Environmental geology of part of the West Fork Basin, Gallatin County, Montana
by Alan Everett Kehew

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science (Geology Option)
Montana State University


Abstract:
The geology of part of the West Fort Basin was studied to obtain practical information relating to the proposed development of a large recreational facility. Both bedrock and surficial geology were mapped to discover relationships which have environmental significance.

The exposed stratigraphic units, in this area, consist of Cretaceous strata with interbedded igneous sills, including the Kootenai Formation through part of the Colorado Group. The three-member Kootenai Formation, mainly sandstone and shale, is the most resistant unit in the area. In contrast to the Kootenai, the overlying weak formations including the Thermopolis Shale, Muddy Sandstone, Albino Formation, and an unnamed sandstone and shale unit,generally provide a poor bedrock base for construction. Various types of mass-gravity phenomena which affect much of the surface underlain by these units, contribute to their poor adaptability to man-made alterations. Varying climatic conditions through Recent geologic history have controlled the character of these mass wastage processes. Microclimatic variations due to different slope orientation affect vegetative growth and geo-morphic processes.

Mass-gravity phenomena show a definite correlation with lithology. Flowage or slump masses are the normal surficial cover for areas underlain by the Thermopolis Shale and the Albino Formation, even when tilting of the strata is slight. Although most of these movements are stabilized under present climatic conditions, their equilibrium is delicate and modifications should be planned with caution. Rockslides and mudflows are less common features, but may involve all stratigraphic units. Slow flowage mass-gravity movements such as talus flow, colluvium and rock glaciers are mostly found on steeper slopes. Rock glaciers present are classified as active and inactive. It is recommended that the active rock glacier in the cirque on Lone Mountain be studied to determine its movement, if any, before the proposed ski lift is installed.

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## ABSTRACT

The geology of part of the West Fort Basin was studied to obtain practical information relating to the proposed development of a large recreational facility. Both bedrock and surficial geology were mapped to discover relationships which have environmental significance.

The exposed stratigraphic units, in this area, consist of Cretaceous strata with interbedded igneous sills, including the Kootenai Formation through part of the Colorado Group. The three-member Kootenai Formation, mainly sandstone and shale, is the most resistant unit in the area. In contrast to the Kootenai, the overlying weak formations including the Thermopolis Shale, Muddy Sandstone, Albino Formation, and an unnamed sandstone and shale unit,generally provide a poor bedrock base for construction. Various types of mass-gravity phenomena which affect much of the surface underlain by these units, contribute to their poor adaptability to man-made alterations. Varying climatic conditions through Recent geologic history have controlled the character of these mass wastage processes. Microclimatic variations due to different slope orientation affect vegetative growth and geomorphic processes.

Mass-gravity phenomena show a definite correlation with lithology. Flowage or slump masses are the normal surficial cover for areas underlain by the Thermopolis Shale and the Albino Formation, even when tilting of the strata is slight. Although most of these movements are stabilized under present climatic conditions, their equilibrium is delicate and modifications should be planned with caution. Rockslides and mudflows are less common features, but may involve all stratigraphic units. Slow flowage mass-gravity movements such as talus flow, colluvium and rock glaciers are mostly found on steeper slopes. Rock glaciers present are classified as active and inactive. It is recommended that the active rock glacier in the cirque on Lone Mountain be studied to determine its movement, if any, before the proposed ski lift is installed.

# INTRODUCTION

## METHOD OF STUDY

The field work for this report was done as part of an environmental research project undertaken by the Montana State University Center for Environmental Studies. Geology represented one of several disciplines which were involved in a study of many aspects of the physical and cultural environment of a sparsely populated area soon to receive a large recreational development. The object of the overall project is to observe environmental changes, having obtained a detailed knowledge of original conditions.

The goal of the present paper is twofold. First, the general geological relationships such as stratigraphy, structure, and geomorphology were examined. This is an attempt to describe briefly the stratigraphic sequence, the structural setting, and geomorphic features of the area mapped. This information is included in the report to give the reader a brief overall geologic background of the area.

The second objective of the study concerns the application of some of this information to the practical problem of productive man-made alterations of the landscape. The writer feels that certain aspects of the subjects mentioned above, as well as their interaction with climatic and biologic processes will be useful in planning the recreational complex.

Approximately ten weeks were spent in the field during the summer of 1970. The geology was mapped on 1:20,000 scale air photos, and transferred by use of a Salzman projector to 1:24,000 scale topographic maps.

