston, in the Crazy Mountain Basin, projects southwestward on line with the Deep Creek fault.

West of this zone, structural contours suggest that Upper Cretaceous and Paleocene strata thicken abruptly (Dobbin and Erdman, 1955). Roberts (1963) reports more than 13,000 feet of strata of this interval near Livingston. This implies that the western part of the Crazy Mountain basin subsided much faster than the eastern part during Late Cretaceous and Paleocene time. If this zone is a northward extension of the Deep Creek fault, and if movement was contemporaneous along both of them, initial uplift of the west side of the Beartooth block could have happened as early as Late Cretaceous time. Most workers suggest that major uplift of the Beartooth block began in middle or late Paleocene time and culminated in the early Eocene on the basis of evidence found along the north and east sides of the massif. These interpretations are not necessarily entirely applicable to the west side of the massif, however, because all sides of the Beartooth Range need not have been uplifted concurrently.

Major structural features within the Beartooth Range include the Cooke City zone and the Mill Creek fault zone which converge near the mouth of Mill Creek Canyon. The Cooke City zone is a prominant, structurally low, northeast-trending linament of faults and shear zones (Foose, Wise, and Garbarini, 1961). The Mill Creek fault zone trends west and northwest along the Mill Creek drainage and separates the upthrown North Snowy block from the downthrown South Snowy block (J. T. Wilson, 1937). Part of the map area includes Paleozoic and Mesozoic strata which have been preserved on the southern downthrown side of the Mill Creek fault zone.

STRUCTURE

The general structural configuration of the map area is that of north- and northwest-dipping Paleozoic and Mesozoic strata deformed by faults of uncertain age, origin, and classification. Dips on these beds range from 30^o to 50^o except near contacts with a large intrusive body. Near the intrusive contact the dip of the beds generally steepens considerably. The most extreme example of this is in a small block of Paleozoic strata near Chico Hot Springs where beds are vertical to overturned along the igneous contact. Much of the folding and faulting of strata in the map area is possibly the result of forces associated with intrusion of dacite porphyry between Emigrant Gulch and Mill Creek.

Faults mapped are of two general types; faults diagonal or normal to igneous contacts and faults parallel to igneous contacts. This distinction is made because of the role played by the igneous intrusive in the genesis of at least some of these faults.

Faults diagonal or normal to igneous contacts were mapped on the basis of stratigraphic displacement observed along the north side of Conlin Gulch in sections 6 and 7, T. 6 S., R. 9 E. Their apparent trend is parallel to the Beartooth mountain front but exposures are poor and topographic expression is lacking so their northeast trend is not certain. On cross-section B-B^1 and on the map they are shown as vertical faults but evidence is insufficient to establish this. Of the four faults mapped, two have apparent downthrow on the west and two have apparent downthrow on the east (see cross-section B-B^1). The net result of these movements is at least 2000 feet of stratigraphic upthrow to the east. The western-most fault mapped, in sec. 6, T. 6 S., R. 9. E., may be of particular importance. This fault may extend southward along the igneous contact into sec. 12, T. 6 S., R. 8 E. If so, it is likely that there is a full section of Paleozoic and Mesozoic strata downthrown and preserved west of the fault between Chico Hot Springs and Conlin Gulch (see cross-section C-C^1). If this is the case, the fault is either a strike-slip fault or a normal fault along which the porphyry might have been intruded. Whether the fault is a product of the forces of intrusion or of uplift along the Beartooth front is unknown but in either case it has contributed about 1100 feet of positive structural relief to the mountain front. Field evidence is too limited to establish the genesis of these faults but possibly they are en echelon movements along the Deep Creek fault or are related to the forces of intrusion. If they were concurrent with intrusion or if they are post-intrusive it is probable that the intrusive would be offset along them. Only one of these is known to offset the intrusive (see cross-section B-B^1). Post-intrusive movement on this fault amounts to about 50 feet. Therefore it is most likely that the greatest movement on these faults occurred before the intrusive porphyry was emplaced.

Faults striking parallel to igneous contacts appear to be high-angle normal faults of generally small stratigraphic displacement (see cross-section A-A^1) and can be termed upthrusts after Billings (1959, p. 195). One upthrust of large displacement is mapped in sec. 7, T. 6 S., R. 9 E. on the north side of Conlin Gulch where Lodgepole Limestone is in fault contact with Meagher Limestone. The stratigraphic displacement on this fault is at least 1200 feet. Upthrusts of lesser displacement were mapped in sections 3 and 8, T. 6 S., R. 9 E. Although poor exposures limited the mapping of these faults and although their exact dip angles and amounts of stratigraphic displacement could not be determined, they seem to be nearly parallel to the igneous contact. The upthrown side of each upthrust is toward the porphyry so it is possible that the forces associated with the emplacement of the intrusive are responsible for movement along these faults.

