The geology of the northern flank of the upper Centennial Valley, Beaverhead and Madison counties, Montana
by Matthew Lee Mannick

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

Abstract:

The Huckleberry Ridge Tuff of the Yellowstone Group covers a large portion of the north side of the upper or eastern Centennial Valley, southwestern Montana. This ignimbrite is the result of the first major eruptive event (2.0 m.y.) of the Yellowstone caldera. The tuff forms dip slopes on the north flank of the valley lapping eastward against Precambrian rocks near Elk Lake and to the northwest along the West Fork of the Madison River.

The Huckleberry Ridge Tuff in the Centennial area is a composite ash flow sheet composed of two distinct cooling units, each displaying vertical zonation of welding density and phenocryst content.

The upper Centennial Valley is influenced by four major structures: the Madison, Gravelly, and Centennial range front, and Cliff Lake faults. The upper Centennial Valley resulted from the down dropping of a half graben against the Centennial Fault along the Gravelly Range Front and Cliff Lake faults. Observations of Huckleberry Ridge Tuff displacement indicate a minimum post Huckleberry Ridge Tuff offset along the Centennial Fault of 5000 to 6000 feet (1525 to 1830 m) out of a total of approximately 10,000 feet (3050 m).

Variations in depositional thicknesses of the Huckleberry Ridge Tuff indicate a paleotopography which included a major river valley (the ancestral Madison River) that entered the upper Centennial Valley from the north. This drainage can be traced northward into the Madison Valley where it joins the present-day Madison River.

Warm spring activity is present along the Gravelly Range Front Fault and may exist along the Cliff Lake Fault.

A potential geothermal reservoir of substantial dimensions may exist in the channel gravels of the ancestral Madison River in the vicinity of the Cliff Lake Fault beneath the Huckleberry Ridge Tuff.

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by

MATTHEW LEE MANNICK

A thesis submitted in partial fulfillment
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ABSTRACT

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INTRODUCTION

Location

The study area is located just north of the Montana-Idaho border about 43 kilometers west of Yellowstone National Park (Fig. 1).

An area encompassing approximately 110 square kilometers located on the north slope of the eastern or upper Centennial Valley (southeasternmost Gravelly Range, Figure 2) was mapped. Data collected from the map area were used to interpret the geology of the Centennial region (study area in Figure 1).

The map area extends northward and westward to the boundary of the Upper Red Rock Lake Quadrangle (Fig. 2) and eastward to the Pleistocene-Precambrian contact east of Elk, Hidden, and Cliff lakes. The southern boundary coincides with the northern edge of the U.S.G.S. geologic map of the southern part of the Upper Red Rock Lake Quadrangle (Witkind, 1976).

Purpose

This study was done in conjunction with a Montana Bureau of Mines and Geology evaluation of the geothermal potential in the Centennial and Madison River valleys. Funding was provided by the Bureau for this paper on the

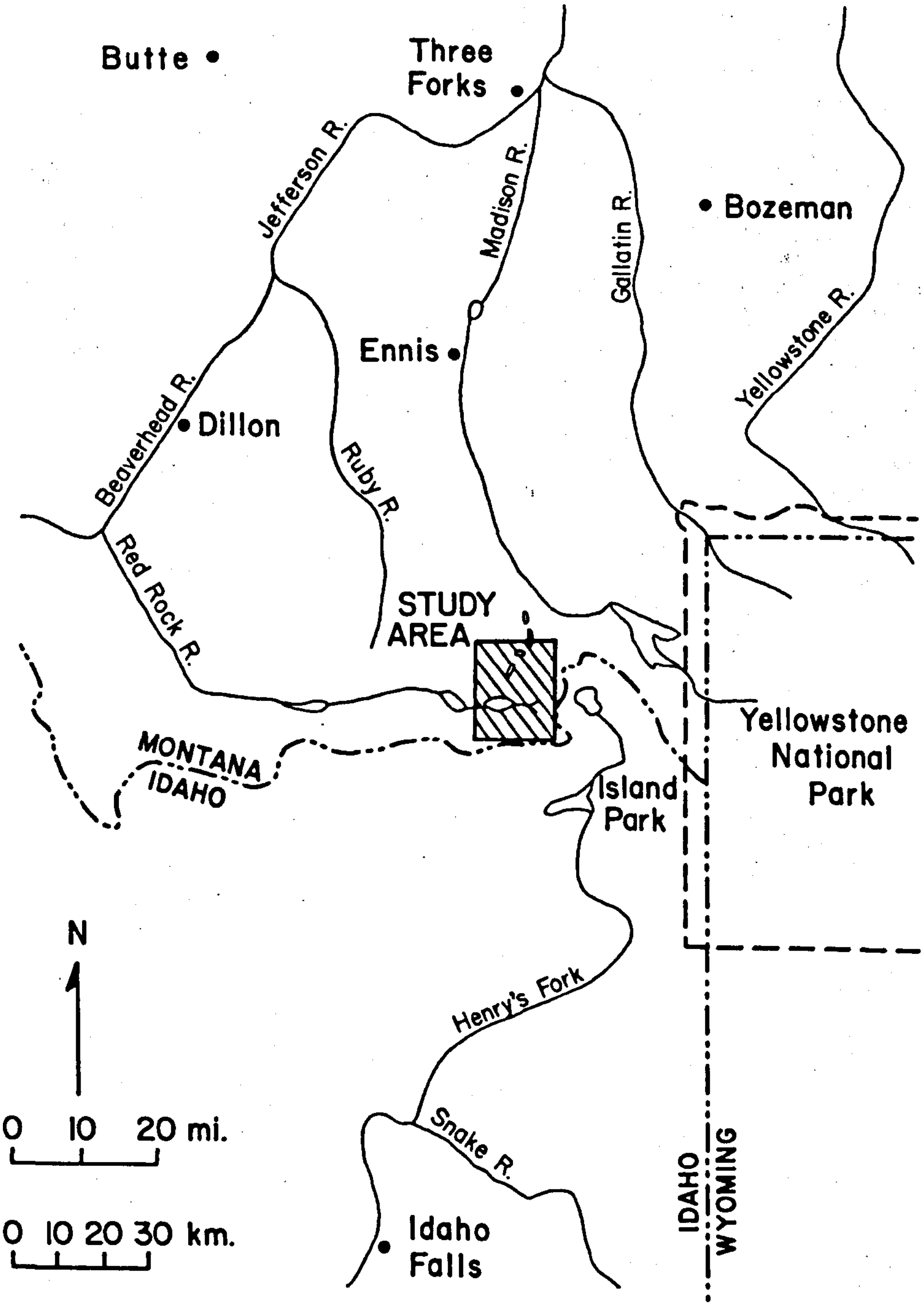


FIGURE 1. Index map.

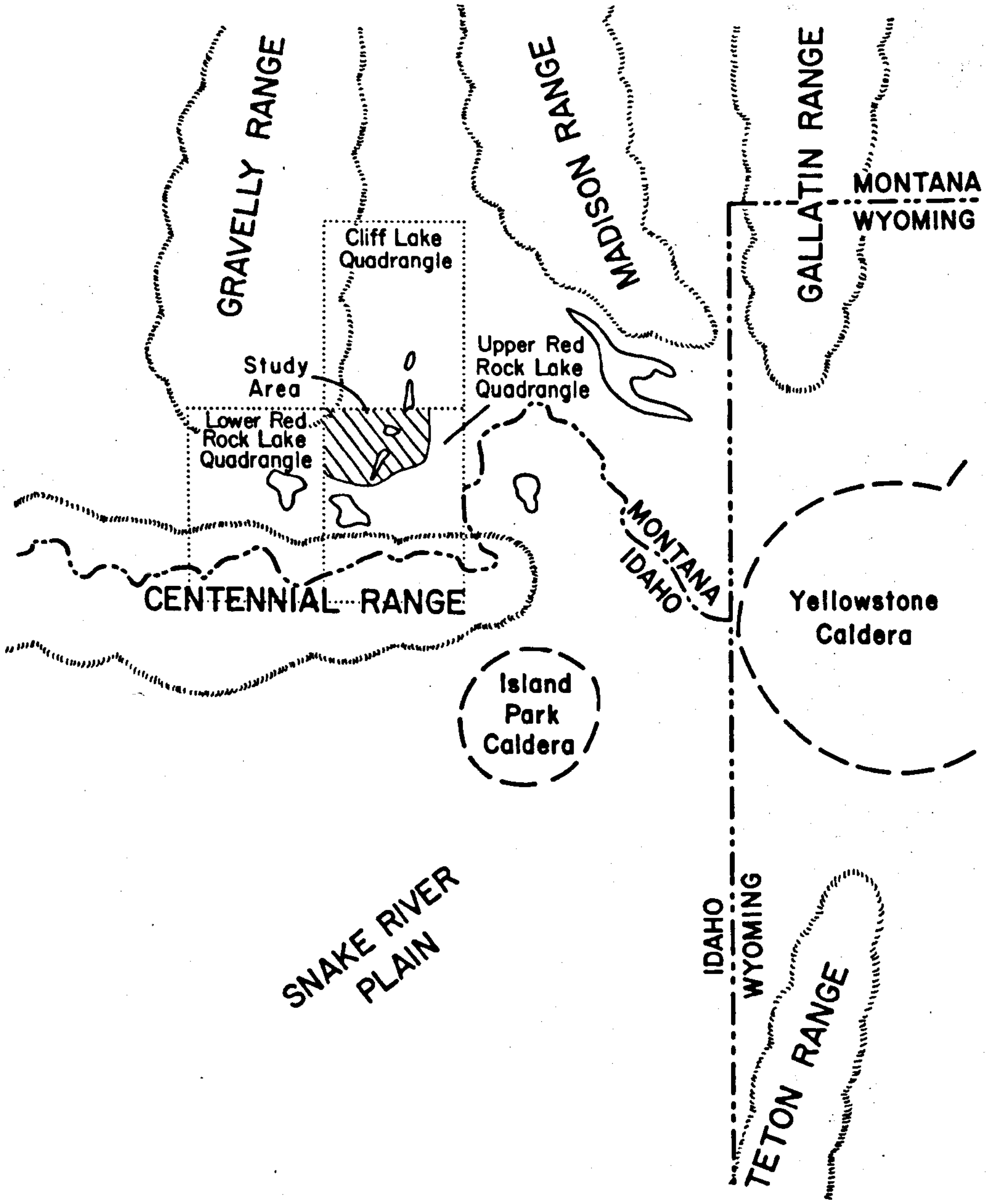


FIGURE 2. Location of map area.

upper Centennial Valley. The structure and volcanic stratigraphy were examined to assist the Bureau in its evaluation of the geothermal systems in the upper Centennial Valley. This evaluation was prompted by the close proximity of the Island Park geothermal field and the presence of warm springs in the Centennial Valley region adjacent to the study area.

Previous Investigations

The Centennial Range and Valley have been examined in little detail previous to this investigation.

Honkala (1949) did the first work on the stratigraphy and general geology of the Centennial region and published additional papers in 1954 and 1960 on the general geology and major structures of the Centennial Mountains and vicinity. These investigations consisted of reconnaissance work generally lacking detail especially when dealing with the volcanic rocks of the region.

The stratigraphy and structure of the Gravelly Range north of the Centennial Valley (Fig. 2) was studied by Mann (1960).

A geologic map of the southern part of the Upper Red Rock Lake Quadrangle, southwestern Montana and adjacent Idaho (Fig. 2) was produced by Witkind in 1976. The map covered a portion of the Centennial Range as well as the floor of the upper Centennial Valley.

Bailey (1977) conducted a geophysical investigation of the seismicity and contemporary tectonics of the Hebgen Lake-Centennial Valley, Montana area.

A portion of the Upper Madison Valley was mapped and evaluated for geothermal potential by Weinheimer (1977 and 1979). This study covered a large part of the Cliff Lake Quadrangle, which is adjacent to and north of the Upper Red Rock Lake Quadrangle (Fig. 2).

The Montana Bureau of Mines and Geology is currently investigating the geology and geothermal potential of the Centennial Valley. Dr. John Sonderegger of the Bureau's hydrology division has been mapping and evaluating geothermal potential in the northern part of the Lower Red Rock Lake Quadrangle (Fig. 2). The Precambrian rocks along the northern flank of the Centennial Valley have been investigated by Dr. Richard Berg of the Bureau. James Schofield conducted a gravity and magnetics study of the Centennial Valley (Upper and Lower Red Rock Lake Quadrangles, Figure 2) as part of a Master of Science degree from the Montana College of Mineral Science and Technology.

Procedure

Field studies of the northern flank of the upper Centennial Valley were undertaken during the summers of 1978 and 1979. Field work consisted of geologic mapping using pace and compass methods aided by air photos. A topographic map with a scale of 1:24000 and contour interval of 20 feet was used as a base for the geologic map.

The volcanic rocks of the area were studied in detail. Volcanic sections were measured using a Brunton compass and Jacob staff and were sampled where lithologies changed. Thin sections were prepared and studied under the petrographic microscope, and correlations of cooling units and the welding variations within them were made from the data. Cross sections were constructed based on interpretations made during the study. Volcanic rocks were sampled at several locations and dated radiometrically (Appendix II) and chemically analyzed (Appendix III). The K-Ar analyses were done at the University of Utah, Department of Geology, and funded by the Montana Bureau of Mines and Geology and the chemical analyses were completed by the Bureau.

ROCK UNITS

Precambrian Rocks

The Precambrian rocks of the upper Centennial region consist of pre-Belt rocks of Precambrian X age (Witkind, 1976). These rocks are exposed along the Centennial Range on the south side of the valley, to the east of Elk, Hidden, and Cliff lakes and west of the West Fork of the Madison River on the north side of the valley (Plate 1).

The Precambrian rocks of the Centennial region consist of low to medium grade metamorphics. These rocks include: gabbro, metadolomite, quartzite, metagranodiorite, amphibolite, and mica schist (Fig. 3). The prominent strike of the foliation is northeast (Witkind, 1972 and 1976).

Paleozoic and Mesozoic Rocks

The Paleozoic and Mesozoic sedimentary sequences are not exposed along the north side of the upper Centennial Valley. The sections may be present at least in part west of Elk and Hidden lakes where they may have been downfaulted and preserved by burial by the Huckleberry Ridge Tuff.

The Paleozoic rocks exposed along the scarp slope of the Centennial Range include marine sediments of the Cambrian through the Permian excluding the Silurian Period

ROCK TYPE	DESCRIPTION
Gabbro	Dark-gray, nonfoliate, coarse-grained; commonly equigranular but locally porphyroblastic with large labradorite metacrysts. Common minerals are labradorite (An_{63}), hornblende, and quartz.
Metadolomite	Light-brown to light-gray, foliated, thick-bedded to massive, and coarsely crystalline. Contains abundant thin to thick quartz beds.
Quartzite	White, light-gray, green, foliate, thin- to thick-bedded, strongly micaceous, medium- to coarse-grained, and equigranular. Bimodal: mostly quartz and muscovite but locally containsminor amounts of microcline, opaque iron minerals, sericite, and chlorite.
Metagranodiorite	Light-gray to gray, foliate, fine- to very coarse-grained, and equigranular. Common minerals are potassic feldspar, hornblende, apatite, sphene, epidote, and opaque iron minerals. Alteration products include sericite and chlorite.
Amphibolite	Dark-gray, strongly foliate, very fine-grained to fine-grained; banded with irregularly alternating laminae of hornblende and quartz-plagioclase. Minor constituents include biotite, apatite, sphene, epidote, zircon, and opaque iron minerals. Alteration products include chlorite, sericite, and calcite.
Mica Schist	Dark-gray to brown, fine- to medium-grained; strongly micaceous; foliate. Major constituents are biotite, quartz, and potassic and plagioclase feldspar. Garnet and staurolite metacrysts are locally common. Accessory minerals include apatite, sphene, zircon, epidote, tremolite, and opaque iron minerals. Common alteration products are sericite, chlorite, and bleached biotite.

FIGURE 3. Precambrian rocks of the upper Centennial Valley.

System	Series	Group	Formation	Description
Permian	Lower Permian		Phosphoria Fm. and Related Permian Rocks	Interfingering units belonging to the Shedhorn Sandstone, Phosphoria Formation, & Park City Formation composed of bedded chert, oolitic phosphatic rock, phosphatic shale, and quartzose sandstones; Carbonate beds at base.
Pennsylvanian	Late Miss. and Penn.		Quadrant Sandstone	Light-brown, fine-grained, quartzose sandstone, locally quartzose; composed largely of angular to subangular quartz grains locally cemented by silica. Contains thin lenticular, light-gray, dense, sandy dolomite beds, 1.2 to 1.5 meters thick, interbedded in upper and basal strata.
			Amsden Formation	Light-gray, medium-bedded to very thick-bedded locally massive, coarsely crystalline dolomite; 5 to 10 cm thick lenses and beds of chert are common.
Mississippian	Lower Miss.	Madison	Mission Canyon Ls.	Bluish-gray, thick-bedded to massive, dense limestone beds.
			Lodgepole Limestone	Bluish-gray thin- to medium-bedded limestone that is very fossiliferous and contains much bedded chert.
Devonian	Upper Dev.		Three Forks Formation	Shaly, light-brown to yellow, locally pale-reddish-brown, calcareous thin-bedded siltstone and sandstone.
			Jefferson Formation	Upper member is light-tan thin-bedded dolomite. Lower member is grayish-brown, dense, medium-bedded to massive, vuggy dolomite; locally contains scattered angular fragments of white to gray chert.
Ordovician	Upper Ord.		Bighorn Dolomite	Light-gray dolomite in even thin beds 2 to 5 cm thick; faint laminae paralleling the bedding.
Cambrian	Upper Cambrian		Pilgrim Dolomite	Light-brown to light-gray, thin- and even-bedded, platy dolomite; nodular-weathered surface sparse glauconite grains.
	Middle Cambrian		Park Shale	Greenish-gray to grayish-red, even-bedded, fissile shale; breaks into minute angular fragments.
			Meagher Limestone	Light-gray to gray even-bedded, thin-bedded limestone; weathers to a crenulated nodular surface. Contains grains and pebbles of Precambrian rocks in basal strata.
			Flathead Sandstone	Reddish-brown, medium-bedded to massive, crossbedded, fine- to coarse-grained, friable sandstone. Locally contains angular to rounded pebbles and cobbles of Precambrian rocks in basal strata.

FIGURE 4. Paleozoic stratigraphy of the Centennial region.

(Fig. 4).

The Mesozoic rocks exposed in the area are of terrestrial as well as marine origin. These include salt and pepper sandstone, quartz sandstone, limestone, claystone, shale, and siltstone as well as reddish and brownish sandstone, siltstone, and claystone (Fig. 5).