Approximately fifteen representative thin sections were studied with the petrographic microscope. Two clay samples were analyzed using X-ray diffraction techniques.

To encourage the use of this report by non-geologically trained persons, a glossary of some of the technical terms used has been included in the appendix.

## DESCRIPTION OF AREA

The area mapped includes about sixteen square miles in part of the drainage basin of the West Fork of the West Gallatin River, in the Madison Range. The West Fork is formed by three smaller streams, the North, Middle, and South Forks of the West Fork, which rise in mountainous terrain near the Madison-Gallatin drainage divide, and flow eastward to form the West Fork on a broad plain approximately two miles west of U. S. Highway 191. The specific area of this report is located between the South Fork and Middle Fork, extending northwest of the lower plain to the crest of Lone Mountain (See index map, Plate I). Elevations range from 6600 feet to 11,166 feet at the top of Lone Mountain. Maximum relief is approximately 4500 feet.

The mouth of the West Fork is located approximately 43 miles south of Bozeman, roughly one half the distance between Bozeman and West Yellowstone, Montana, along U. S. Highway 191 which parallels the

West Gallatin River. Gravel roads extend along the South Fork to the Ousel Falls campground, and up both sides of the Middle Fork to Andesite Lookout Tower on the south, and to the head of the Middle Fork near the Madison-Gallatin drainage divide, on the north. These roads will be substantially improved in the near future, to provide for a much greater volume of traffic in connection with the development of the recreational complex.

PREVIOUS WORK

Hall (1961) has summarized the early exploration of the upper Gallatin region, as well as the pioneer geologic work. The first important study was made by Peale (1896) in his study of the Three Forks quadrangle. Two other more recent works were extensively relied upon in the present study of the area. R. W. Swanson (1950), compiled a bedrock map including the area to be studied here. Several rather insignificant corrections were made in the bedrock geology of this map, and the detail was expanded in several ways. The portion of the Colorado Group present, mapped by Swanson as "upper Cretaceous undifferentiated" was divided into smaller units. In addition, the surficial geology was mapped in detail for the first time. W. B. Hall's excellent general work (1961) on the upper Gallatin region included this study area in a reconnaissance structural map. His discussions of the stratigraphy, structure, and geomorphology in the above paper, as well as in two smaller more specific papers (1960 a,b), were invaluable in the preparation of this report.

## TOPOGRAPHIC SETTING

Dominating the area at its western boundary stands Lone Mountain, an impressive peak of 11,166 feet. Eastward, from the base of this mountain, lies a prominent northeast trending anticlinal ridge, named Andesite anticline for an outcrop of an igneous sill at the highest point along its axis, near which a lookout tower is located. This ridge is separated from Lone Mountain by a small synclinal valley, and bordered on the east by a portion of a syncline. Between this syncline and the Middle Fork is a large flat-topped hogback, sloping east-northeast, which is locally known as Flatiron Mountain. Beyond the map area to the east lies a broad flat plain which was mapped by H. Walsh under the auspices of the M.S.U. Center for Environmental Studies.

# STRATIGRAPHY AND ENVIRONMENTAL ASPECTS

## GENERAL STATEMENT

In keeping with the environmental theme of the project, the stratigraphy is discussed mainly as it relates to the evolution of the existing landscape.

Most stratigraphic study within the West Fork basin is difficult due to the extreme scarcity of bedrock exposure. Timber cover throughout the Madison Range is very heavy. The most important reason for the lack of outcrops, however, is the nature of the rocks themselves, because in this specific area, a large part of the exposed section consists of shale, claystone, and other extremely non-resistant rocks. Only the thin sandstone units within the shales are resistant enough to crop out at all. The only consistent exposures are located along stream valleys and even here shales are commonly covered by colluvium and vegatative growth. Due to the properties of these rocks, they are very conducive to mass gravity movements, another factor which contributes to the poor exposure of bedrock.

In the following discussion, regional stratigraphic correlation and depositional history of the units are only briefly mentioned. Only descriptions concerning physical properties of the rocks found in this specific area are important in considering development of the area. The reader is referred to Hall (1961) for pertinent information concerning the regional relations of these sedimentary rocks.

The importance of studying stratigraphy concerns its relation to the topographic expression of various units. In a regional sense, climate is perhaps the most important factor in determining the manner in which a certain rock type will relate to the topography. It determines which erosional processes will occur and at what intensity. In a small area, however, in which the climate is generally constant, the response of the physical properties of the rock to the climate is important in defining the different landforms associated with different rock types.