The mechanics of intrusion have not been definitely established but evidence in and near the map area indicates that the igneous material, a dacitic magma, spreads out into nonresistant Middle Cambrian strata as half-domed concordant bodies. The Paleozoic and Mesozoic rocks were upwarped and faulted by the outward pressure from the intrusion (see cross sections A-A^1, C-C^1, and D-D^1). In most of the map area, the contact between igneous and sedimentary rocks is parallel or nearly parallel to bedding (see figure 4). The source of the magma is not known but it is presumed to have originated at depth in or below the Precambrian metamorphic rock and to have moved to the top of the Precambrian through a fissure or series of fissures. It is likely that the magma utilized faults in the basement rock to move upward. A logical place for such igneous conduits would be near the mouth of Mill Creek Canyon, where the Cooke City zone, the Mill Creek fault zone, and the Deep Creek fault converge. This concept is strengthened by the presence of intruded dacite porphyry closely associated with the Mill Creek fault zone along Mill Creek and its east fork (J. T. Wilson, unpub. Ph.D. thesis, Princeton University, 1937). Lacking evidence, I did not map the Deep Creek fault between

Emigrant Gulch and Mill Creek, but its presence along much of the mountain front implies that it should also be present in the map area. If so, it is possible that the intrusive utilized the fault as far south as Chico Hot Springs. The Lodgepole Limestone along the igneous contact near the Hot Springs has dips ranging from vertical to overturned. This could be the result of a very steep force component from intrusion and/or drag from range front faulting. Other lines of evidence for range front faulting in and near the map area are a travertine deposit and breccia in the Rierdon formation in sec. 6, T. 6 S., R. 9 E., the hot springs at Chico, a travertine deposit in the Lodgepole Limestone in sec. 12, T. 6 S., R. 8 E., and a calcareous talus breccia, spring, and recent scarp (Montagne, personal communication, 1964) on the Blakeslee Ranch directly south of the mouth of Emigrant Gulch. The travertine deposits and the springs suggest that faulting has occurred but do not necessarily indicate the location of the fault(s). The age relationship between major faults and intrusion in the Mill Creek area is not certain. J. T. Wilson (unpublished Ph.D. thesis, Princeton University, 1937) reported that intrusives are not disturbed by major faults in the Mill Creek-Stillwater area. However, recent expressions of uplift along the Deep Creek fault north and south of Mill Creek indicate post-intrusive movement along the mountain front. If the intrusive were not involved in major uplift and if major uplift culminated in the middle Eocene, as suggested by Foose, and others (1961), the intrusives in the map area are late Eocene or younger.

IGNEOUS GEOLOGY

The intrusive dacite porphyry discussed under the previous heading is exposed across the entire southeast side of the map area where it forms the areas of higher elevations. The Paleozoic-intrusive contact coincides with a series of topographic saddles separating the steep slopes on the intrusive rock from the lower, more subdued topography formed by Paleozoic sedimentary rock. This intrusive is one of several in the Mill Creek-Stillwater area, all of which have almost identical compositions (J. T. Wilson, unpublished Ph.D. thesis, Princeton University, 1937). Thin-sections were made from specimens collected near Chico in the west-central part of sec. 12, T. 6 S., R. 8 E. on the 5600-foot contour, in the northwest corner of sec. 17, T. 6 S., R. 9 E. at the head of Conlin Gulch on the 7320-foot contour, and in the center of sec. 9, T. 6 S., R. 9 E. at the head of Davis Gulch on the 6560-foot contour. A detailed petrologic analysis was not a major objective of this study, so only a general description is submitted here. The three thin-sections all had similar compositions which are generalized below.

Phenocrysts--25% to 40%

Plagioclase (zoned) - 50% to 80%, An_{32-38}

Measured by ext. ∠ - 14° to 20°, biax. neg.

Hornblende - 10% to 15%, prismatic, high birefringence, moderate pleochroism (med. green to dark green), opaque minerals in altered edges, some twinning.

Biotite - 10% to 20%, platy, high birefringence, strong pleochroism (med. brown to dark brown)

Quartz - 0% to 10%

Groundmass: 60% to 75%

Plagioclase - 80% to 85%
K-feldspar - 5% to 10%, approx. by Becke line method.
Ferromagnesians - 5% to 10%
Opaques - about 5%, concentrated around ferromagnesian minerals in alteration rim.