Cenozoic Nonvolcanic Rocks

The nonvolcanic rocks of Cenozoic age in the study area are primarily of fluvial and lacustrine origin. These rocks unconformably overlie rocks of Precambrian, Paleozoic, and Mesozoic age in the Centennial region. Cenozoic nonvolcanic rocks both overlie and underlie Pleistocene volcanics unconformably in the region (Plate 1). Several of the following rock descriptions were taken from Witkind (1976).

Tertiary limestone — Pale yellow-brown to light gray, thin to medium bedded, finely crystalline limestone. Unit protrudes up through Pleistocene volcanics to form patchy knobs along the northern flank of the upper Centennial Valley adjacent to the valley fill sediments.

Quaternary lacustrine deposits — Light brown to brown, well sorted, unconsolidated silt and sand.

System	Series	Group	Formation	Description
Cretaceous	Lower Cret.		Kootenai Formation	Consists of a basal conglomerate and conglomeratic "salt and peper" sandstone; a middle light-gray marly limestone and claystone unit; and an upper light-gray marly limestone-claystone bed, containing coiled gastropod molds.
Triassic	Upper Jur.		Morrison Formation	Thin quartzose sandstone beds interlayered with a claystone-siltstone sequence. Sandstone is light-brown, thin- to medium-bedded, lenticular, crossbedded, fine-grained, and friable. Claystone-siltstone sequence consists of varigated grayish-green to pale-red beds.
	Upper and Middle Jurassic	Ellis	Swift Formation	Grayish-brown to greenish-gray, sandy, oolitic limestone, thin- to medium-bedded, and crossbedded; rich in shell fragments and rounded chert grains.
			Rierdon Formation	Light-gray marly limestone that is locally a calcareous claystone.
			Sawtooth Formation	Light-gray, oolitic, thin-bedded limestone containing a few thin light-gray claystone interbeds; fossiliferous, rich in distinctive star-shaped crinoid plates.
Triassic	Lower Triassic		Thaynes Formation	Light-brown thin-bedded limestone; breaks into platy fragments; interbedded chert layers 5 to 10 cm thick.
			Woodside Formation	Reddish-brown, thin-bedded, fine-grained sandstone and shaly siltstone, locally platy; ripple marked.
			Dinwoody Formation	Light-brown to light-gray and yellowish-gray thin- to medium-bedded limestone and calcareous siltstone; platy, even-bedded with many dark-gray shale interbeds; locally fossiliferous (linguloid brachiopods and pelecypods).

FIGURE 5. Mesozoic stratigraphy of the Centennial region.

Quaternary dune sand — Brown, unconsolidated well-sorted quartz sand; frosted angular to subrounded grains.

Quaternary alluvium (Holocene) — Unconsolidated fluvial deposits of silt, sand, and gravel.

Quaternary colluvium (Holocene) — Unconsolidated rubble along the lower portions of steep slopes.

Quaternary displaced Huckleberry Ridge Tuff — Unconsolidated rubble ranging up to boulder size. Formed by the mass wasting of cliffs composed of Huckleberry Ridge Tuff. Large sections of tuff separate from and accumulate at the base of the cliff creating a hummocky topography.

Quaternary displaced basalt — Unconsolidated boulders of basalt found along slopes near the West Fork of the Madison River.

Quaternary sand and gravel deposit — Unconsolidated poorly sorted sand, gravel, cobbles, and boulders that form low mounds or cap small hills. Deposits near Elk Springs may represent material left at the outlet of a former glacial lake in the Centennial Valley as the lake drained northeastward to join the Madison River via the Cliff Lake Fault trench.

Quaternary deposit of coalesced old alluvial fans — Low broad lobate deposit resulting from the coalescence of several old alluvial fans. Composed of unconsolidated fluvial silt, gravel, cobbles, and a few boulders. Coarser material near apexes of fans grades into finer grained materials, such as silt and sand, near distal edges. Probably formed before or during the life of the glacial lake.

Quaternary young alluvial fan deposit — Low lobate deposit of unconsolidated moderately well-sorted silt, sand, gravel, and cobbles at mouths of streams, most of which empty into the Centennial Valley. Constituent rock types reflect bedrock exposed along streams. Precambrian crystalline and Cenozoic volcanic rocks predominate along the north side of the Centennial Valley. Probably formed after glacial lake had disappeared.

Quaternary travertine — Light gray compact travertine found on east shore of Elk Lake (Berg, Personal Communication, 1979).

Cenozoic Volcanic Rocks

The Cenozoic volcanic rocks of the upper Centennial Valley include localized basalts of both Tertiary and Pleistocene age as well as Pleistocene welded tuffs which cover extensive portions of the north flank of the valley

(Plate 1).

Quaternary-Tertiary basalt — Dark gray to black, dense, fine-grained extrusive rock. Locally vesicular, it contains abundant magnetite with sparse olivine phenocrysts. Primarily exposed as thin flows which commonly display columnar jointing. This rock is petrographically similar to the basalt near Elk Lake (Pleistocene basalt) which has been dated at 2.38 million years. These two basalts may be the same age and may have originated from the same magmatic source at depth.

Pleistocene basalt — Dark gray to black, dense, fine-grained extrusive rock. Contains sparse olivine phenocrysts and is locally vesicular. This basalt has been K-Ar dated at 2.38± 0.44 million years by whole rock analysis (Appendix II, C).

This unit is exposed only at the south end of Elk Lake where its depositional relationship with that of the Huckleberry Ridge Tuff is questionable. The basalt occurs as boulder piles and is not exposed in place. The unit appears to have either cut through and flowed over the Huckleberry Ridge Tuff or cut through and flowed over the first cooling unit of the tuff. The basalt appears to have risen from a magma source, possibly related to the Snake River Plain-Yellowstone volcanic system, via the deep-seated Cliff Lake Fault (Plate 1). A similar basalt dated at slightly less than 2.4 million years is known to have originated from this volcanic system in Yellowstone National Park 40 miles (64 km) to the east of Elk Lake (Christiansen and Blank, 1972).

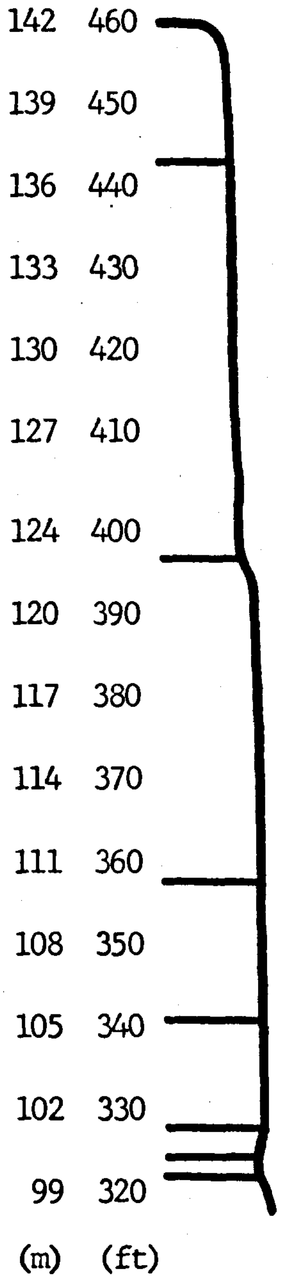
Pleistocene Huckleberry Ridge Tuff — The Huckleberry Ridge Tuff, which originated from the Yellowstone caldera, is the oldest (2.0 m.y.) of the three formations that comprise the Yellowstone Group volcanics of Christiansen and Blank (1972).

The tuff found in the upper Centennial Valley is petrographically similar to that of the type section of the Huckleberry Ridge Tuff (Christiansen and Blank, 1972). The Huckleberry Ridge Tuff has been subdivided into three members (cooling units of a compound ash flow sheet) at the type section (Christiansen and Blank, 1972), two of which are present in the upper Centennial Valley. The lower cooling unit (Qh_1) in the Centennial Valley can be correlated with the lower member described at the type section and the upper cooling unit (Qh_2) with the middle member. The lower member at the type section contains a thick zone of dense welding beneath a zone of partial welding. Phenocrysts decrease in number toward the top of this member. The lower cooling unit of the tuff in the Centennial region contains a smaller percentage of phenocrysts overall but a similar pattern of welding and phenocryst distribution. The upper cooling unit in the Centennial region is similar to the middle member of the type section with a phenocryst poor zone near the base of the unit. Phenocrysts increase in abundance and size toward the top of the second member of the tuff at both locations. The third and uppermost member of the tuff described at the type section occurs only south of central Yellowstone National Park (Christiansen and Blank, 1972).

K-Ar dates of around 2.0 million years have been attained from the tuff at the following locations (Appendix II, A,B,D,E): 1 mile NNW of Hidden Lake, the south end of Elk Lake, the cliff face on the west bank of the Madison River 2 km north of the mouth of Wall Canyon, and the northeast slope of Flatiron Mountain.

The description (prepared using work of Smith, 1960 as a guide) which follows represents the Huckleberry Ridge Tuff sequence located 1 mile NNW of Hidden Lake (Figs. 6 & 7). A chill zone is present as float at the base of the outcrop (basal Qh_1). The tuff of the chill zone is vitric, partially welded, and contains 3 to 5% sanidine with trace amounts of quartz and olivine phenocrysts all of which range up to 3 mm in diameter. The olivine phenocrysts appear in these pyroclastic rocks of rhyolitic composition as the result of the partial mixing of the bimodal magmatic system beneath the Yellowstone region at the time of eruption. The bimodal system consists of basaltic material beneath magmas of rhyolitic composition (Struhsacker, 1978). Above the basal chill zone is a zone of dense welding 75 meters thick, in which devitrified shards are extremely flattened and deformed (Fig. 8, Photomicrograph A). This portion of the tuff contains 3 to 5% sanidine phenocrysts at the base of the zone which decrease upward to 1 to 2% near the top. Phenocryst size also varies vertically from an average diameter of 1.5 mm near the base to 0.5 mm at the top. The zone of dense welding grades upward into a zone of

FIGURE 6. Huckleberry Ridge Tuff measured section located 1 mile NNW of Hidden Lake (NW¼,NE¼, sec 4, T13S, R1E).



Light-gray, punky, nonwelded tuff, contains 10% sanidine & 5% quartz phenocrysts (.5-2 mm diam.), and slightly flattened pumice. Weathers to light-pink ash.

Light-gray, massive, porphyritic tuff. Contains 20-25% sanidine & 1% quartz phenocrysts (1-4 mm diam.).

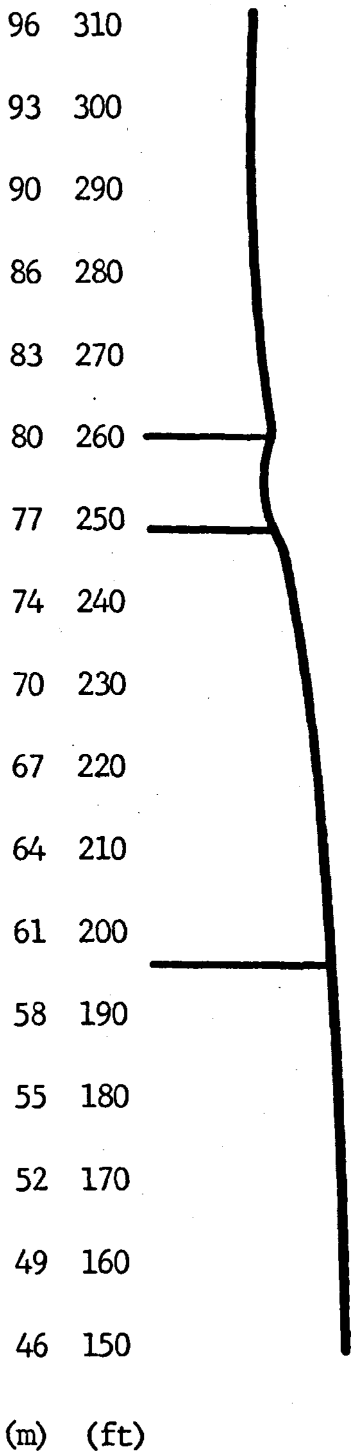
Medium-gray, porphyritic welded tuff. Contains flattened pumice altered to clay, 10% sanidine, and 5% quartz phenocrysts (1-4 mm diam.).

Dark-gray, massive, porphyritic welded tuff. Contains 3% sanidine & 1% quartz phenocrysts (.5-1 mm diam.).

Gray-brown, massive, porphyritic welded tuff with crude concoidal fracturing. Contains 10-15% sanidine & 1% quartz phenocrysts (.5 mm diam.).

Chill zone

Ash bed

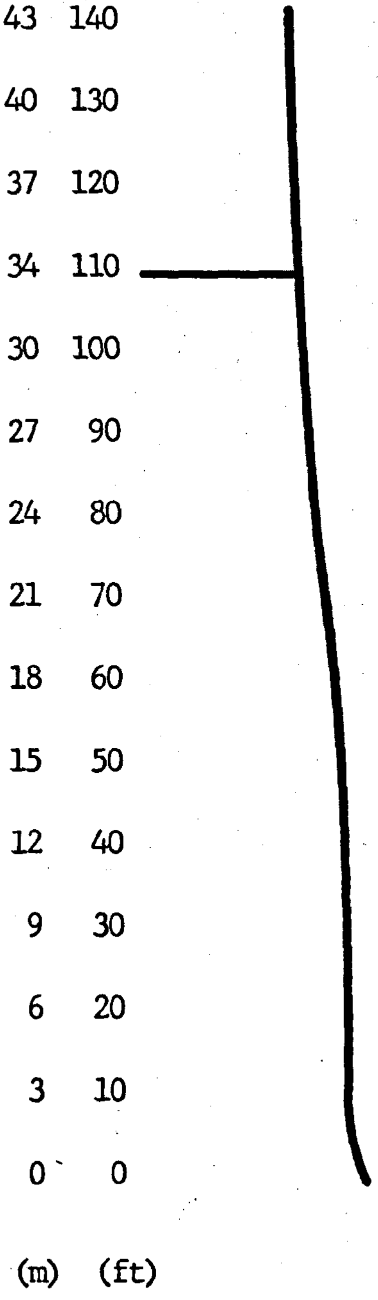


Dark-gray to black, lithophysal welded tuff. Contains 1% sanidine phenocrysts (.2 mm diam.) and spherical vugs filled with secondary feldspar altered to clay.

Reddish-brown welded tuff. Contains 1% sanidine phenocrysts (1mm diam.), flattened pumice fragments, and spherical pockets coated with feldspar altered to clay.

Medium-gray, porphyritic welded tuff. Contains 2% sanidine phenocrysts (.5 mm diam.) and minor vugs filled with feldspar crystals. Weathers to light-gray.

Medium to dark-gray, porphyritic, flow banded welded tuff. Contains 5% sanidine phenocrysts (1.5 mm diam.).



Dark-gray, porphyritic, flow banded welded tuff. Contains 5% sanidine phenocrysts (1.5 mm diam.).

Black, dense, porphyritic, vitric welded tuff resembling obsidian. Contains 5% sanidine phenocrysts (1-3 mm diam.) and rock fragments. This unit seen only at base of cliff.

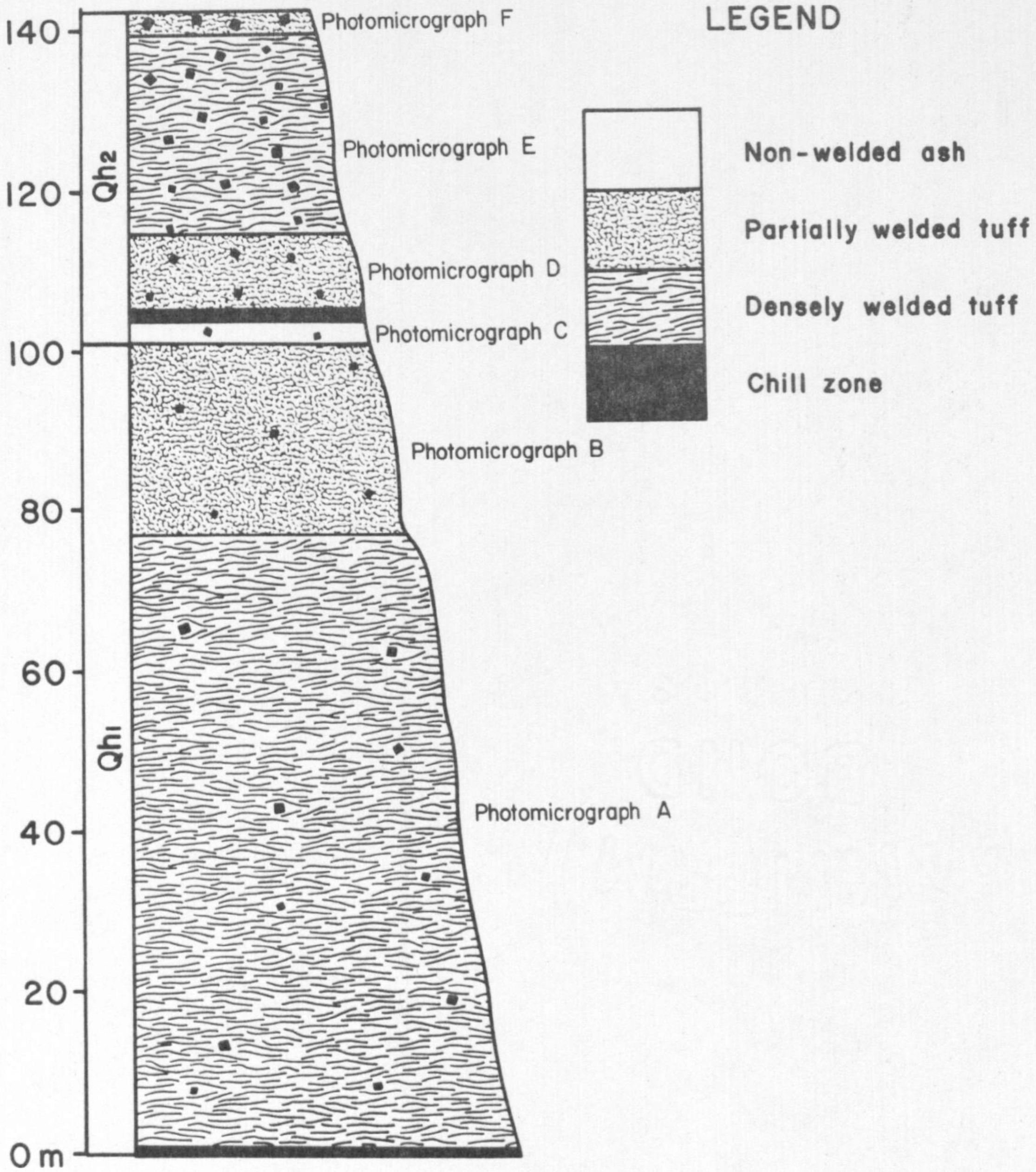


FIGURE 7. Zonal variations in welding density of the Huckleberry Ridge Tuff with photomicrograph locations. (NW¼,NE¼, Sec.4, T13S,R1E).