The rock is here called a dacite porphyry on the basis of texture and composition according to Wahlstrom (1955, p. 307).

Other, more basic igneous rock is present in a small exposure in the northeast corner of sec. 6, T.6 S., R. 9 E. on a low subdued ridge paralleling the mountain front. Wisconsin piedmont ice has smoothed the ridge and deposited abundant erratics of various lithologies so bedrock mapping was extremely difficult. Specimens were collected at two locations about 60 feet apart along the ridge and were found to have similar compositions in thin-section. One sample has very well developed megascopic and microscopic flow structure with thin layers of iron oxide accumulated parallel to the crystal orientation. It is mostly microcrystalline with only a few scattered phenocrysts (about 5%) of which about 90% are pyroxene. The second specimen has more phenocrysts (about 25%) of which about 70% are pyroxene. The second specimen has no apparent flow structure or orientation of minerals. The compositions of these specimens are generalized as follows:

Phenocrysts

20% orthopyroxene - moderate pleochroism (lt. green to tan), moderate birefringence, parallel extinction, biaxial negative - hypersthene.

60% clinopyroxene - no pleochroism, high birefringence, some twinning, altered rim generally present, biaxial positive, $2V \approx 50^\circ$, augite (Wahlstrom, 1955, p. 165).

10% plagioclase - ext. $\angle$ 27° to 29°, biaxial positive (An_{49-53}). Zoned.

5% hornblende - strong pleochroism (lt. brown to dark brown), mostly remnants of crystals removed by alteration.

5% opaques - apparently magnetite

Groundmass

70% plagioclase
15% ferromagnesian minerals
10% opaque minerals

The composition of the plagioclase phenocrysts (An_{49-53}) places the specimens lithologically as basic andesites or as basalts according to Wahlstrom (1955, p. 307). Because the plagioclase phenocrysts are likely to be somewhat more calcic than the plagioclase of the groundmass, the term andesite or basic andesite would probably be the more appropriate.

The origin and correlation of the andesite is unknown but two pyroxenes (hypersthene and a clinopyroxene) are also present in the Gallatin volcanics (R. A. Chadwick, personal communication, 1964) and in the volvanic breccias of the South Snowy block of the Beartooth Range (A. Basler, personal communication, 1964). Present evidence is insufficient to establish such a correlation although it is possible that the andesite described above may be an erosional remnant of the Gallatin volcanics and/or the breccias of the South Snowy block.

GEOMORPHOLOGY

The geomorphic history of the map area records the activities of wind, water, and glacial ice in late Cenozoic time. Because of the variable intensities of the geomorphic processes in time, descriptions and discussions in this paper are separated into the following three categories: (1) Pre-Wisconsin Geomorphology and Glacial Geology, (2) Wisconsin Geomorphology and Glacial Geology and (3) Post-glacial Geomorphology.

Pre-Wisconsin Geomorphology and Glacial Geology

Evidence found by workers in other parts of the upper Yellowstone Valley suggests the activity of high-level glacial ice before the advent of Wisconsin piedmont glaciation. Glacial erratics found at high elevations along the mountain front by Horberg (1940, p. 295) and by Montagne (personal communication, 1963) and the writer indicate that piedmont ice once filled the southern end of the valley at Yankee Jim Canyon and extended at least as far north as Pine Creek. This concept presents many questions; for instance, in the map area, no evidence for high-level pre-Wisconsin glaciation was found. However, the areas of higher elevation between Emigrant Gulch and Mill Creek are underlain by Tertiary intrusive porphyry which is easily modified by mass-wasting processes so it is likely that glacial debris and/or abrasional features high on the mountain front would be removed during peri-glacial conditions associated with the lesser Wisconsin ice advance.

The topography of the map area before Wisconsin glaciation was probably quite different from that of the present. The morphology of the mountain front may not have changed appreciably but the valley floor appears to have had considerable pre-Wisconsin relief. Exposures (see pages 24, 25, & 26) suggest that, prior to Wisconsin glaciation, the Tertiary sediments and Pleistocene basalt stood as erosional remnants on a dissected valley floor into which the Yellowstone River and its tributaries had cut to at least their present depths. The river is now, in many places, downcutting through alluvium and glacial ~~till of pre-Wisconsin and~~/or Wisconsin age. For example, at the north end of the valley, in the lower canyon of the Yellowstone, the river is flowing on alluvium which was deposited over Paleozoic strata. The river cut the canyon through a bedrock barrier, then deposited alluvium in that canyon, and now appears to be downcutting in the alluvium. Because the valley floor is covered with glacial and glaciofluvial deposits, it is likely that the material in the lower canyon was deposited during the Wisconsin glacial stage when the river was overloaded with outwash. In Emigrant Gulch, Emigrant Creek is downcutting in alluvium deposited after the gulch was eroded in Precambrian bedrock. These sediments are most logically identified with Wisconsin glaciation and will be discussed under subsequent headings in this paper. A deposit of unconsolidated cross-bedded sand and gravel (see figure 9.) exposed in a highway-cut about half a mile south of the Wanigan also indicates that the pre-Wisconsin river channel was at least as low as the elevation of the present channel at that point. The top of this deposit is about 100 feet above the river and is covered by Wisconsin glacial till. The bottom is not exposed but is probably at least as low as the present river bed. Whether this material is a tributary stream deposit, a river deposit, or

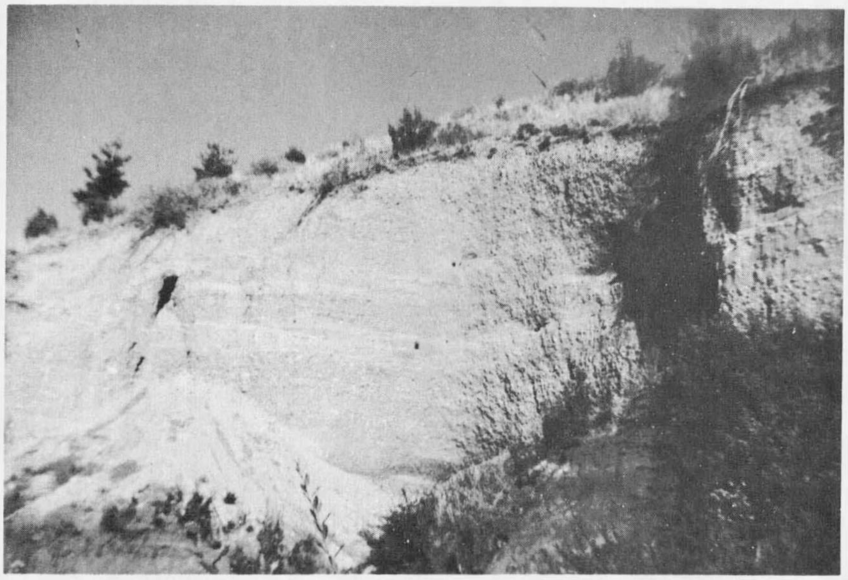


Figure 9. Cross-bedded sand and gravel one mile south of Wanigan.

an outwash deposit cannot be determined but any one of these possibilities suggests that the river had eroded down to at least its present elevation at that point before the advent of Wisconsin glaciation.

Wisconsin piedmont ice apparently somewhat levelled the valley floor by filling the low areas with considerable thicknesses of debris and by leaving only a veneer of material on the topographic highs.

Wisconsin Geomorphology and Glacial Geology

Description

Piedmont glacial activity during the Pleistocene epoch re-shaped the upper Yellowstone Valley with constructional and abrasional features which characterize much of the present valley topography. Wisconsin glacial features of the valley have been previously described by Weed (1893), Alden (1932), and by Horberg (1940). These workers established the concept that Wisconsin piedmont glacial ice descended the upper Yellowstone Valley from what is now Yellowstone National Park and moved as far north as Elbow Creek. Much of the map area includes deposits and associated glaciofluvial features formed at the receding terminus of piedmont ice. Wisconsin ice and melt-water in the upper Yellowstone Valley left terminal and lateral moraines, scattered deposits of debris, abrasional grooves, ice-marginal and outwash channels, and outwash plains, all of which are present in the map area. Along the mountain flank the glacial debris consists of scattered erratics which clearly mark the highest position of Wisconsin piedmont ice as it moved down the valley. On the west side of the main valley, the till is at least 400 feet thick at the mouth of Eight Mile Creek (Horberg, 1940, p. 283) and could be much thicker in other places. Its thickness in the map area appears to be dependent upon a preglacial topography of considerable relief developed by the Yellowstone River and its tributaries. For example, near the Wanigan where the river has carved a cliff in glacial debris and the underlying Tertiary sediments, the till is as thin as 40 feet. About three miles downstream, the river has cut its way through at least 150 feet of glacial till and is still flowing on it.