FIGURE 8. Photomicrographs of the Huckleberry Ridge Tuff. The photomicrographs were taken at 35 X power under plane light with a scale of 1 mm indicated on the photo. (See Figure 7 for sample locations).

PHOTOMICROGRAPH A — Photo A displays the zone of dense welding in the lower cooling unit (Qh_1) of the Huckleberry Ridge Tuff. Note the extreme flattening and deformation of shards due to compaction under high temperatures. The shards comprising the ground mass have been devitrified.

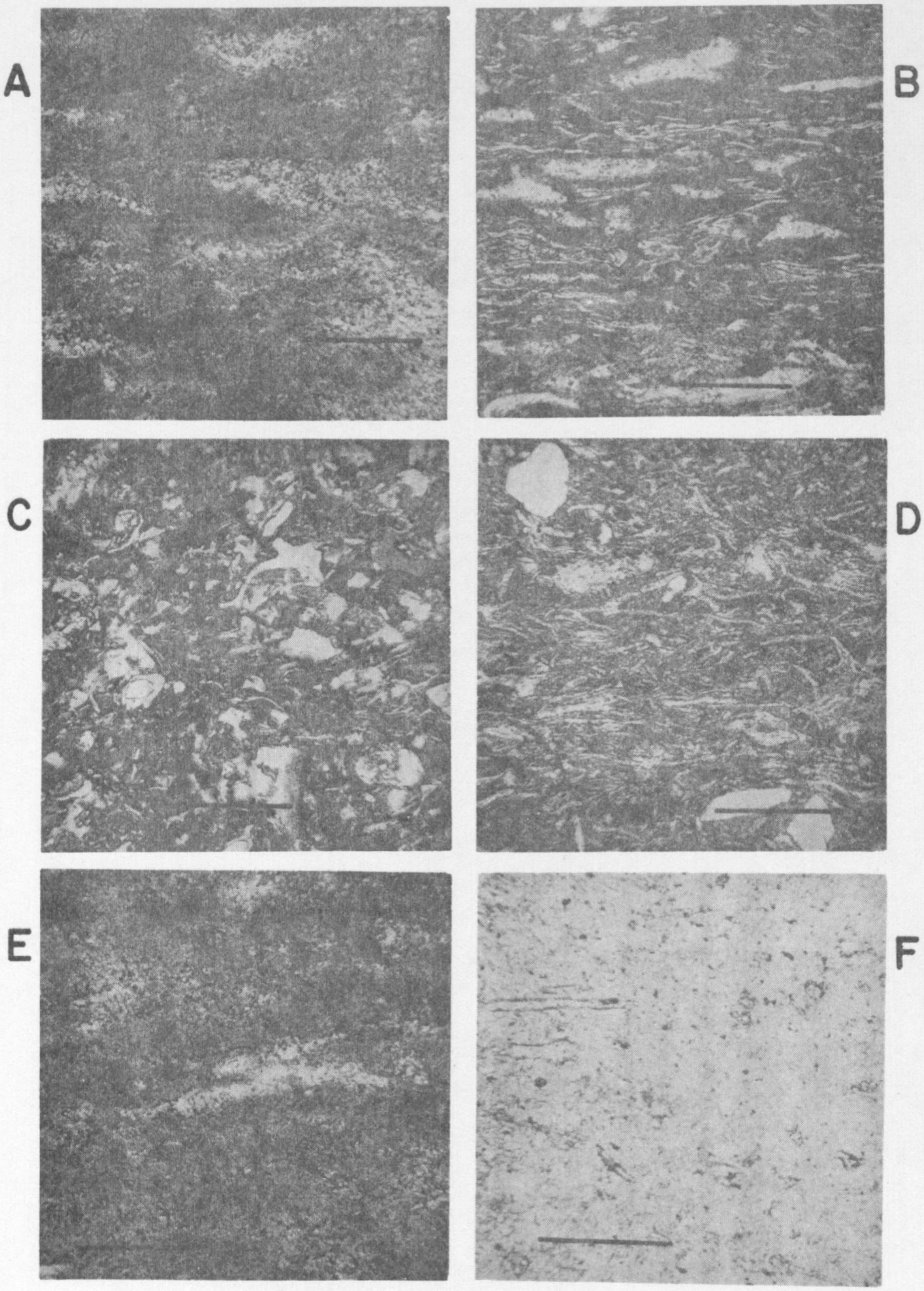
PHOTOMICROGRAPH B — Photo B displays the zone of partial welding in the lower cooling unit (Qh_1). Note that the shards are easily recongizable and only moderately deformed due to compaction under moderately high temperatures and are devitrified. Also note the elongate vugs which are the result of the vapor phase of the ash flow. These vapor phase vugs have been filled with feldspar crystals (vapor phase crystallization).

PHOTOMICROGRAPH C — Photo C displays the zone of no welding at the base of the upper cooling unit (Qh_2). Note the random orientation of the glass shards with little or no deformation. Triple junctions produced at the corners of adjacent gas bubbles are abundant. The shards in this photo are unaltered and vitric.

PHOTOMICROGRAPH D — Photo D displays a zone of partial welding near the base of the upper cooling unit (Qh_2). Note that the shards are easily recognizable and only moderately deformed and are devitrified.

PHOTOMICROGRAPH E — Photo E displays the zone of dense welding in the upper cooling unit (Qh_2). Note the extreme flattening and deformation of shards due to compaction under high temperatures. The shards in this photo are devitrified.

PHOTOMICROGRAPH F — Photo F displays the upper zone of partial welding in the upper cooling unit (Qh_2) of the Huckleberry Ridge Tuff. This photo represents the upper part of the tuff that has been weathered to clays. Note that the shard ghosts are only moderately deformed due to compaction under moderate temperatures.


A
B
C
D
E
F

partial welding that is approximately 25 meters thick. The zone of partial welding contains 1 to 2% sanidine phenocrysts averaging 1 mm across in a groundmass of devitrified shards that are slightly deformed. Also present are trace amounts of quartz and olivine phenocrysts. This zone of partial welding coincides with the vapor phase of the ash flow (Fig. 8, Photomicrograph B). Vesicles filled with minute feldspar crystals, that readily weather to clay when exposed to surface conditions, are associated with the vapor phase of this cooling unit.

Immediately above the zone of partial welding is a compacted ash bed that is ½ meter thick. The ash bed separates the lower cooling unit (Qh_1) from the upper (Qh_2). This vitric ash contains undeformed glass shards together with 2% sanidine and 1% quartz phenocrysts averaging 3 mm across (Fig. 8, Photomicrograph C). The presence of quartz phenocrysts indicates that the ash bed is related to the second eruptive pulse of the Huckleberry Ridge Tuff. Quartz phenocrysts are rare in the lower member but are relatively abundant in the second member of the tuff. The fact that the ash is unaltered and has not been removed by erosion is further evidence for association with the second member of the tuff.

Overlying the ash bed is the vitric chill zone of the upper cooling unit (Qh_2). The glass shards of this zone are moderately deformed and partially welded. This chill zone contains 2 to 3% sanidine phenocrysts up to 2 mm in diameter as well as trace amounts of quartz and olivine phenocrysts. The basal chill zone grades vertically into a 9 meter thick zone of partial welding in which the shards are devitrified and moderately deformed (Fig. 8, Photomicrograph D). This portion of the tuff contains 10 to 15% sanidine with 1% quartz phenocrysts all ranging up to 1.5 mm in diameter. The zone of partial welding grades upward into a zone of dense welding that has undergone devitrification (Fig. 8, Photomicrograph E). This 27 meter thick zone contains 10% sanidine phenocrysts at the base and increases vertically to 25% near the top. The phenocrysts of this zone range up to 4 mm in diameter. Quartz and olivine phenocrysts averaging 1% of the rock are also present in this zone. The zone of dense welding grades upward into a zone of partial welding that is devitrified and contains 15 to 30% sanidine, 5% quartz, and 1% olivine phenocrysts (Fig. 8, Photomicrograph F). The phenocrysts of the zone of partial welding average 3 mm in diameter. The upper portion of the zone has probably been removed by erosion and the 5 meters remaining are badly weathered.

The upper cooling unit of the Huckleberry Ridge Tuff as seen at this location is thinner (42m) than the lower cooling unit (100m). The upper unit has a zone of dense welding, which is thinner than that of the lower cooling unit, sandwiched between two zones of partial welding (Fig. 7). The lower unit has a very thick zone of dense welding with only a thin partially welded zone beneath (chill zone). This indicates a much higher emplacement temperature for the lower cooling unit.

The timing of the Huckleberry Ridge Tuff emplacement into the upper Centennial Valley was such that the lower member (Qh_1) was allowed to cool as a single simple cooling unit before being covered by the second member (Qh_2). The emplacement of the second unit followed soon enough after the first episode to prevent extensive erosion of the (Qh_1) surface. Potassium-argon dates of the upper and lower cooling units are identical within the resolution of the dating method (Appendix II, A and B).

The dimensions of the welding zones vary with depositional thickness of the tuff and distance from the source. The thickness of the Huckleberry Ridge Tuff can vary greatly over a short distance when deposited over uneven paleotopography. Stratigraphic sections at the type section (Christiansen and Blank, 1972), Elk Lake, Hidden Lake, Cliff Lake, Curlew Creek, and Wall Canyon display changes in the dimensions of the individual cooling units and welding zones within them (Fig. 9).

The Huckleberry Ridge Tuff can be traced discontinuously from the Yellowstone caldera region into the Centennial area and northward into the Upper Madison Valley where the tuff thins and eventually terminates (Figs. 9 & 11). The Huckleberry Ridge Tuff has been measured at over 300 meters in thickness in the vicinity of the Yellowstone caldera (Christiansen and Blank, 1972) and is present at Targhee Pass, Idaho, in thicknesses of up to 200 meters. The tuff is 123 meters thick to the west at Elk Lake and decreases in thickness northward to 91 meters at Hidden Lake, 86

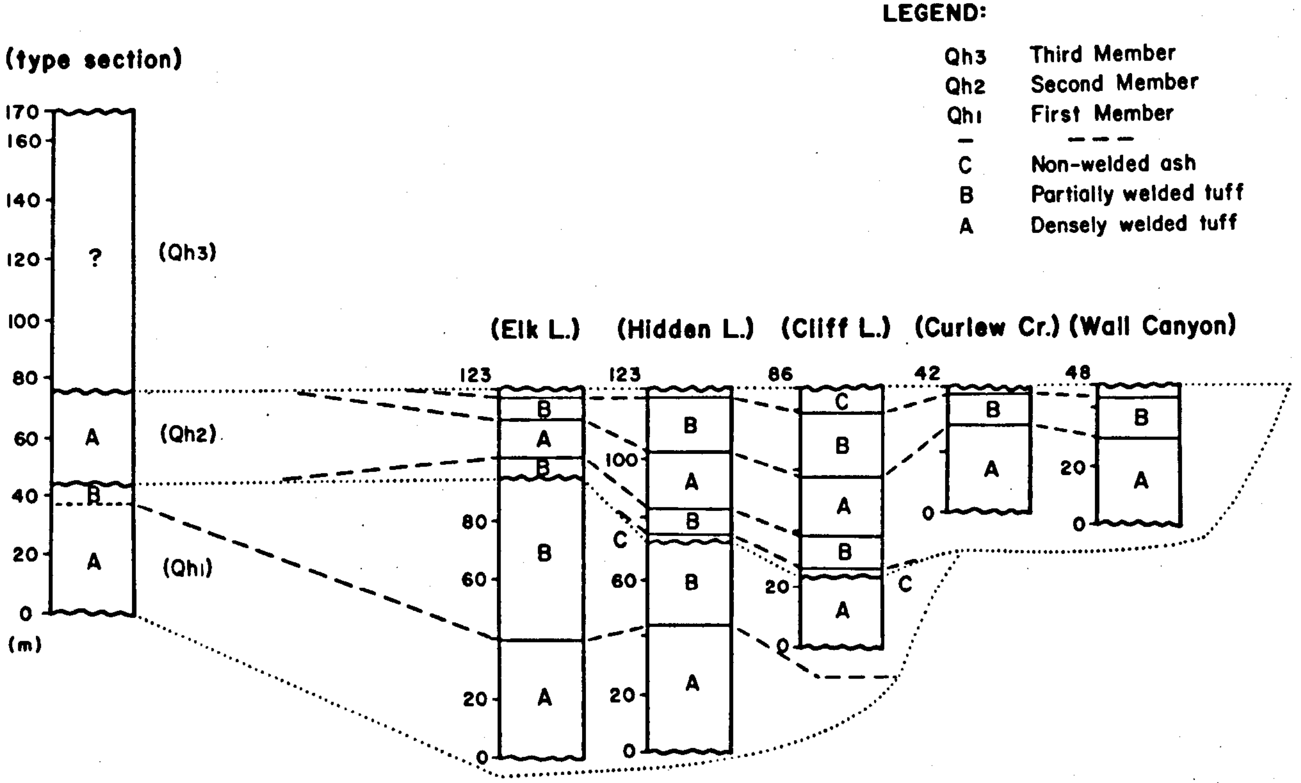


FIGURE 9. Stratigraphic correlation of the Huckleberry Ridge Tuff. Measured sections are located in Figure 10. Horizontal not to scale. (See Appendix I for lithologic descriptions of sections.)

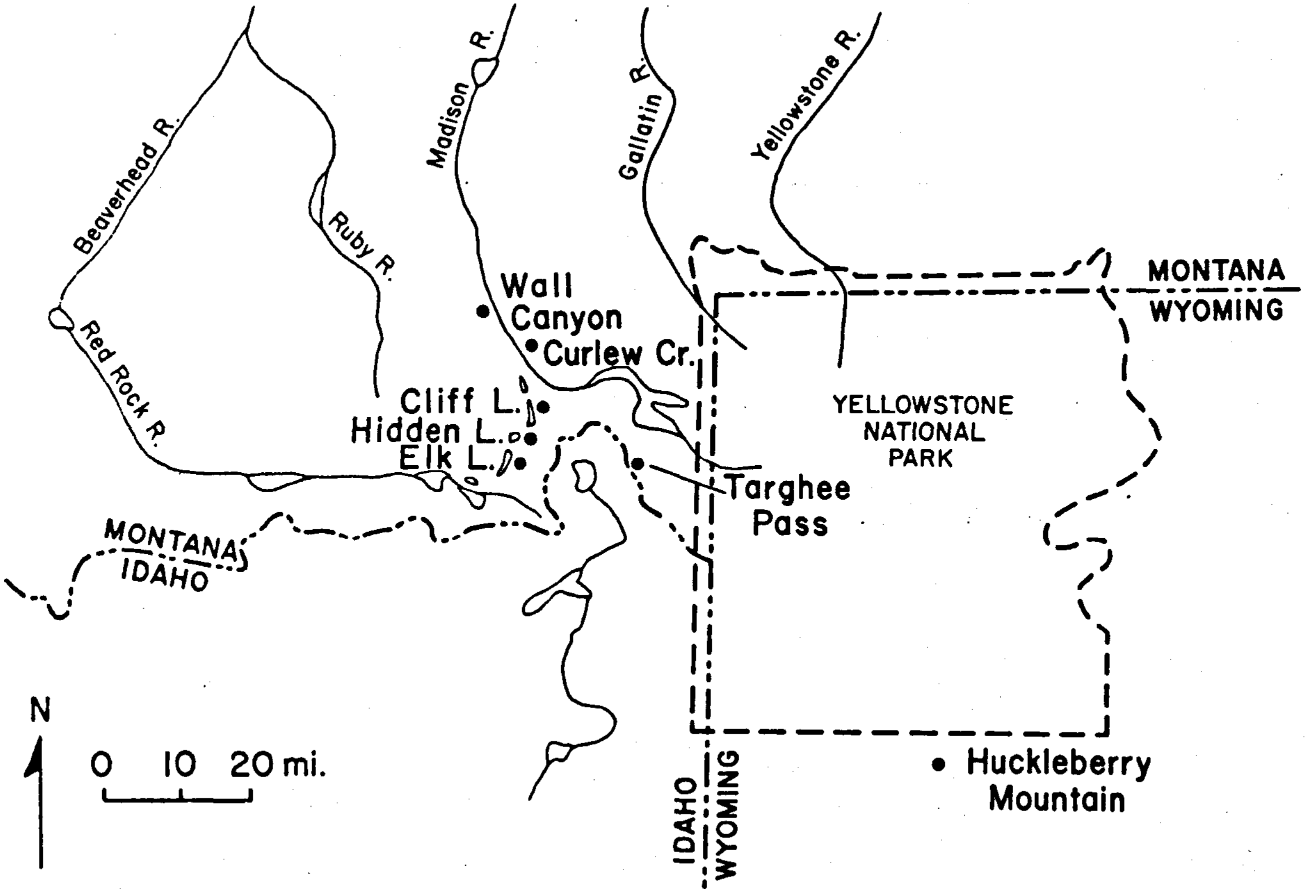


FIGURE 10. Measured section location map (see Figure 9).