Abrasional grooves are present on the south shoulder of the mouth of Conlin Gulch but were either poorly developed or have not been well preserved. The highest of these, cut in Tertiary intrusive rock, appears to be the best developed and is at an elevation of about 6100 feet. It is about 200 feet long and has a maximum width of about 20 feet. The bottom of the groove is very smooth and slopes northward along the valley wall. Its elevation at the mouth of Conlin Gulch and the highest elevations of erratics in the area, when projected north to the glacial terminus, suggest a gradient of about 190 feet per mile for the top of the piedmont ice.

The activities of outwash waters north of the glacial terminus produced a large well-developed outwash plain which now extends from Elbow Creek northward for about five miles. In contrast to the ungraded knob and kettle topography of the moraine to the south, the outwash plain is a smooth northward-graded surface. Alden (1932, p. 62, 123) and Horberg (1940, p. 291) suggest that this surface correlates on a regional scale with a pre-Wisconsin erosional surface termed "No. 3 bench" by Alden. It is not likely that this correlation is valid, however, because "No. 3 bench", directly southwest of Livingston is at an elevation of almost 5000 feet (Horberg, 1940, p. 291) while the outwash surface in question, only a few miles to the south, is as low as 4750 feet and has a northward gradient. Unless serious structural movement has occurred since "No. 3 bench" was formed, there can be no correlation between the two surfaces. The material on which the outwash surface is formed could be either pre-Wisconsin or Wisconsin in age and could be the result of outwash deposition or of normal stream and/or river deposition. At any rate the present surface appears to be the result of the activities of Wisconsin glacial outwash waters and there is no evidence to indicate any affinity between it and previous surface formation.

A second and younger outwash plain emanates from a Wisconsin ice-marginal channel near Chico Hot Springs and spreads northward as far as the Mill Creek School where it merges almost imperceptibly with a large alluvial fan of Mill Creek. The alluvial fan and the outwash plain comprise essentially a single surface but drainage textures on aerial photographs show that the fan was produced by west-flowing streams from Mill Creek Canyon while the outwash plain was formed by north-flowing streams from the piedmont glacial terminus. Both surfaces have similar gradients and appear to merge, so it is likely that the outwash plain and the fan were formed concurrently. The outwash plain described above is apparently younger than the one north of Elbow Creek because the two are separated by glacial moraine. The younger surface most likely formed around a piedmont glacial terminus between the mouths of Emigrant Gulch and Conlin Gulch. This surface will be referred to hereafter as the inner outwash plain to differentiate it from the older, outer outwash plain.

The ice-marginal channel from which the inner outwash plain emanates probably serviced both Emigrant Creek and melt-water from Wisconsin piedmont ice. It parallels the mountain front between the mouth of Emigrant Gulch and Chico Hot Springs where it broadens into the surface described above. Before development of the inner outwash plain, the ice-marginal channel probably continued northward along the mountain front between Conlin Gulch and Mill Creek where the Wisconsin glacial moraine is cut by several poorly developed stream channels. Apparently, as the recession of piedmont ice continued, the waters flowing in the ice-marginal stream developed new channels circumfluent to the receding glacial terminus.

The terraces present at the head of the inner outwash plain near Chico Hot Springs suggest that Emigrant Creek and glacial melt-water flowed around the ice terminus at this point for a considerable time. The ice-marginal channel was eventually blocked by moraine (see figure 10.) at some stage of glacial activity and Emigrant Creek was forced to cut a new channel westward across the till. This channel, which extends from the mouth of Emigrant Gulch to its juncture with the Yellowstone River in sec. 34, T. 5 S., R. 8 E., is well developed (see figure 11.) but has no terraces. Near the mouth of Emigrant Gulch this abandoned channel merges with a later fan into which the present channel of Emigrant Creek is now entrenched. Whether this latest fan formed as a direct result of glacial recession or whether it formed after the glacier had left the area cannot be determined. In either case, the gradient of the later surface is about 160 feet per mile as compared to a gradient of about 115 feet per mile for the abandoned channel.

In Emigrant Gulch, near White City, a deposit of coarse unconsolidated material has been preserved on the south side of the present stream bed. The surface of this deposit now stands about 160 feet above the bottom of the gulch at that point and slopes westward toward the mouth of the gulch with a gradient of about 100 feet per mile. Similar material has been preserved on the south wall of Emigrant Gulch near its mouth but the top of the deposit at this point has been removed by erosion. The gradient of the surface, projected from an elevation of 5960 feet near White City, indicates that these deposits once filled the gulch to an elevation of about 5800 feet near its mouth. These sediments may have

Figure 10. Ice-marginal channel blocked by moraine between Emigrant Gulch and Chico Hot Springs.