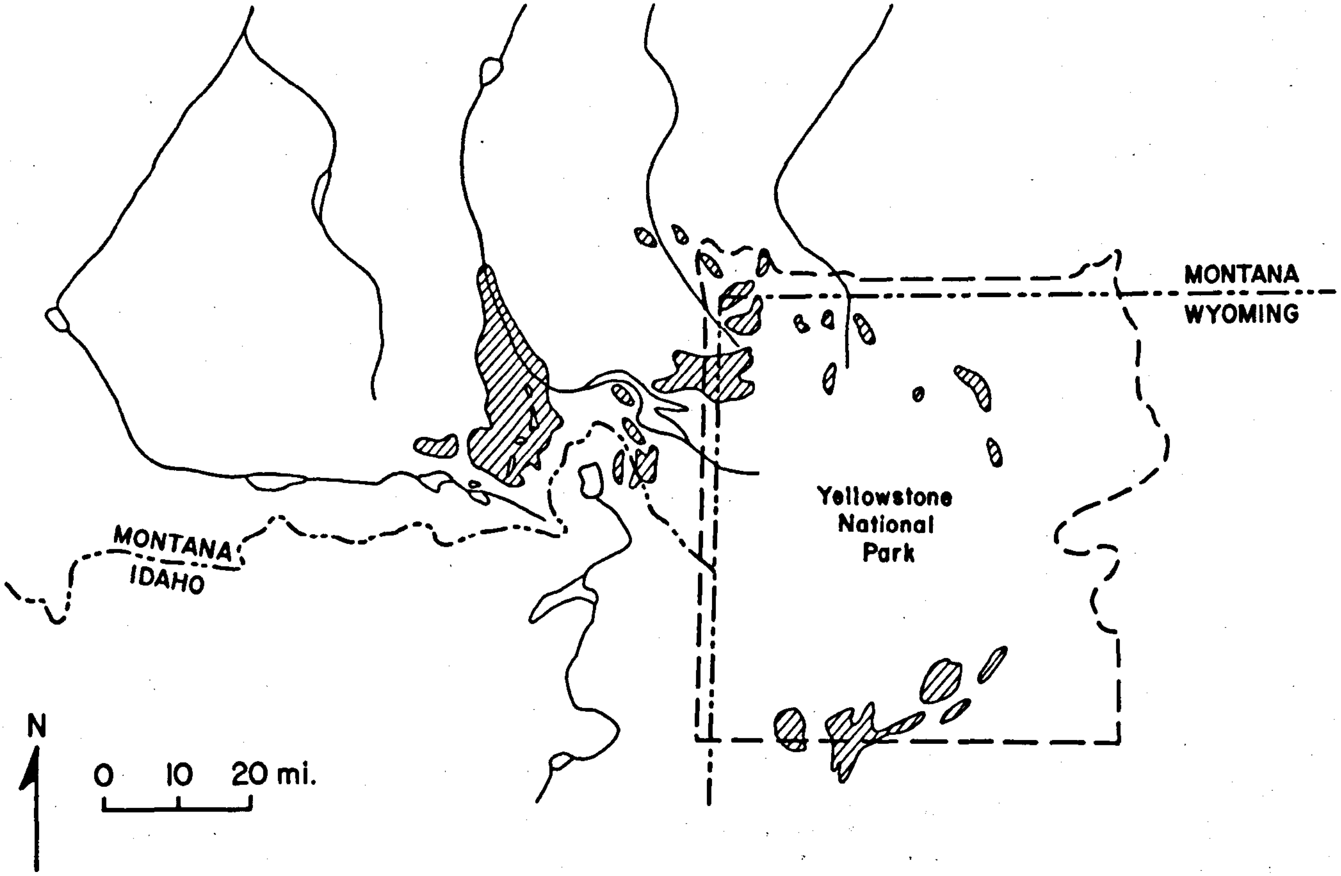


FIGURE 11. Regional distribution of the Huckleberry Ridge Tuff. Compiled from: Christiansen and Blank (1972), Witkind (1972 & 1976), Weinheimer (1979) and Sonderegger (Personal Communication 1980).

meters at Cliff Lake (Weinheimer, 1979), 48 meters at Wall Canyon (Weinheimer, 1979), and thins to zero near Ruby Creek in the Madison Valley (Appendix I).

The thinning of the tuff away from the Yellowstone caldera, the correlation of cooling units from the Yellowstone area to the Centennial region, and potassium-argon dates strongly support the theory that the tuff traveled into the Centennial Valley from the Yellowstone caldera and not from a local vent.

Pleistocene Mesa Falls Tuff — The Mesa Falls Tuff is the second formation of the Yellowstone Group (Christiansen and Blank, 1972). The tuff originated from the Island Park caldera 1.2 million years ago.

The Mesa Falls Tuff of the Centennial region is a single ash flow sheet. The tuff is brownish gray with phenocrysts of quartz and sanidine that comprise up to 45% of the rock situated in a groundmass of devitrified shards. Phenocrysts of quartz and sanidine range up to 5 mm in diameter. This tuff is seen only locally in the Centennial Valley.

Pleistocene Lava Creek Tuff — The Lava Creek Tuff is the youngest formation of the Yellowstone Group (Christiansen and Blank, 1972). The tuff originated from the

Yellowstone caldera 0.6 million years ago. The tuff is light gray, punky to dense, and has a fine-grained to aphanitic groundmass of devitrified shards. Phenocrysts of sanidine and quartz, averaging less than 1 mm across, make up 2 to 10% of the rock. Spherical vesicles mark the presence of a gas phase at the top of the ash flow sheet. The Lava Creek Tuff is present to the east of the Centennial Valley but is absent from the study area.

STRUCTURE

The prominent fault system along which the Centennial Range and Valley developed sharply cuts Laramide structures. The Centennial Range, like the Teton Range of Wyoming to the southeast, dips under the Snake River Plain and is probably, therefore, part of the Snake River structural system (Hamilton, 1960). The east-west trending structures of the Centennial area were probably activated as the Snake River downwarp, with associated volcanic activity, migrated eastward toward the Yellowstone-Island Park region in the late Pliocene-early Pleistocene (Hamilton, 1965).

The structure of the Northern flank of the upper Centennial Valley was determined and mapped by discerning offset of key strata of the ash flow sequence of the Huckleberry Ridge Tuff. During emplacement, ash flow tops generally assume even upper surfaces which display very low angles of dip away from the source (Ross and Smith, 1960). The Huckleberry Ridge Tuff is a composite sheet made up of two such ash flow units which are closely spaced in time but cooled individually. It is assumed, therefore, that the contact between the two flows should be nearly horizontal with only a very gentle dip away from the source. Displacement of the tuff should then be detectable as long as the contact between the two cooling units is identifiable.

The north side of the upper Centennial Valley is influenced by four major structures: The Madison, Cliff Lake, Gravelly, and Centennial faults (Fig. 12). The Madison, Cliff Lake, and Gravelly faults are post-Laramide tensional structures that approximately parallel the northwest and northeast trending Laramide compressional features. The Huckleberry Ridge Tuff forms benches that have been disturbed by movement along the four structures.

The Madison normal fault trends in a general north-northwest direction and is located to the east and northeast of the Centennial Valley. The Huckleberry Ridge Tuff benches east of the Elk-Hidden-Cliff-Wade lake chain are dipping from 3 to 5 degrees in an easterly direction into the Madison Fault which is down on the west.

The Elk-Hidden-Cliff-Wade lake chain is situated along a normal fault (the Cliff Lake Fault)(Fig. 12) that nearly parallels the Madison Fault. The Cliff Lake Fault has the same relative orientation as the Madison Fault in the vicinity of Elk Lake, being downdropped on the west (Fig. 13). The Huckleberry Ridge Tuff has been displaced a maximum of 122 meters (400 ft) along the Cliff Lake Fault at Elk Lake. The relative sense of displacement of the fault is reversed to the north at Cliff Lake where the east side

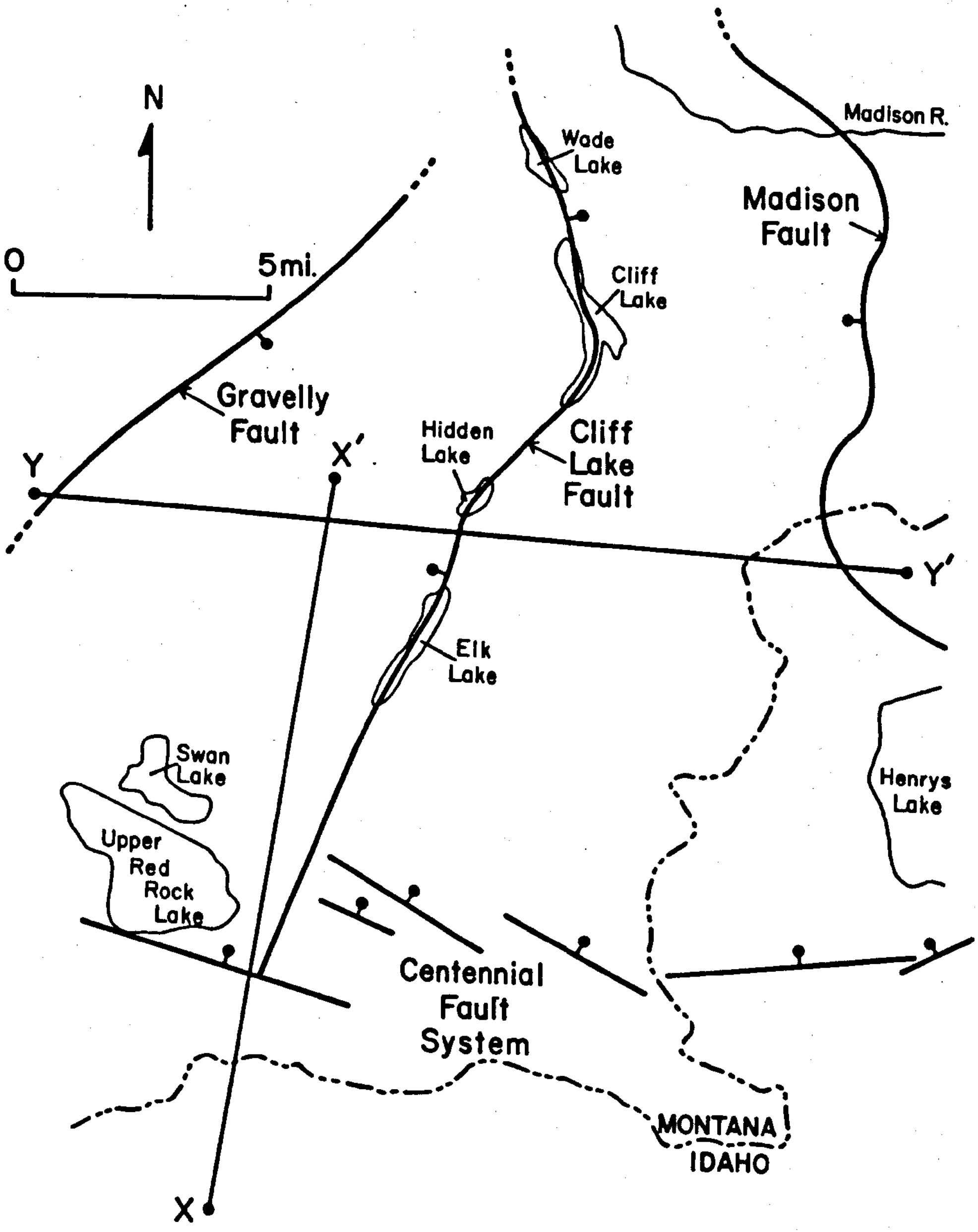


FIGURE 12. Cross-section location map. Also shows faults.

GENERAL EAST-WEST CROSS-SECTION OF THE CENTENNIAL VALLEY REGION

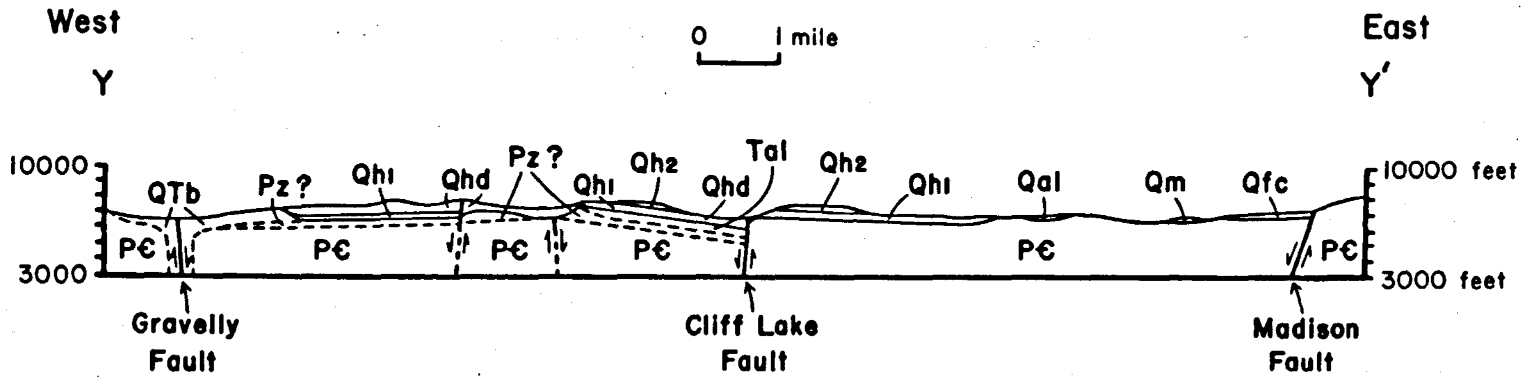


FIGURE 13. General east-west cross-section of the upper Centennial region. See cross-section Y-Y′ Figure 12 for location. Qal= Quaternary alluvium, Qfc= Coalesced alluvial fans, Qhd= Displaced Huckleberry Ridge Tuff, Qm= Mesa Falls Tuff, Qh_2= Huckleberry Ridge Tuff (upper Cooling unit), Qh_1= Huckleberry Ridge Tuff (lower cooling unit), QTb= Basalt, Pz= Paleozoic rocks, PЄ= Precambrian rocks.

of the fault is down approximately 99 meters (325 ft) (Weinheimer, 1979)(Fig. 14). The Cliff Lake Fault is, therefore, a scissor fault with its hinge located near the southern extreme of Cliff Lake. A Pleistocene basalt located just south of Elk Lake appears to have come up through the crustal weakness generated by movement along the Cliff Lake Fault, indicating that the fault existed at the beginning of or possibly prior to Pleistocene time. The Cliff Lake Fault is probably equivalent to the Odell Creek Fault (Fig. 14) of Honkala (1960) which trends north and cuts the Centennial Range southwest of Upper Red Rock Lake. The Odell Creek Fault is down on the west as was the Cliff Lake Fault before later rotation.

The Gravelly Range Front Fault has been mapped along the West Fork of the Madison River just north of the Upper Red Rock Lake Quadrangle (Weinheimer, 1979). This fault probably extends southward into the Centennial Valley. Evidence for displacement along the fault in the study area is weak. Late Tertiary-early Quaternary and Pleistocene volcanics are in contact with Precambrian rocks along the proposed fault zone. This contact may be depositional or faulted with basalt localized along the fault. The genetic nature of this contact is questionable because of a lack of

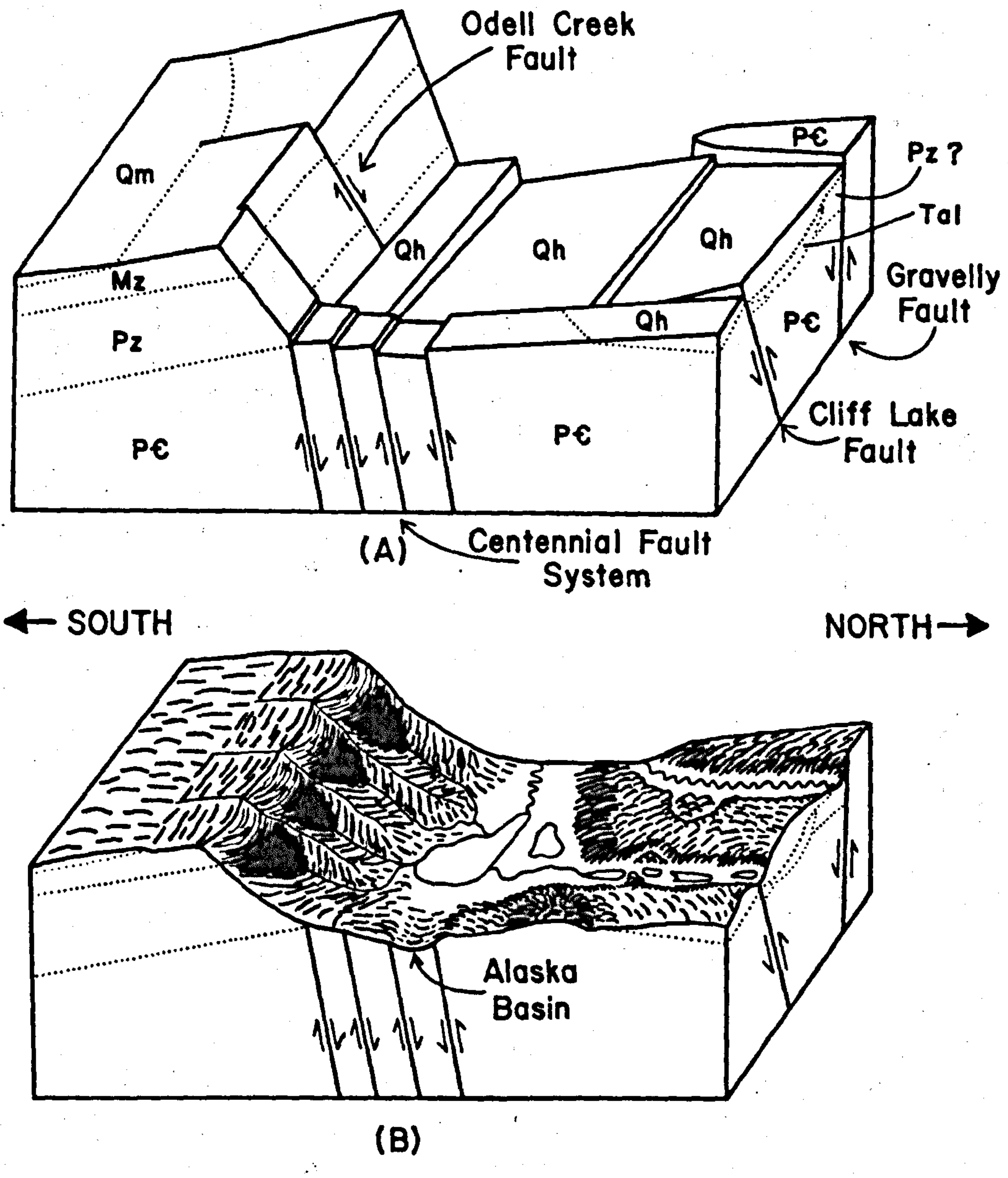


FIGURE 14. (A) Structural block diagram of the upper Centennial Valley, Montana.
(B) Structural block diagram displaying present topography of the upper Centennial Valley, Montana (same area as A).

outcrop of volcanic rock (seen only as float along contact zone).

The Centennial Range Front Fault is a normal fault that trends east-west and is downthrown on the north forming the Centennial Valley (Honkala, 1960). The upthrown Centennial Range is situated to the south. The Huckleberry Ridge Tuff bench along the northern flank of the upper Centennial Valley is fractured into blocks that have an average dip of 3 to 4 degrees to the south into the Centennial Fault (Fig. 15). Portions of the bench also dip locally into the Cliff Lake and Gravelly faults (Fig. 18). The area to the west of Elk and Hidden lakes appears to be a half graben that has been dropped into the Centennial Fault along the Cliff Lake and Gravelly faults. The Paleozoic and Mesozoic sections may be preserved at least in part in the half graben beneath the Huckleberry Ridge Tuff (Figs. 13 & 15). The Centennial Fault is not a single clean break but rather a series of step faults creating a number of blocks beneath the valley floor (Schofield, Personal Communication, 1980). Alaska Basin (Fig. 14) in the easternmost extreme of the Centennial Valley is probably a downdropped block resulting from this phenomenon. The rate of movement along the Centennial Fault appears to have increased since Pinedale time.