Figure 11. Old Emigrant Creek Channel. View is downstream north.

been deposited in a lake formed behind a barrier of piedmont ice and/or moraine. The material is very coarse and does not contain varved silts and clays which typify glacial lake deposits but the steep walls of the very narrow Emigrant Gulch probably account for this. Also, these deposits are close to the wall of the gulch where coarse material would accumulate. This surface was formed earlier than the ice-marginal channel and other channels associated with piedmont glacial recession. It lies at a much higher elevation so was probably formed during the piedmont glacial maximum rather than when the ice was receding. Contemporary deposits of similar origin at higher elevations than present moraine have also been preserved in Six Mile Gulch about five miles south of the map area (J. Montagne, personal communication, 1963).

Discussion

The concept of Wisconsin glaciation in the upper Yellowstone Valley as outlined by Weed (1893) implies a single phase of glacial activity. Alden (1932, p. 123) described an inner and an outer piedmont terminal moraine near the mouth of Mill Creek and suggested that two phases of glaciation had occurred but he did not submit any detailed explanation of the relationship except to note that the supposedly younger inner moraine extended into an "inner valley" which had been eroded into the outer and apparently older Wisconsin terminus by the Yellowstone River. Wisconsin moraine in the upper Yellowstone Valley was first differentiated and attributed to two distinct phases of glacial activity by Horberg (1940) who termed them the early Wisconsin (Bull Lake) and late Wisconsin

(Pinedale) substages in an attempt to correlate with Wisconsin substages (Blackwelder, 1915) in the Wind River and Green River basins, Wyoming. In this concept, the inner moraine of Alden (1932, p. 123) is considered to be Pinedale and the outer moraine is mapped as Bull Lake. Part of Horberg's evidence for two substages of glaciation in the main valley is the relationship between two distinct terminal moraines at the mouth of Pine Creek, near the north end of the valley. These moraines, the products of valley glaciation in Pine Creek Gulch, indicate two separate phases of glaciation between which a period of considerable erosion occurred. The center of the older moraine (Bull Lake) was removed by Pine Creek before the younger moraine (Pinedale) was deposited. The Pinedale (?) terminus was then deposited beyond the Bull Lake (?) terminus. Also, the younger sequence was deposited in a deep gap cut between the lateral moraine of the older sequence and the canyon mouth. Because this relationship exists at the mouth of Pine Creek, Horberg attempted to apply the same concept to piedmont glaciation in the main valley. Evidence strengthening his Bull Lake - Pinedale concept of glaciation in the main valley includes a peat zone (not presently exposed) buried by glacial moraine on the north side of the present channel of Emigrant Creek, the ice-marginal channel blocked by glacial moraine between Chico Hot Springs and the mouth of Emigrant Gulch (see Figure 10.) and the presence of younger moraine in the "inner valley" of the Yellowstone about two miles north of Emigrant as first described by Alden (1932, p. 123). Further, Horberg (1940, p. 297) describes the Pinedale (?) deposits as having a more youthful appearance than the Bull Lake moraine. The ages of Bull Lake and Pinedale substages have not yet been definitely established in terms of years but carbon-14 age determination from Jackson Hole, Wyoming (Love, 1956, p. 149,150) suggest possible ages of about 27,000 years for the Bull Lake substage and about 9,000 years for the Pinedale substage.

Horberg's concept has since been challenged by Montagne (personal communication, 1962) on the premise that the evidence for two substages of Wisconsin glaciation is not conclusive. Part of the purpose of this paper is to further evaluate any evidence for or against the concept.

Because the map area includes much of the till deposited at the distal end of the piedmont ice, it is probably the most likely place in the upper Yellowstone Valley for evidence pertinent to the glacial history. The criteria used in an attempt to distinguish glacial deposits of different ages in this study were: (1) degree of preservation of distinctive glacial features, (2) progress of weathering and composition of debris, (3) degree of soil profile development, (4) stratigraphic relationships between soil, outwash, and till, and (5) physiographic relationships of moraine, outwash plains, and stream channels. The time interval between Bull Lake and Pinedale glacial substages is uncertain but should be sufficient for the development of notable differences in the topographic preservation, degree of weathering of material, and soil profile development of Bull Lake and Pinedale deposits. Stratigraphic and physiographic relationships can indicate advance and recession of glacial ice but do not necessarily indicate any great time interval between phases of activity. For this reason, conclusive evidence for two distinct substages of Wisconsin glaciation must include some sort of time-dependent factor.