GENERAL NORTH-SOUTH CROSS-SECTION OF THE
UPPER CENTENNIAL VALLEY

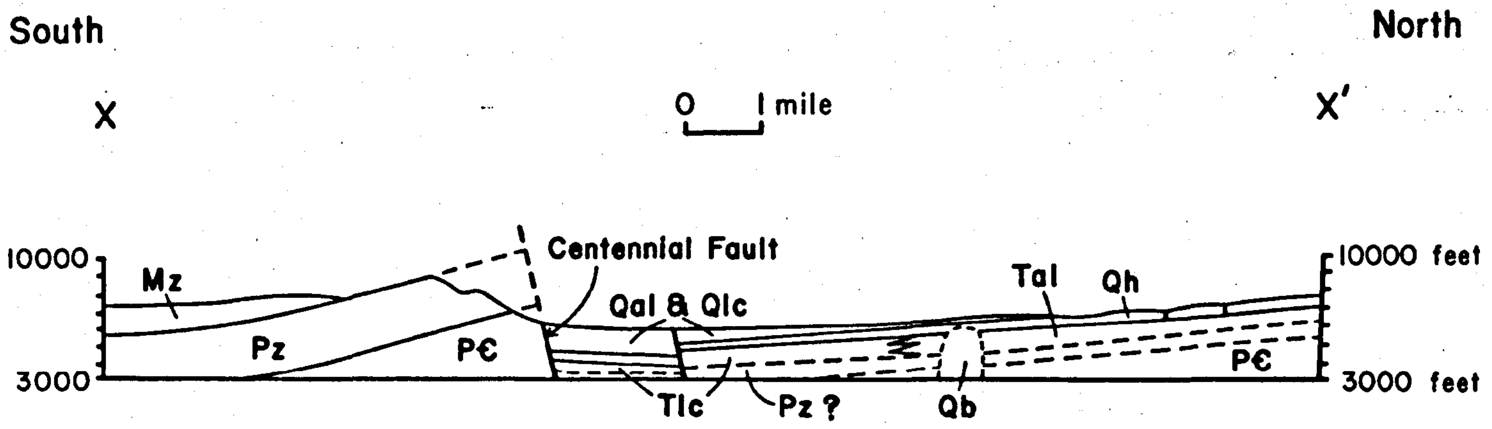


FIGURE 15. General north-south cross-section of the upper Centennial Valley. See cross-section X-X´ Figure 12 for location. Qal= Quaternary alluvium, Qlc= Lacustrine deposits, Qh= Huckleberry Ridge Tuff, Qb= Pleistocene basalt, Tal= Tertiary alluvium, Tlc= Lacustrine deposits, Mz= Mesozoic rocks, Pz= Paleozoic rocks, PЄ= Precambrian rocks.

The average rate of post-Huckleberry Ridge Tuff movement, measured by visually returning the southward dipping bench of Huckleberry Ridge Tuff in the upper Centennial Valley to horizontal, is 0.10 centimeter per year (0.04 in/yr). A post-Pinedale rate of 3.05 centimeters per year (1.2 in/yr) was measured using the offset of a line of hanging glacial valleys of Pinedale age. The line of hanging glacial valleys is present on the scarp slope of the Centennial Range just south of Upper Red Rock Lake (Fig. 16). This uniform line is situated approximately 396 meters (1300 ft) above the valley floor (Fig. 17) and stands above what has been mapped as Pinedale moraine at the foot of the range (Witkind, 1976). The east-trending Centennial Range has been dissected by north-trending faults breaking the range into blocks (Honkala, 1960). Glacial valleys terminate at different elevations from one block of the range to another. This relationship, together with a lack of piedmont glacial deposits and the presence of triangular faceting up to the cirques, indicates at least 396 meters (1300 ft) of post-Pinedale displacement and thus a rate of 3.05 centimeters per year (1.2 in/yr).

Siesmic studies (Bailey, 1977 and Trimble and Smith, 1975) have demonstrated that the Centennial, the Cliff Lake,

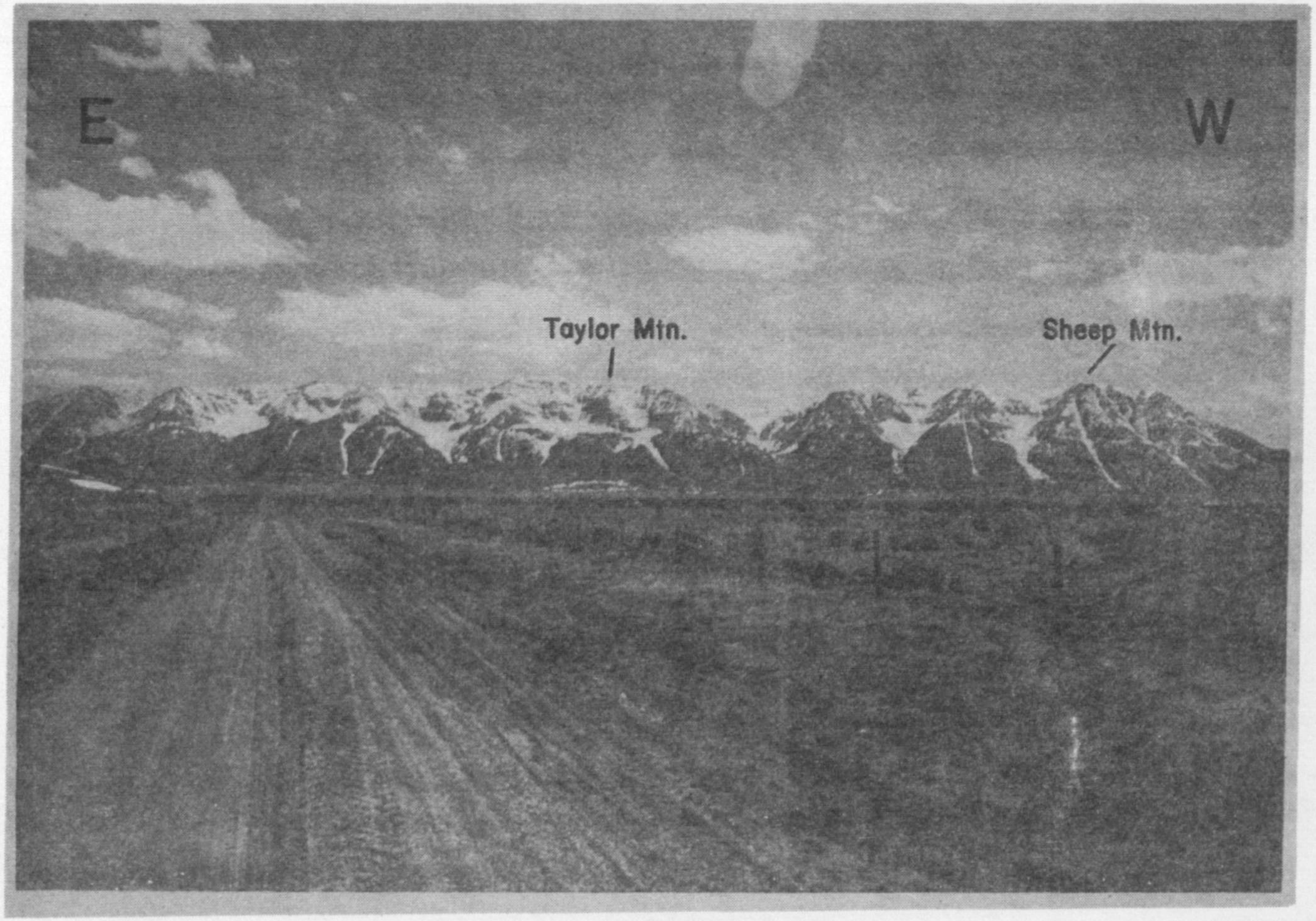


FIGURE 16. North slope of the Centennial Range along the upper Centennial Valley, Montana. Note the line of hanging glacial valleys.

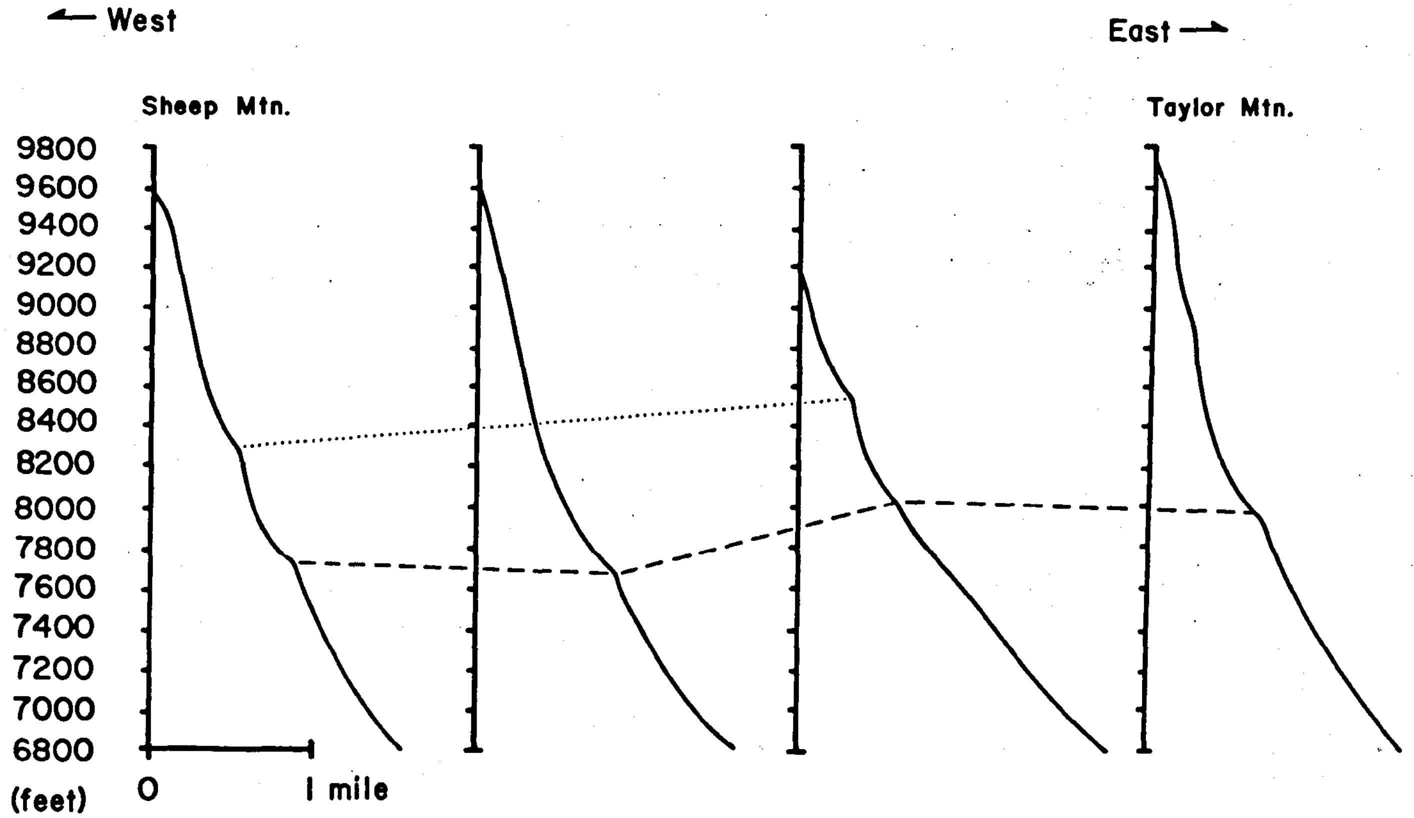


FIGURE 17A. Topographic profile displaying level of hanging glacial valleys from Sheep Mountain east to Taylor Mountain, upper Centennial Valley, Montana.

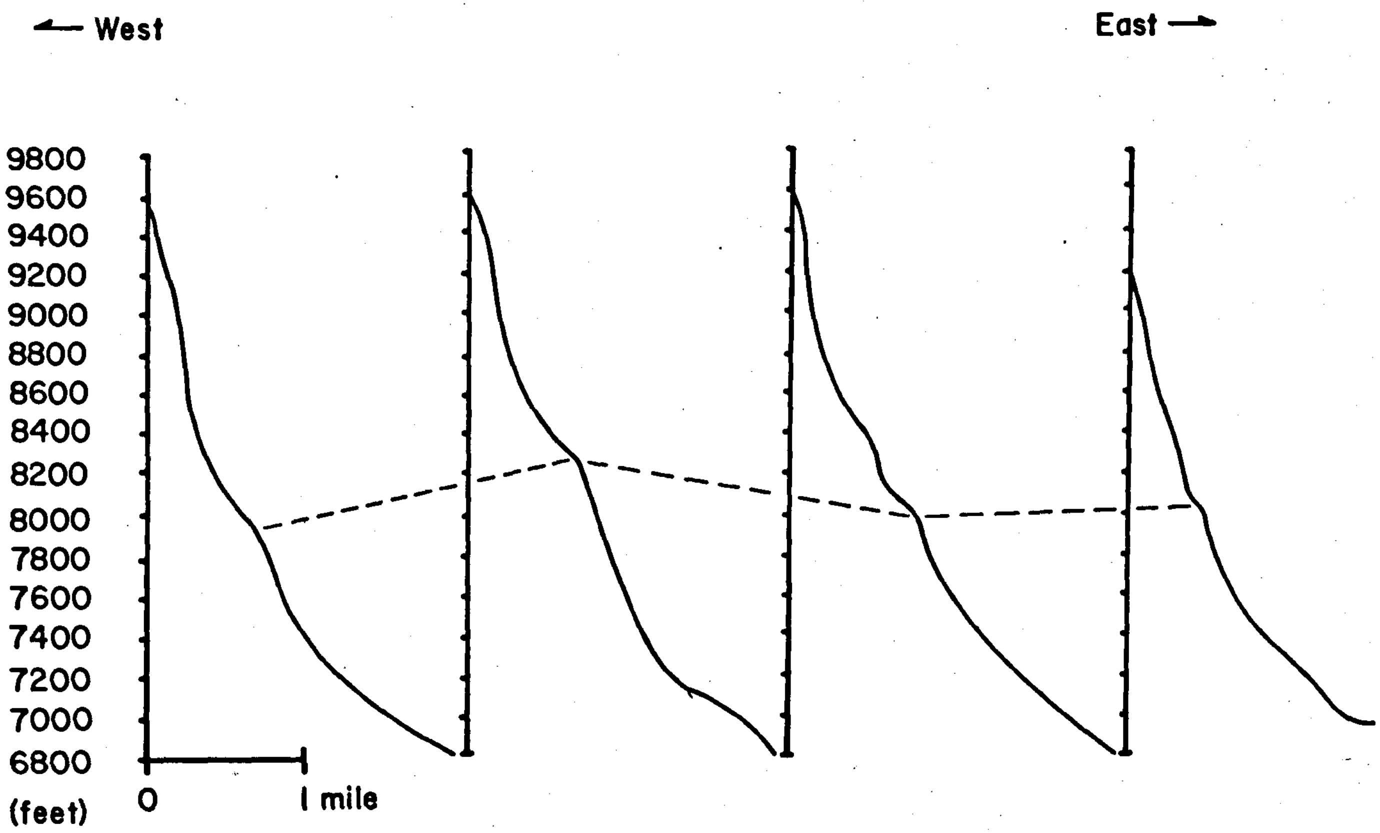


FIGURE 17B. Topographic profile displaying levels of hanging glacial valleys below unnamed peaks east of Taylor Mountain, upper Centennial Valley, Montana.

and the southern part of the Madison faults are active today.

In addition to these major structures, many minor faults have developed in response to stresses created by movement along the east-trending Centennial Fault and the generally north-trending Cliff Lake, Gravelly, and Madison faults (Fig. 18). The numerous minor faults of the upper Centennial Valley generally have total offsets of less than 100 feet.

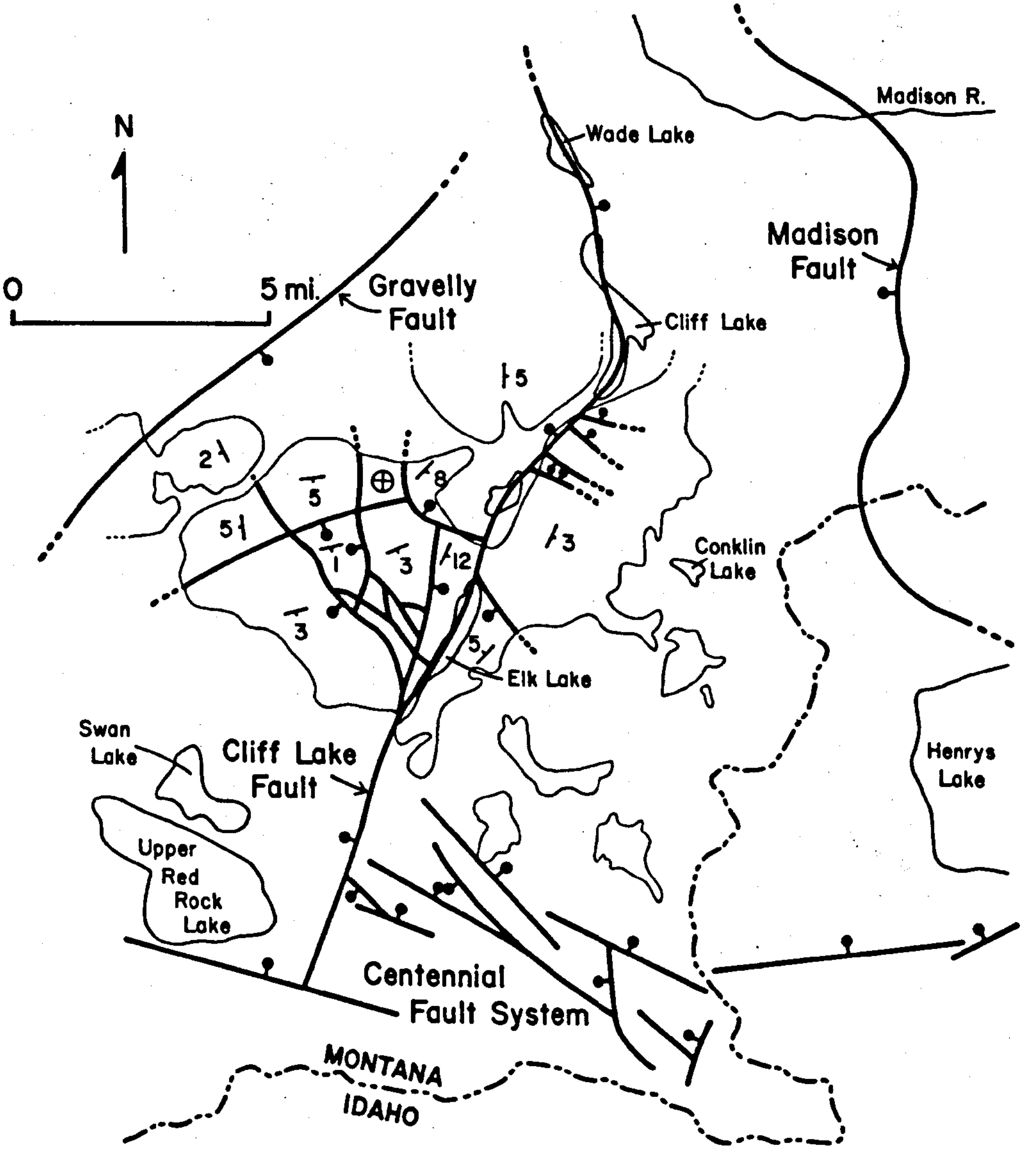


FIGURE 18. Structure map of the Qh_1 top, upper Centennial Valley and vicinity.