(1) Preservation of distinctive glacial features - In the map area and in the entire upper Yellowstone Valley, no distinction could be found in the degree of preservation of glacial features. Some places appear to have a slightly more youthful character but these places are present on both Bull Lake (?) and Pinedale (?) moraine. Further, aerial photographs of the valley floor show no apparent difference between moraines classified by Horberg as Bull Lake and Pinedale.

(2) Progress of weathering and composition of debris- The progress of weathering of material comprising Bull Lake (?) and Pinedale (?) moraines appears to be identical. None of the material in the glacial till appears to be extensively weathered with the exception of certain schistose rocks. These metamorphic rocks of Precambrian age are quite susceptible to weathering and so are easily exfoliated and decomposed. Further, the composition of glacial debris in both Bull Lake (?) and Pinedale (?) deposits appears to be consistent with that described on page 28 throughout the area.

(3) Soil profile development - Substages of Wisconsin glaciation have been distinguished in other areas by the degree of soil profile development. For example, profiles on Bull Lake and Pinedale till on the east slope of Rocky Mountain National Park, Colorado are described by Richmond (1960) as being quite different. Bull Lake soils in that area are well developed and are as much as five feet thick in contrast to the immature Pinedale soils with thicknesses of 12 to 18 inches. However, an attempt to distinguish substages of Wisconsin glaciation in Indiana on the basis of soil profile by Thornbury (1940) was essentially unsuccessful. According to Flint (1949), age correlations of glacial drift generally cannot be reliably

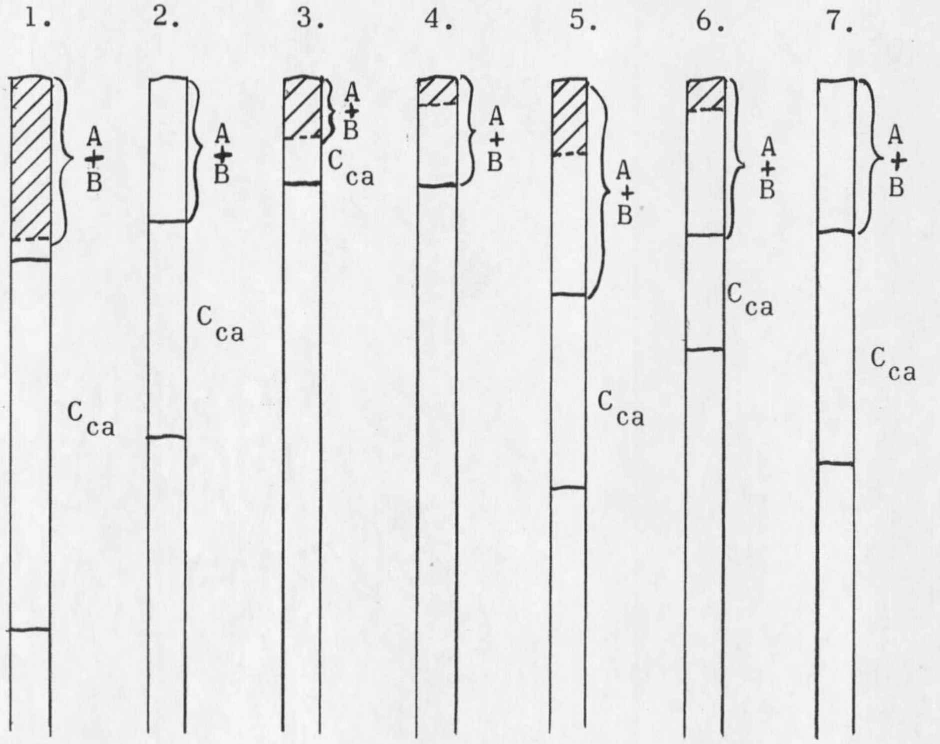
determined on the basis of soil profile development because of the complexity of soil forming factors.

In this study, soil profiles on Pinedale (?) and Bull Lake (?) moraines were examined at various places in and near the map area in an attempt to differentiate deposits of the two substages. If a study of this type is to be valid, a consideration must be given to the variables affecting soil profile development. The most important variables are time, type of parent material, climate, vegetation, and topography. Because time is the variable to be considered, the other soil forming factors must be carefully controlled. The soil profiles to be studied must be located in areas of similar climate, vegetation, and topography, and must have originated from the same type of parent material. The profiles studied were located along road cuts in reasonably flat surfaces. The parent material (glacial till and loess) and the vegetation (short grass) were reasonably similar where the soils were examined.