GEOMORPHOLOGY

The Huckleberry Ridge Tuff forms flat benches that rise up to 8200 feet in elevation and are vegetated with grasses and sage brush. These benches are dipping gently into the Centennial, Madison, Cliff Lake, and Gravelly faults forming gentle slopes on the dip sides and vertical cliffs on the scarp sides (Fig. 19). Large scale mass wasting occurs along the Huckleberry Ridge Tuff cliffs where large sections of welded tuff separate from the cliff and pile up at the base creating a hummocky topography that is generally vegetated with Lodgepole pine, spruce, and Douglas fir.

The geometry of the Huckleberry Ridge Tuff along the northern flank of the upper Centennial Valley is such that the thickest portion of the tuff forms a crude north-south trending axis (Fig. 20). The tuff thins to either side of this axis. The axis coincides with the modern day Madison River to the north and appears to be the result of the filling of an ancestral Madison River drainage that was cut into the upper Centennial half graben. It appears that this river flowed southward into a large lake occupying the Centennial Valley area. This lake has been recorded by the presence of freshwater limestone in the valley. Gravity data by Schofield (Personal Communication, 1980) indicates the presence of approximately 305 to 610 meters (1000 to 2000 ft) of alluvial gravels beneath the tuff. The gravels thicken to the south toward the Centennial Valley and to the west along the valley. These data together with the geometry of the tuff (Figs. 20 & 21) indicate that the Pliocene Madison River flowed in a direction opposite to that of the present Madison River. In addition to the ancestral Madison River, it appears that another drainage flowing westward along the Centennial Fault east of the Centennial Valley entered the valley near what is now the Alaska Basin (Fig. 21). Judging from the pre-2.0 million year old paleotopography (Fig. 21) and the distribution of the Huckleberry Ridge Tuff (Fig. 11), it appears that the Huckleberry Ridge ash flow gained access into the Centennial Valley along this drainage.

Glacial deposits are absent on the tuff benches along the north side of the Centennial Valley. Glacial deposits of pre-Bull Lake time are present on top of the Huckleberry Ridge and Mesa Falls tuffs northeast of the study area in the Madison Valley (Weinheimer, 1979). Here, Bull Lake glaciers advanced several kilometers from the high valleys along the Madison Range into the Madison Valley. Pinedale glaciers extended approximately equal distances into the

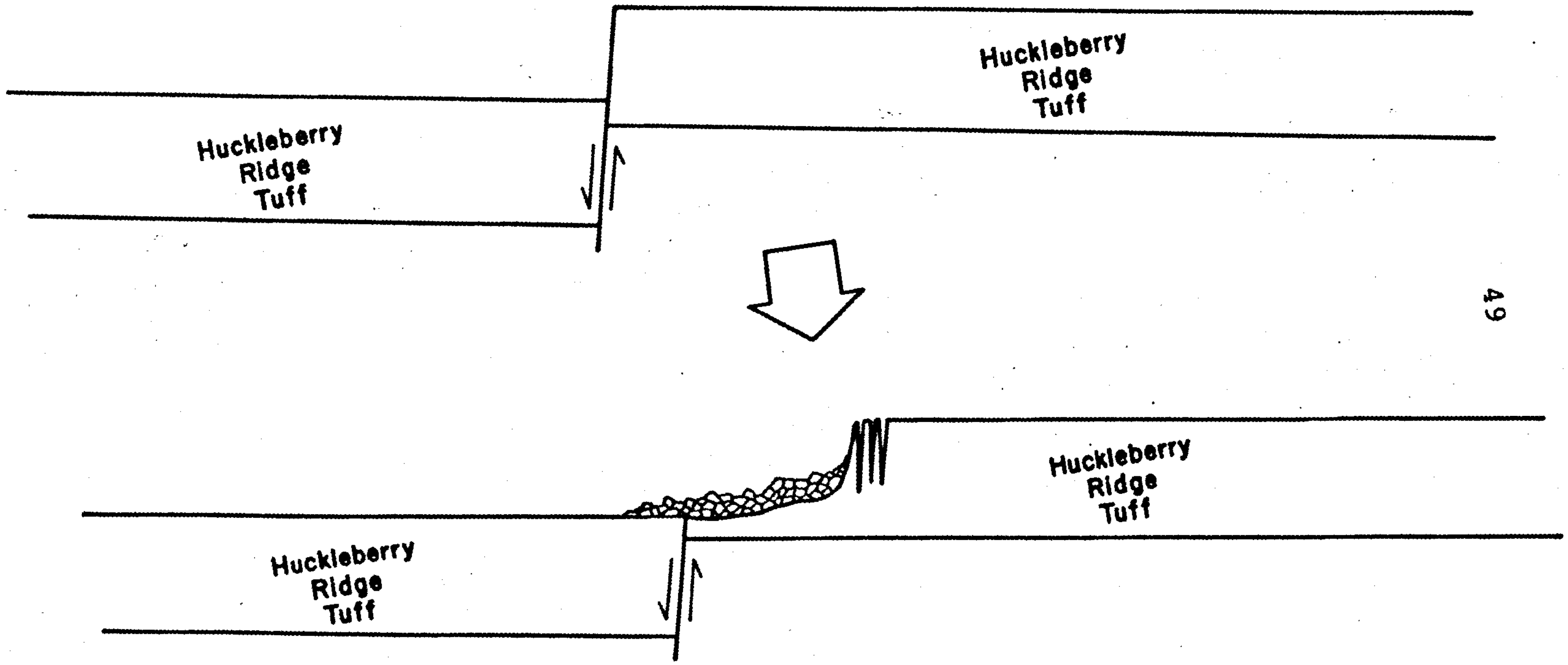


FIGURE 19. Formation of dip slopes and the mechanism of mass wasting along scarp slopes of the Huckleberry Ridge Tuff benches.

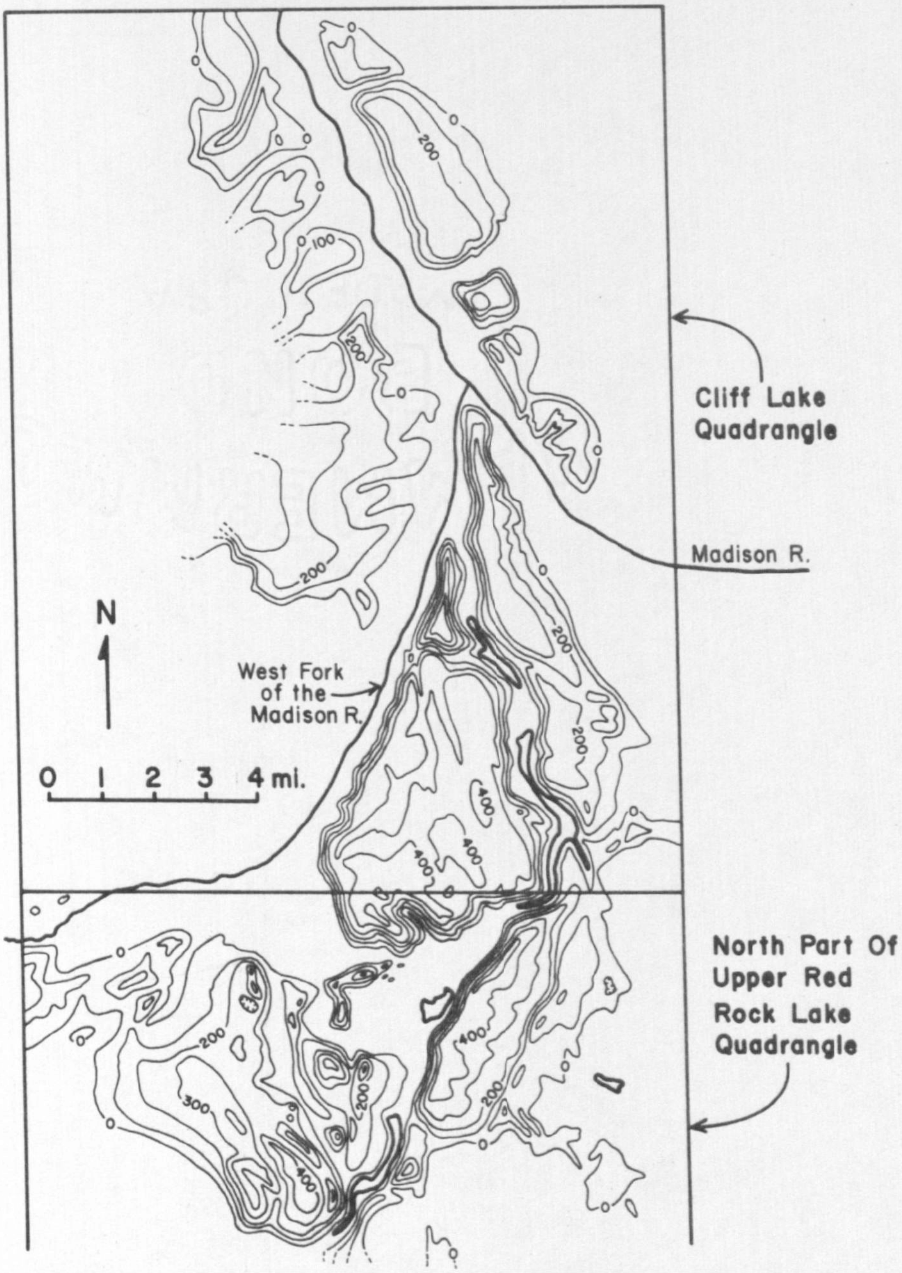


FIGURE 20. Isopach map of the 2.0 m.y. old Huckleberry Ridge Tuff. Contour interval is 100 feet.

Madison Valley. Pre-Bull Lake deposits are the most prominent glacial deposits found in the Gravelly Range north of the study area (Hadley, 1960). The Pinedale moraines of the Gravelly region are small and confined to the upper parts of glacial valleys.

The only evidence of glaciation in the Centennial area is found along the Centennial Mountain Range (Witkind, 1972 and 1976). Pinedale moraines are present at the base of the range just south of Upper Red Rock Lake and east and west along the Centennial Range. Bull Lake and pre-Bull Lake deposits are widely scattered east of the Cliff Lake Fault trace on the northern slope of the Centennial Range and Red Rock Pass but are absent along the range adjacent to the upper Centennial Valley (Witkind, 1976).

Well-rounded 10 to 20 cm cobbles are present as scattered patches at various locations along the north side of the upper Centennial Valley (Plate 1). These deposits appear as a thin veneer usually only a single cobble thick and are most common on top of the Huckleberry Ridge Tuff benches at elevations of up to 8200 feet to the west of the Cliff Lake Fault. Most of the cobbles are white to dark gray quartzite; however, basalt cobbles are also present. The source area for these cobbles is probably the Gravelly

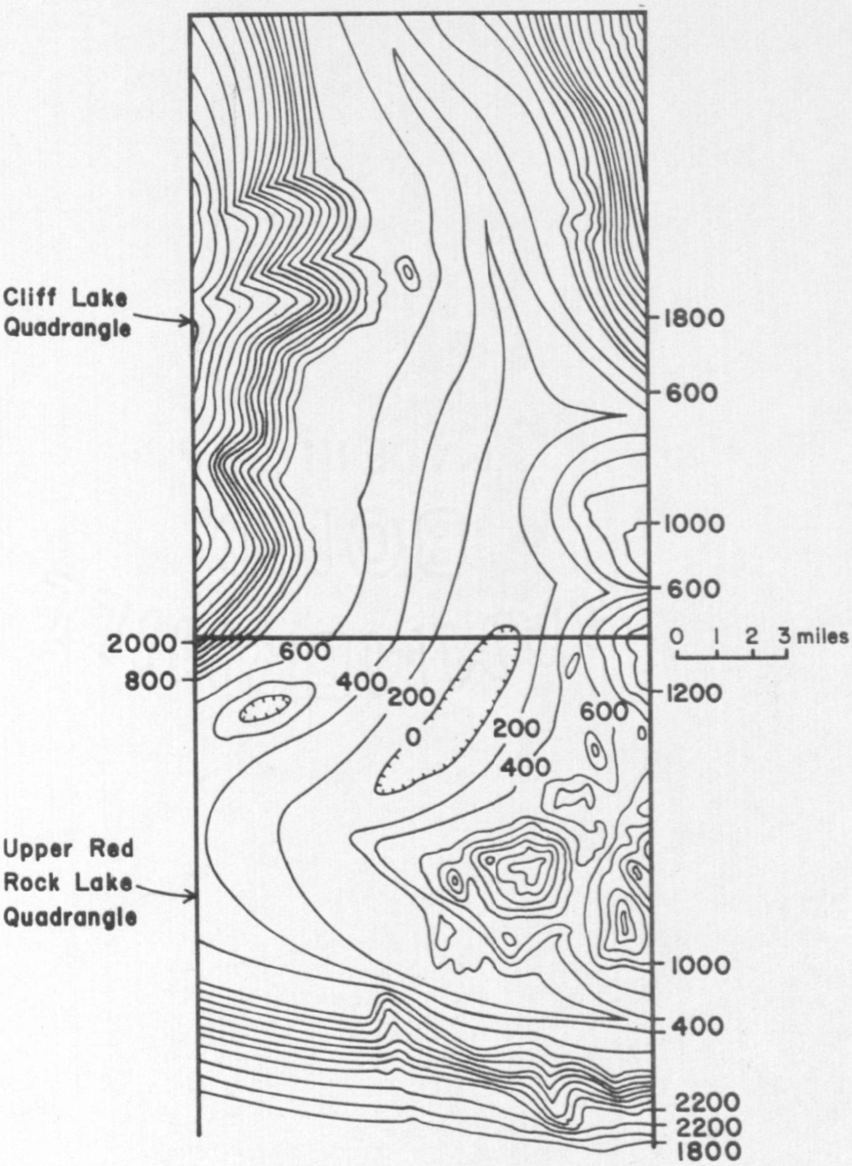


FIGURE 21. 2.0 m.y. old paleotopography of the Upper Red Rock Lake and Cliff Lake quadrangles. Contour interval is 200 feet. Cliff Lake Quadrangle data is modified from Weinheimer (1979). The paleotopography was derived using an arbitrary datum (0 elevation) from relative thicknesses of the Huckleberry Ridge Tuff accounting for post tuff structure.

Range, approximately 6 km to the northwest. These deposits are interpreted as sheet-wash deposits shed off the Gravelly Range and laid down over a late Pleistocene-Holocene Huckleberry Ridge Tuff surface. The sheet-wash deposits could not have been transported across the West Fork of the Madison River Valley which now separates the deposits from the probable source. This indicates that the West Fork of the Madison River did not exist at the time of sheet-wash deposition.

The drainage systems of the north side of the upper Centennial Valley are directly related to the Quaternary structure of the region. Streams cutting the Huckleberry Ridge Tuff benches form a crude rectangular drainage pattern. These benches have been dissected by small intermittent streams (subsequent streams) which follow fault traces. One of the larger recent subsequent streams occupied a trench along the Cliff Lake Fault. This small river probably drained the Centennial Valley which was at the time occupied by a glacial lake (Witkind, 1976). The steady decrease in elevation from Elk to Wade Lake is evidence for a northward flow of the drainage. The stream was dammed by the slumping of tuff from the Huckleberry Ridge Tuff benches that rimmed the trench as the glacial lake receded. The recession of the glacial lake has been recorded as old beach lines seen to the south of Upper Red Rock Lake (McMannis and Honkala, 1960). The damming of the river created Elk, Hidden, Goose, Otter, Cliff, and Wade lakes.

PRECENOZOIC GEOLOGIC HISTORY

The Centennial region is located in the Basement Province of Montana (McMannis, 1965). The Centennial portion of this province is characterized by extensive exposures of pre-Belt metasedimentary, metamorphic, and igneous rocks of Precambrian X age. The province is also characterized by an absence of Belt strata and a relatively thin Paleozoic and Mesozoic sequence.

Precambrian

The pre-Belt basement of southwestern Montana has a dominant northeast-striking structural grain in rocks displaying several metamorphic events ranging from 1,500 to 2,700 million years in age (McMannis, 1965).

The area just north of the Centennial Valley, in the vicinity of the Gravelly Range, was the site of a northeast-trending sediment collecting geosyncline during Precambrian time (Mann, 1960). This trough, termed the Cherry Creek geosyncline, was deformed in the late Precambrian by compressional forces to form a positive topographic element extending from near Dillon toward the northeast. This highland (the Cherry Creek landmass) extended southward into the Centennial region and served as a source for sediments shed to the north and west during Belt time. This landmass underwent erosion through the late Precambrian and was bevelled at the close of early Cambrian time.

Paleozoic

Southwestern Montana underwent several episodes of subsidence and upwarping throughout the Paleozoic Era. The Centennial region was covered by intermittent Paleozoic seas from which a relatively thin blanket of sediments was received.

The Cambrian and Ordovician were times of generally stable tectonic conditions in this region. A positive arch onto which Cambrian, Ordovician, Silurian, and Devonian seas lapped and sediments thinned existed in extreme southwestern Montana just west of the Centennial Valley (McMannis, 1965). The main Cordilleran seaway of the Cambrian and Ordovician was located to the west of the Montana-Idaho border. Uplift along the Montana-Idaho border in southwesternmost Montana during the late Ordovician caused a retreat of the sea.

Silurian seas probably covered the Centennial region resulting in the deposition of marine sediments. Silurian and early Devonian sediments are, however, absent in the Centennial region due to early Devonian upwarping and subsequent erosion (Mallory and others, 1972).

The region was again covered by seas from the late

Devonian into the Mississippian. A northeast-trending negative feature had developed in southwesternmost Montana just west of the Centennial Valley during this time. Mississippian sediments thicken westward from the Centennial region toward this feature. The Mississippian trough may have been a principal route connecting the central Montana seas with those of the major geosyncline to the west and southwest during Big Snowy time (McMannis, 1965).

A period of erosion occurred prior to the deposition of Pennsylvanian strata in the region. The Pennsylvanian and Permian marine sediments, which are separated by a disconformity, thicken westward from the Centennial region toward the main geosyncline in Idaho.

Mesozoic

The early Triassic of southwestern Montana was marked by the transgression of a sea from which silty limestones were deposited. Reddish and brownish sediments were laid down later in the Triassic as the sea regressed creating restricted marine and littoral environments in the Centennial region.

Marine sediments were deposited unconformably in the Centennial region during the early Jurassic. These sediments thinned to the northeast onto a large island located in the vicinity of the present-day Snowcrest and Gravelly ranges (McMannis, 1965). In the late Jurassic the western seaway, along which the earlier seas had advanced into the area, was destroyed. Increasing tectonism in an area west of Montana produced a flood of debris that was carried eastward into southwestern Montana. This event produced the nonmarine Morrison sequence. This sequence thickened westward across the Centennial region (McMannis, 1965).

Following a period of erosion, deposits of the Cretaceous seas were laid down over bevelled edges of the Jurassic, producing angular relationships between the Jurassic and Cretaceous of the area (Mann, 1960). The early Cretaceous miogeosynclinal region of southwestern Montana and Idaho became emergent and began to shed sediments to the east to form the nonmarine Kootenai Formation. The Kootenai overlies the Jurassic unconformably and thickens west of the Centennial region. By late Cretaceous time, sharp orogenic uplift was occurring. This orogenic activity (Laramide) continued through the early Eocene. Volcanism in the southwestern part of Montana and the intrusion of granitic plutons north of the Centennial region accompanied the Laramide deformation. Strong east-west compressional forces created a complicated zone of thrust faulting and folding in the Gravelly Range at the same time that imbricate thrusts were formed along belts in northwestern Montana (Mann, 1960). The Snowcrest and Gravelly ranges rose on the west and east limbs of this feature respectively (Mann, 1960). This fold system extends eastward to the Madison Valley anticline.

CENOZOIC GEOLOGIC HISTORY

Paleocene

Laramide deformation continued into the early Tertiary. Thrusting and folding of the Blacktail and Greenhorn uplifts occurred as extensions of the Bighorn uplift. This activity west and northwest of the Centennial region resulted in the deposition of the Beaverhead Formation (Eardley, 1960, and Honkala, 1960). The Beaverhead conglomerate was derived from Paleozoic limestones and quartzitic sandstones.

Eocene

The Eocene was a time of uplift, volcanism, and erosion in southwestern Montana. Laramide deformation continued into the early Eocene; the Beaverhead Formation was cut by a thrust fault west of the study area (Honkala, 1960). Early Eocene deformation resulted in two systems of folds and thrust faults, one trending northeast and a later system trending northwest (Eardley, 1960). The Madison thrusts and folds to the northeast and the broad gentle arch of the ancestral Teton Range southeast of the Centennial area originated during this time. Compressional deformation ceased before middle Eocene time in the region (McMannis, 1965, and Mann, 1960). Volcanism followed Laramide deformation in the middle Eocene with the Gallatin, Absaroka, and

Yellowstone volcanic fields beginning to form east of the study area (Eardley, 1960).

Oligocene

The early Oligocene was a time of erosion and volcanism. Andesitic volcanism reached a climax during the late eocene-early Oligocene east of the Centennial region in the southern portion of the Absaroka Range (Chadwick, 1970). Late Eocene-early Oligocene rhyolites were extruded to the northwest near Dillon (Beaverhead volcanic field) and basaltic volcanism occurred near Virginia City north of the Centennial region during early Oligocene time (Chadwick, 1978).

The Snake River Basin appears to have begun to form in the Oligocene. The Snake River Plain is thought to be a continental tensional rift feature. Two mechanisms have been proposed for the formation of this structure. One theory is that the Snake River Plain with associated volcanic rocks is the result of the movement of the North American plate across a mantle plume or hot spot (Morgan, 1972). The other theory deals with the drifting northward of the Idaho Batholith (Hamilton and Meyers, 1966). The latter theory is presently more widely accepted. This theory concerns an ever widening rift, floored with basaltic rock.

The rift appears to be oldest to the west and becomes younger to the east where it terminates with the Island Park and Yellowstone calderas (present apex of rift).

Miocene

Erosion and volcanism dominated the Miocene history of southwestern Montana. The Black Butte basalt was extruded in the Gravelly Range north of the Centennial Valley during late Oligocene-early Miocene time. Snake River Plain downwarping and volcanism was probably active southwest of the Centennial region at this time. The Snake River activity does not, however, appear to have influenced the Centennial region during the Miocene.

Pliocene

Block faulting of the Madison Range began in Pliocene time (Eardley, 1960). The north-trending Madison Range Front Fault cut Laramide structures at a 60 degree angle; other faults such as the Gravelly Range Front and Cliff Lake faults broke parallel to the previously established Laramide structures.

The Snake River Plain structure had migrated far enough to the east by late Pliocene time to begin to influence the Centennial and Teton regions (Fig. 2)(Hamilton, 1965). The

Centennial and Teton range front faults were probably created at this time. Assuming the rift theory to be true, the tensional forces would have created crustal thinning and downwarping in the Snake River Plain region followed by faulting and volcanism. As the rift migrated (opened) eastward, the southern flank of the Centennial and northwestern flank of the Teton ranges began to dip into the downwarp. As these blocks continued to tilt into the downwarp during late Pliocene-early Pleistocene time, the uplifted edges broke to form range front faults which now mark the north side of the Centennial Range and southeast side of the Teton Range. Offset along the Teton Fault is approximately twice that of the Centennial Fault. This difference appears to be the result of the orientation of the faults. The Centennial Fault cut across preexisting Laramide structures while the Teton Fault was enhanced by cutting along them (Love, 1968).

The Centennial Range in the late Tertiary-early Quaternary was topographically much lower than it is today. Based on a total offset of 3050 meters (10,000 ft) (Schofield, Personal Communication, 1979) a maximum of 915 to 1220 meters (5000 to 6000 ft) of displacement had occurred along the Centennial Fault prior to the emplacement of the Huckleberry Ridge Tuff. The late Pliocene-early Pleistocene Centennial Valley was occupied by a large lake in which freshwater limestone was deposited. The ancestral Madison River flowed southward into the Centennial lake through a major valley cut into the upper Centennial Valley half graben.

Quaternary

The entire upper Centennial Valley region was at a sufficiently low enough elevation to permit the 2.0 million year old Huckleberry Ridge Tuff to flow into the valley from the Yellowstone caldera. The ash flow entered the area from the east leaving a blanket of tuff over much of the valley. It then traveled northward up the ancestral Madison drainage, diverting the river from the Centennial Valley.

Movement along the Centennial Fault continued throughout the Quaternary, displacing the Huckleberry Ridge Tuff a minimum of 1525 to 1830 meters (5000 to 6000 ft) in the last 2.0 million years. The Centennial Range was sufficiently high 1.2 million years ago to block the passage of the Mesa Falls ash flow into the upper Centennial Valley from the Island Park caldera. The only portions of the ash flow to enter the valley crossed the divide through low passes such as one near Hell Roaring Canyon (see map by

Witkind, 1976). Major volcanism occurred again in the Yellowstone caldera region 0.6 million years ago producing the Lava Creek Tuff. This ash flow was entirely blocked from the upper Centennial Valley and is exposed along the lower southeastern slopes of the Centennial Range.

Alpine glaciers formed in the mountain ranges surrounding the Centennial Valley at different times throughout the Pleistocene. Deposits of pre-Bull Lake, Bull Lake, and Pinedale glaciations indicate that the ice originated in high cirques and traveled downward, cutting U-shaped valleys which often reached the larger valley floors such as the Madison Valley (Weinheimer, 1979). Glacial meltwater accumulated in the Centennial Valley to form a large lake which drained at several locations including a stream situated in the Cliff Lake Fault trench. The West Fork of the Madison River began to cut a valley approximately along the Huckleberry Ridge Tuff-Precambrian contact (Gravelly Fault) during the late Pleistocene-early Holocene time. The Centennial Valley glacial lake eventually receded to form the Upper and Lower Red Rock lakes and associated ponds and marshes. As the lake receded, the drainage along the Cliff Lake Fault trench was dammed by mass wasting to create Elk, Hidden, Goose, Otter, Cliff, and Wade lakes.

It appears that the rate of movement along the Centennial Fault has increased since Pinedale time to over an inch per year. The Centennial, Cliff Lake, and southern Madison faults continue to be seismically active today.

GEOTHERMAL POTENTIAL

Evidence for warm spring activity along the northern flank of the upper Centennial Valley in the Upper Red Rock Lake Quadrangle is scant. Warm springs have, however, been identified adjacent to the area. The Sloan Cow Camp (30°C) and West Fork Swimming Hole (28°C) warm springs are located along the Gravelly Range Front Fault immediately to the north (Weinheimer, 1979). A warm spring has been identified southwest of Elk Lake (Sec. 11, T14S, R1W)(Sonderegger, Personal Communication, 1979). This spring is located on the Centennial Valley floor in approximate line with the Cliff Lake Fault. The Cliff Lake Fault would allow the circulation of meteoric water at depth. Thermal waters rising along the fault would mix with shallow cold groundwater and eventually with surface water when penetrating the valley fill sediments.

The possibility exists that the lakes along the Cliff Lake Fault have been at least in part warmed a few degrees by heated waters circulating along the fault. Elk, Hidden, and Goose lakes were found to be at least partially open in late November while the larger Henrys Lake and marshes of the upper Centennial Valley were covered by ice. Elk and Goose lakes were at least half open while Hidden Lake and the algae-covered pond just north of Hidden Lake were virtually free of ice. Otter, Cliff, and Wade lakes were not examined at this time. A deposit of travertine along the eastern shoreline of Elk Lake (Berg, Personal Communication, 1979) further indicates the presence or at least past existence of thermal spring activity along the Cliff Lake Fault.

A sizable geothermal reservoir may exist beneath the Huckleberry Ridge Tuff in the gravels (Tal in Figs. 13 & 15) of the ancestral Madison River channel on the northern side of the upper Centennial Valley (Sections 3,4,8,9,16,17, and 20 of T13S, R1E). A portion of the river channel coincides spatially with the Cliff Lake Fault. This reservoir, if present, probably terminates southward at a facies change (from coarse- to fine-grained material) where the ancient river entered the lake-filled Centennial Valley. This potential thermal system is consistent with those present in the Upper Madison Valley (Weinheimer, 1979). Cold water circulates down through deep-seated fault systems to depths at which the geothermal gradient, possibly amplified by the Yellowstone magmatic system, rises sufficiently to heat the water substantially before this water rises again toward the surface.

It is recommended that a temperature survey be conducted in the lakes along the Cliff Lake Fault. A study measuring surface water temperatures together with temperature change with depth in the lakes would prove valuable in detecting and outlining any hot spring activity at the bottoms of the lakes. Positive results in the temperature study would warrant further studies. Gravity and/or resistivity studies could then be conducted along the north side of the upper Centennial Valley to assess reservoir potential.

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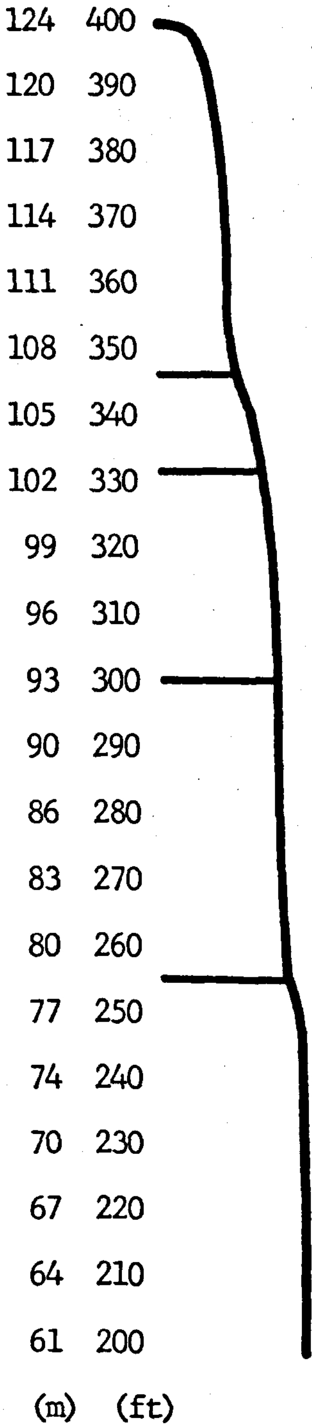
APPENDICES

APPENDIX I
MEASURED SECTIONS

SECTION A. Cliff north of Elk Lake (SW¼,SE¼, sec 16, T13S,R1E).



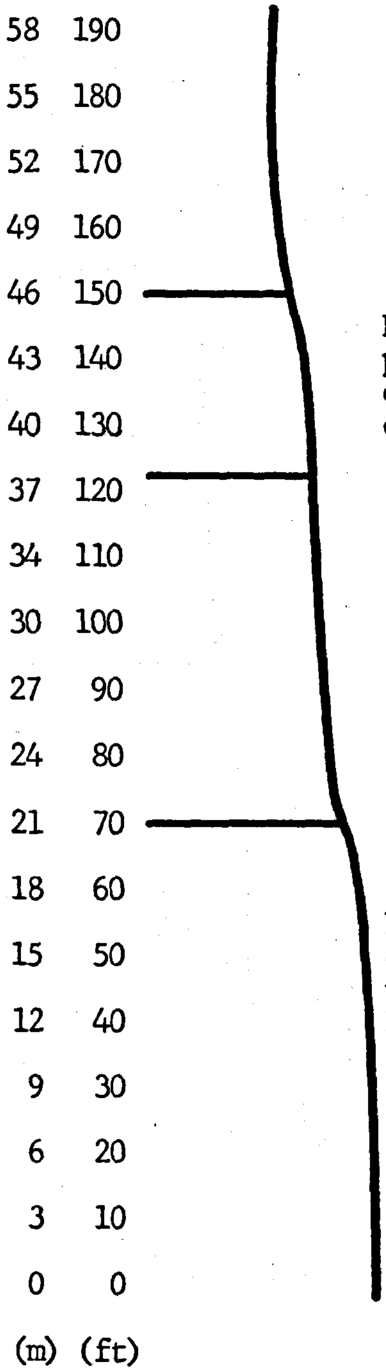
Light-gray, low density tuff that becomes punky near top, contains 10% sanidine and quartz phenocrysts that range up to 4 mm in diameter.

Dense, dark-gray welded tuff, displays a crude concoidal fracture.

Dark-gray to dark-brown densely welded tuff, contains 10% sanidine and quartz phenocrysts ranging up to 2 to 3 mm in diameter. Compaction-flow banding present.

Gray welded tuff, contains elongate vesicles up to 20 cm in length (sometimes filled with pumice), 1 to 2% sanidine phenocrysts ranging up to .5 mm in diameter.

Medium-gray welded tuff, contains elongate pumice bands (compaction or flow banding), and 1 to 2% sanidine with trace amounts of quartz phenocrysts ranging up to .5 mm in diameter.

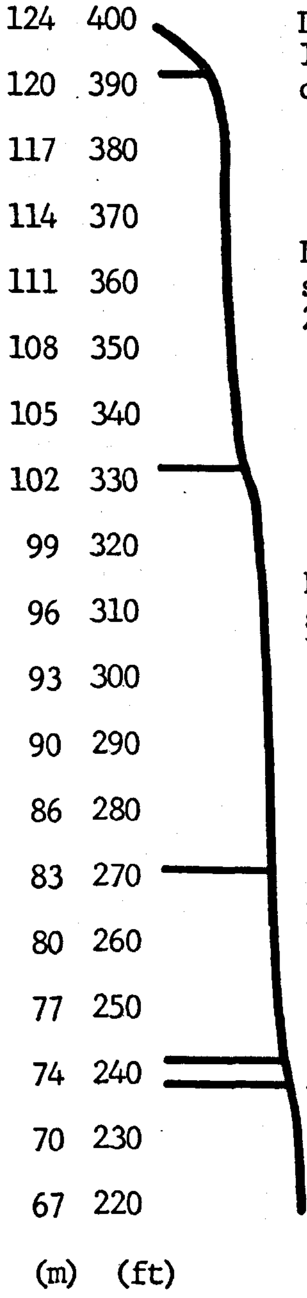


Reddish-brown welded tuff, contains elongate pumice bands and 3 to 5% sanidine with minor quartz phenocrysts ranging up to 3 mm in diameter.

Dark-gray to dark-brown densely welded tuff, contains 8 to 10% sanidine with minor quartz phenocrysts ranging up to 2 mm in diameter. Flow or compaction banding present.

Float of black vitric tuff in talus.

SECTION B. Cliff on north side of Hidden Lake (NE¼,NW¼, sec 10, T13S, R1E).