Profile characteristics noted in this study, that might indicate a relative time factor, are the depth and the thickness of the C_{ca} horizon. Other characteristics which might have been useful for comparison include depths and thicknesses of A and B horizons, organic and ionic constituents in those horizons, and types of clay present. These characteristics are all interrelated to some degree and are associated with the soil forming factors that cause C_aCO_3 accumulation so were not utilized in this study. Table II shows the results of C_{ca} horizon comparisons in this study. If any gross morphologic difference between Bull Lake (?) and Pinedale (?) soils exists in the upper Yellowstone Valley, it should have been noted in the comparison

TABLE II. Soil Profile Comparisons

Number	Location	Possible Substage
1.	N. E. corner, sec. 13, T. 5 S., R. 8 E.	Bull Lake
2.	N. W. corner, sec. 5 T. 5 S., R. 9 E.	Bull Lake
3.	N. E. corner, sec. 34, T. 5 S., R. 8 E.	Pinedale
4.	N. E. corner, sec. 3, T. 6 S., R. 8 E.	Pinedale
5.	N. W. corner, sec. 1, T. 6 S., R. 8 E.	Pinedale
6.	S. E. corner, sec. 27, T. 5 S., R. 8 E.	Pinedale
7.	W. side, sec. 31, T. 6 S., R. 8 E.	Pinedale



scale 1:20   loess - ▨

of these soil profiles. The only possible distinction which might be noted in these profiles is that the two Bull Lake (?) soils appear to have a deeper and thicker C_{ca} horizon. The validity of this distinction is questionable, however, because only a few profiles were compared. The character of the C_{ca} horizon and the rest of the profile varies a great deal in both Bull Lake (?) and Pinedale (?) soils in the map area. Some exposures show the supposed younger soil with a better developed profile than that of the older soil (compare 5 and 7 with 2). This situation can, in some exposures, be attributed to different local variables, e.g. depth of loess, which influence profile development (compare 5 with 2) but, in other exposures, it is apparently not consistent with these variables (compare 7 with 2). If the concept of two substages of glaciation is correct, the soils that developed on deposits of different ages do not appear to have any gross morphologic distinctions despite at least a 10,000 year age difference. It is possible that climatic conditions were such that profile development proceeded too slowly between Bull Lake and Pinedale glacial substages to account for any notable difference in the respective soils. Or, it is possible that wind removed the soil as fast as it formed. Whatever the explanation may be, if two substages of Wisconsin glaciation occurred in the upper Yellowstone Valley, it is evident that the gross features of soil profiles cannot be used reliably for substage distinction.

(4) Stratigraphic relationships - In the map area, a number of stratigraphic relationships are present which may be pertinent to the Bull Lake - Pinedale concept of Wisconsin glaciation. Among these are deposits of outwash

and loess which appear to be overlain and underlain by glacial till. For example, on the north side of a dredge pond near the mouth of Emigrant Gulch, outwash deposits overlie glacial till and appear to be also overlain by till. Exposure of this relationship is poor (see figure 12) but by close scrutiny and by digging, the outwash can be traced beneath moraine at the mouth of Emigrant Gulch.

Thin deposits of silt and fine sand which are apparently buried by glacial till are exposed along the old Emigrant Creek channel about one mile above its juncture with the highway in sec. 34, T. 5 S., R. 8 E. and along the east bank of the Yellowstone River in sec. 23, T. 5 S., R. 8 E. Both of those deposits appear to be loess which has accumulated on, and then been covered by, glacial till. However, both exposures are located on steep slopes so slumping may have produced this relationship.

In a small gully in the south part of sec. 34, T. 5 S., R. 8 E., a sequence of possible glacial lake deposits with interbedded glacial till is exposed. The north side of the gully shows a thick deposit of silt with an upper zone of coarsely varved clay beds overlain by glacial till of varying thickness. The till is overlain by a thin, irregular zone of silt and clay which is in turn overlain by more glacial till. If these zones of clay and silt are true glacial lake deposits or if they are loess deposits, at least three advances of piedmont ice must have occurred.

All of the stratigraphic relationships described above suggest that Wisconsin piedmont glacial activity was episodic and characterized at least by intraglacial advances and retreats if not distinct Wisconsin substages. These relationships do not indicate any great time-break in