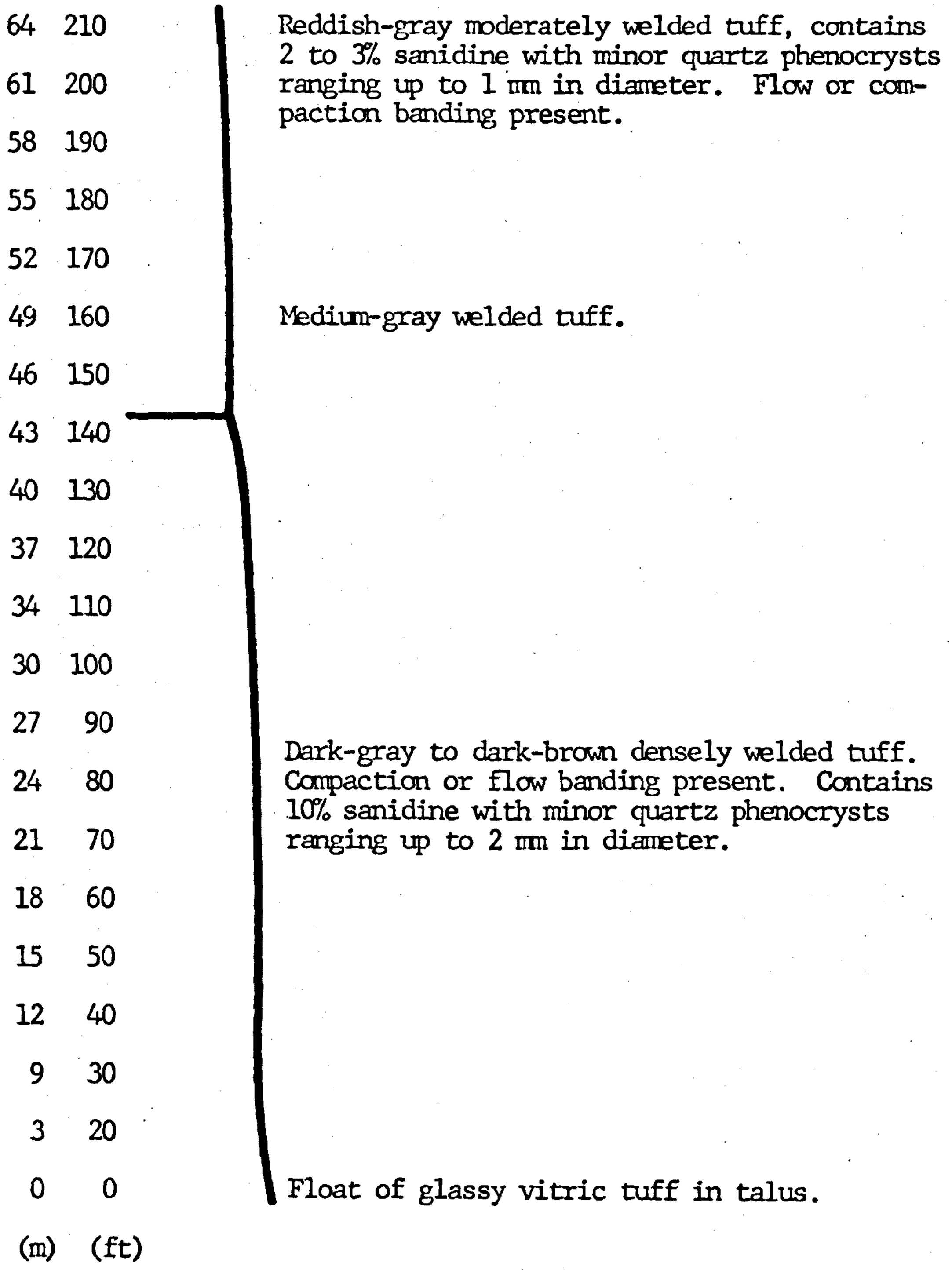
Light-gray, low density, punky tuff, contains 10 to 15% sanidine and quartz phenocrysts (4 mm diam.).

Light-gray moderately welded tuff, contains 10% sanidine and quartz phenocrysts ranging up to 2 mm in diameter.

Dark-gray, densely welded tuff, contains 10% sanidine and quartz phenocrysts ranging up to 1 mm in diameter.

Dark-gray welded tuff, contains 5 to 8% sanidine and quartz phenocrysts ranging up to 1 to 2 mm in diameter.

Ash bed with glass in float.



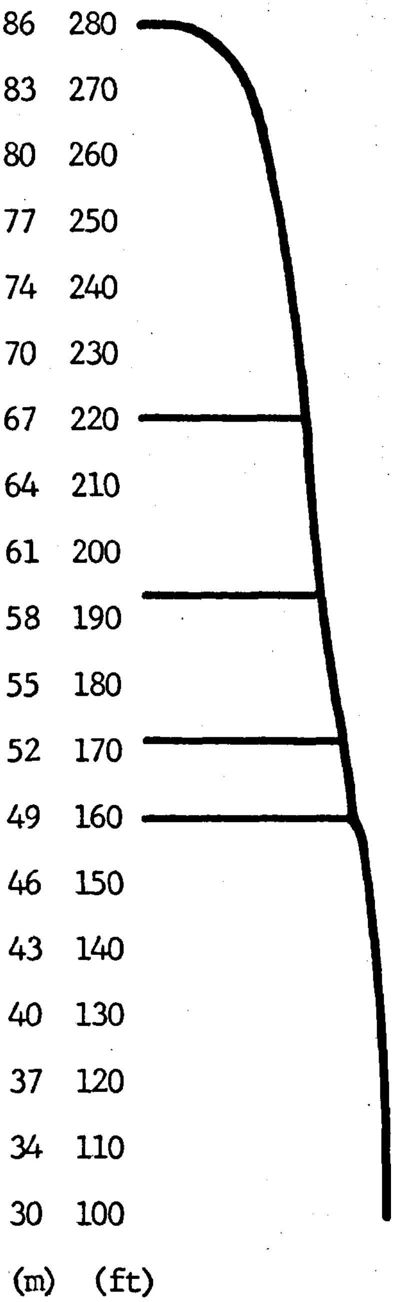
Reddish-gray moderately welded tuff, contains 2 to 3% sanidine with minor quartz phenocrysts ranging up to 1 mm in diameter. Flow or compaction banding present.

Medium-gray welded tuff.

Dark-gray to dark-brown densely welded tuff. Compaction or flow banding present. Contains 10% sanidine with minor quartz phenocrysts ranging up to 2 mm in diameter.

Float of glassy vitric tuff in talus.

SECTION C. Cliff on east side of Cliff Lake, 1 mile south of boat ramp (SW¼, sec 13, T12S, R1E)(Weinheimer, 1979).



Light-gray non-welded slightly compacted vesicular, weathers to light-pink ash.

Gray slightly welded tuff.

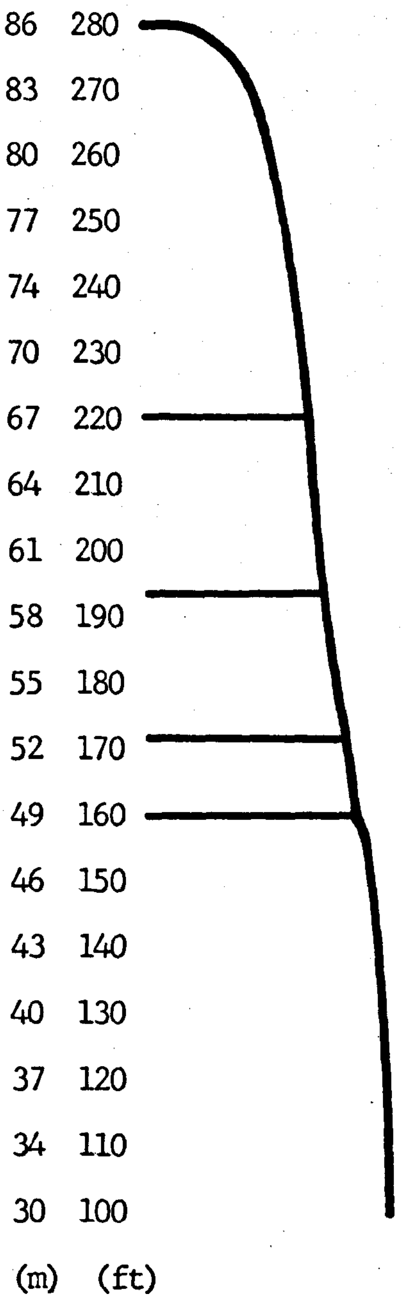
Dark-gray (weathers to red-gray or dark-brown), welded moderately consolidated tuff, layers 2 to 3 cm.

Dark-gray (weathers to light-gray), welded moderately consolidated tuff, layers 0.75 to 1.0 m.

Dark-brown welded tuff, layers 1 to 2 cm.

Gray massive compacted welded tuff; displays concoidal fracture.

SECTION C. Cliff on east side of Cliff Lake, 1 mile south of boat ramp (SW¼, sec 13, T12S, R1E)(Weinheimer, 1979).



Light-gray non-welded slightly compacted vesicular, weathers to light-pink ash.

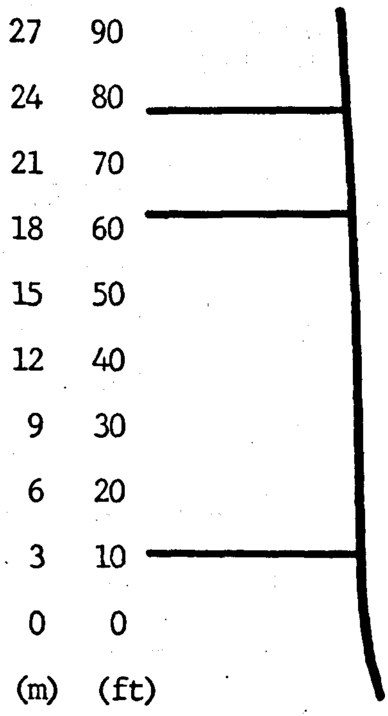
Gray slightly welded tuff.

Dark-gray (weathers to red-gray or dark-brown), welded moderately consolidated tuff, layers 2 to 3 cm.

Dark-gray (weathers to light-gray), welded moderately consolidated tuff, layers 0.75 to 1.0 m.

Dark-brown welded tuff, layers 1 to 2 cm.

Gray massive compacted welded tuff; displays concoidal fracture.



Gray (weathers to yellow and brown grus), compacted flow banded welded tuff.

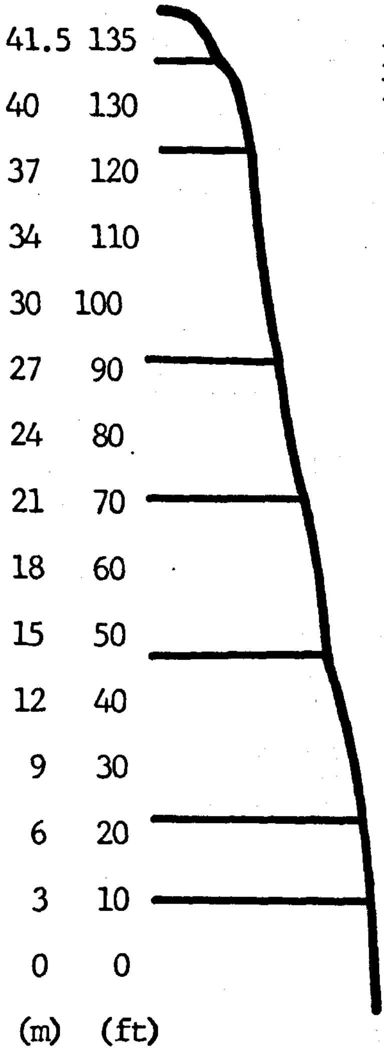
Top of first pulse, light-gray lightly compacted vesicular tuff. Precambrian gravel inclusions, vesicules 2.5 cm.

Gray porphyritic (quartz, sanidine 15%) dense, flow banded, thinly layered welded tuff.

Gray-brown porphyritic dense flow-banded welded tuff.

No osbidian in float.

SECTION D. One km north of the mouth of Curlew Creek (sec 13, T10S, R1E)(Weinheimer, 1979).



Precambrain granite and gneiss alluvium.

Light gray-pink slightly compacted unwelded tuff, weathered pitted surface. 5% Precambrian rock fragment inclusions.

Yellow-brown weathered fractured porphyritic welded tuff, 1 to 5% quartz and sanidine phenocrysts (1 mm).

Gray welded tuff; weathers to light tan or pink; concoidal fracture.

Light-gray, vesicular, limonitized welded tuff; flattened 1 to 5 mm vesicules comprising 5% of the rock.

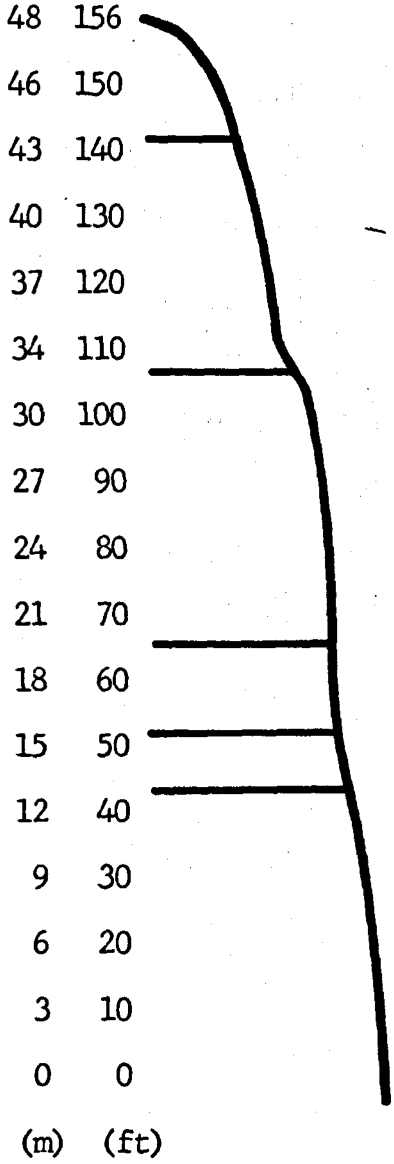
Gray (weathers to light-brown grus), blocky, densely welded tuff. Contains 10% quartz and sanidine phenocrysts (1 to 2 mm dia.), and 0.5% metamorphic rock inclusions.

Light gray-pink dense welded tuff.

Tan rhyolite grus float.

Upper limit of black obsidian float, contains 5% quartz, sanidine phenocrysts.

SECTION E. One km west of the mouth of Wall Canyon (NW¼, sec 18, T10S, R1E)(Weinheimer, 1979).



Pink slightly welded tuff, weathered pitted surface.

Light-gray, vesicular, slightly welded tuff, weathering to rounded ash blocks; contains quartz and sanidine phenocrysts, 1 to 2 mm in diameter, and Precambrain rock fragment inclusions.

Gray (weathers to light-pink or tan) massive welded tuff; displays concoidal fracture. Contains a few vesicles, and 15% quartz and sanidine phenocrysts 1 mm in diameter.

Red-gray tuff (same as 0 to 15 m).

Dark-gray vesicular welded tuff (2 to 3 cm vesicles).

Dark-brown massive welded tuff; dark gray and yellow flow banding.

Brown weathered surface; tuff alters to yellow and brown grus. Contains quartz and sanidine phenocrysts 1 mm in diameter.

Covered, no obsidian float.

APPENDIX II

POTASSIUM-ARGON AGE DATES

SAMPLE A.

Location: 1 mile NNW of Hidden Lake (44°43.83'N, 111°36.84'W; NW¼ NW¼ NE¼ S4,T13S,R1E).

Formation: Upper cooling unit (Qh_2) of the Huckleberry Ridge Tuff.

Rock type: Rhyolitic ash flow tuff.

Collected by: Dr. J. Sonderegger, MBMG.

Analytical data: K=7.45%, $*Ar^{40}=2.716\times10^{-10}$moles/gm, atm. $Ar^{40}=35\%$

Dated by: S. H. Evans, University of Utah, Dept. of Geology.

Age: 2.05 ± 0.07 m.y. (sanidine)

SAMPLE B.

Location: South end of Elk Lake (44°39.24'N, 111° 38.84'W; NW¼ SE¼ S31,T13S,R1E).

Formation: Lower cooling unit (Qh_1) of the Huckleberry Ridge Tuff.

Rock type: Rhyolitic ash flow tuff.

Collected by: Dr. J. Sonderegger, MBMG.

Analytical data: K=7.49%, $*Ar^{40}=2.659\times10^{-10}$moles/gm, atm. $Ar^{40}=27\%$.

POTASSIUM-ARGON AGE DATES (continued)

Dated by: S. H. Evans, University of Utah, Dept. of Geology.

Age: 2.05 ± 0.07 m.y. (sanidine)

SAMPLE C.

Location: South end of Elk Lake (44°39.24'N, 111° 38.84'W; NW¼ SE¼ S31,T13S,R1E).

Formation: Pleistocene basalt (no formal name).

Rock type: Basalt.

Collected by: Dr. J. Sonderegger, MBMG.

Analytical data: K=0.36%, $*Ar^{40}=0.1489\times10^{-10}$moles/gm, atm. $Ar^{40}=93\%$.

Dated by: S. H. Evans, University of Utah, Dept. of Geology.

Age: 2.38 ± 0.44 m.y. (whole rock)

SAMPLE D.

Location: NE slope of Flatiron Mountain (44°50'27"N, 111°38'45"W; SW¼ SE¼ S30,T11S,R1E).

Formation: Huckleberry Ridge Tuff.

Rock type: Rhyolitic ash flow tuff.

Collected by: G. J. Weinheimer, MSU.

POTASSIUM-ARGON AGE DATES
(continued)

Analytical data: K=5.850%, $*Ar^{40}$=0.000837 ppm, $Ar^{40}/\Sigma Ar^{40}$=16%.

Dated by: Geochron Laboratories, Inc.

Age: 2.0 ± 0.1 m.y. (sanidine)

(from Chadwick, 1978)

SAMPLE E.

Location: Cliff face on W bank Madison River 2 Km N of mouth of Wall Canyon, Madison Co., MT (44°59'33"N, 111°39'45"W; SE¼ NE¼ S1,T10S,R1W).

Formation: Huckleberry Ridge Tuff.

Rock type: Rhyolitic ash flow tuff.

Collected by: Dr. R. A. Chadwick, MSU.

Analytical data: K=6.888%, $*Ar^{40}$=0.000945 ppm, $*Ar^{40}/\Sigma Ar^{40}$=17%.

Dated by: Geochron Laboratories, Inc.

Age: 1.9 ± 0.1 m.y. (sanidine)

(from Chadwick, 1978)

APPENDIX III

CHEMICAL ANALYSES OF RHYOLITE TUFFS AND BASALT

ROCK UNIT	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	MnO %
Huckleberry Ridge Tuff (Qh_1) (Sec. 31,T13S,R1E)	75.0	11.4	3.74	0.25	0.72	3.1	4.9	0.205	0.042
Huckleberry Ridge Tuff (obsidian of Qh_1) (Sec. 2,T13S,R1W)	78.5	11.5	3.08	0.06	0.66	3.4	4.7	0.210	0.035
Huckleberry Ridge Tuff (Qh_2) (Sec. 4,T13S,R1E)	80.1	11.6	4.40	0.03	0.51	3.2	4.9	0.264	0.044
Pleistocene basalt (Sec. 31,T13S,R1E)	50.1	15.3	14.0	7.18	9.25	2.6	0.4	2.75	0.148
Mesa Falls Tuff (Weinheimer, 1979)	71.73	12.4	6.971	0.415	1.00	3.734	3.879	0.25	-----

(Samples were analyzed by the Montana Bureau of Mines and Geology)

1 folded map in pocket