The effect of climate on exposed sedimentary strata is extensive. All mass gravity phenomena in this area were, and are, controlled or influenced by water. Under the present climatic conditions in the West Fork drainage, most landslide features are relatively stable. Scarps are less topographically prominent features than scarps on those slides which are known to have occurred recently. Vegetation on the slump blocks or slide deposits is established in a normal manner. Most features have no scarps or tension cracks related to recent movement.

One of the contributing causes of landsliding is a gradual decrease in the amount of shearing strength, or the resistance of a mass of material to failure and downslope movement, by prolonged periods of high water availability to the sediments. This water increases the pore pressure within the rock, which eliminates the cohesive effect of a small amount of water in the pores. Certain time intervals in the Pleistocene such as the periods of glacial melting and retreat would provide water to initiate a relatively high frequency of sliding. More specifically, the fresh hummocky topography of many earthflows, a type of mass-gravity movement related to landsliding, might indicate an age of late Wisconsin (Pinedale) time, the age of the last major glacial episode, from about 10,000 to 30,000 years before present. Landslides have occurred since then, although at less frequent intervals, due to a dryer climate. Mass movements showing evidence of recent movement such as distinct scarps and "drunken forests" are few in comparison to the older features. Several man-induced landslides show that such stability can be quickly altered if the natural state is disturbed. An example of this can be seen on a logging road which was built diagonally up the south side of Flatiron Mountain. In the several years since this road was built, the slope has failed and erased a portion of the road. Apparently the slump was an adjustment by the slope to the effect of the road cut. Other examples can be seen in adjoining areas.

One interesting sidelight is the difference in micro-climate between slopes facing north and slopes facing south. North-facing slopes receive less direct sunlight than south-facing slopes, and thus retain some of the moisture that would be lost by evaporation with more sunlight. The difference in the vegetative patterns and geomorphic processes between these slopes is striking.

The comparative lack of moisture on south-facing slopes is manifested in a lack or sporadic distribution of tree growth in certain areas. This phenomena was discussed by Patten (1963, 1970). He found that in addition the slope orientation, fine grained sedimentary rocks or alluvium prevent good forest establishment due to low moisture availability. Patten states (1970), that lodgepole pine is presently invading these open areas due to more advantageous climatic conditions. An excellent example is found in the north canyon wall (south-facing slope) of the South Fork. The fine-grained, clay rich rocks of the Albino Formation form several bands of tree-less sage covered zones along the entire length of the ridge (See Figure 7). Well drained sandy zones in similar settings support tree growth that cannot exist on the clay-rich shale beds due to the low moisture availability of the latter. One factor involved in the moisture availability is probably the impermeability of the rocks. These same impermeable zones support quite dense tree growth on north-facing slopes, which indicates that direction of slope face is a more important factor than is the presence of impermeable beds.

The two types of slopes also exhibit different forms of downslope movement of debris. The north and south sides of Flatiron Mountain can be compared to understand these relationships. The south-facing slope with its general lack of vegetation, maintains well developed talus piles at the foot of outcrops. The north-facing slope, however, with a dense low vegetation in addition to trees, probably moves a greater volume of material downslope and results in a noticeable lack of outcrops of resistant sandstone units in contrast to south-facing slopes.

It probably cannot be proved, but the more rapid forms of landsliding may vary according to facing of slopes. Flow forms such as earthflow would be expected more frequently on north-facing slopes because of greater water content, while slumping or sliding should be more prevalent on south-facing slopes. Exceptions to this would relate to the other factors involved, such as inclination of the slope, stratigraphic units involved, and structure of the beds.

Several lithologic factors combine to influence the landform of a particular rock type. Grain size, mineral composition, porosity, and degree of consolidation or cementation all determine the resistance of a rock to weathering, and mass movement. The stratigraphic section will now be discussed in relation to these factors. Figure 2 illustrates the units in question.

## MORRISON FORMATION

Rocks representing the Morrison Formation of Jurassic age (Kimmeridgian according to Imlay, 1952), are exposed at one location within the present map area. This place is at the core of Andesite anticline below the Kootenai Formation where the Middle Fork cuts through the anticline (See Plate I). Only the very top of the formation is exposed here. This unit is non-resistant and is mostly covered by colluvium, talus from the Kootenai Formation, and heavy vegetative growth. The lithology consists of dark gray to black fissile shale which weathers into very small shale chips and covers the surface below, and dark gray to black siltstone which is more resistant than

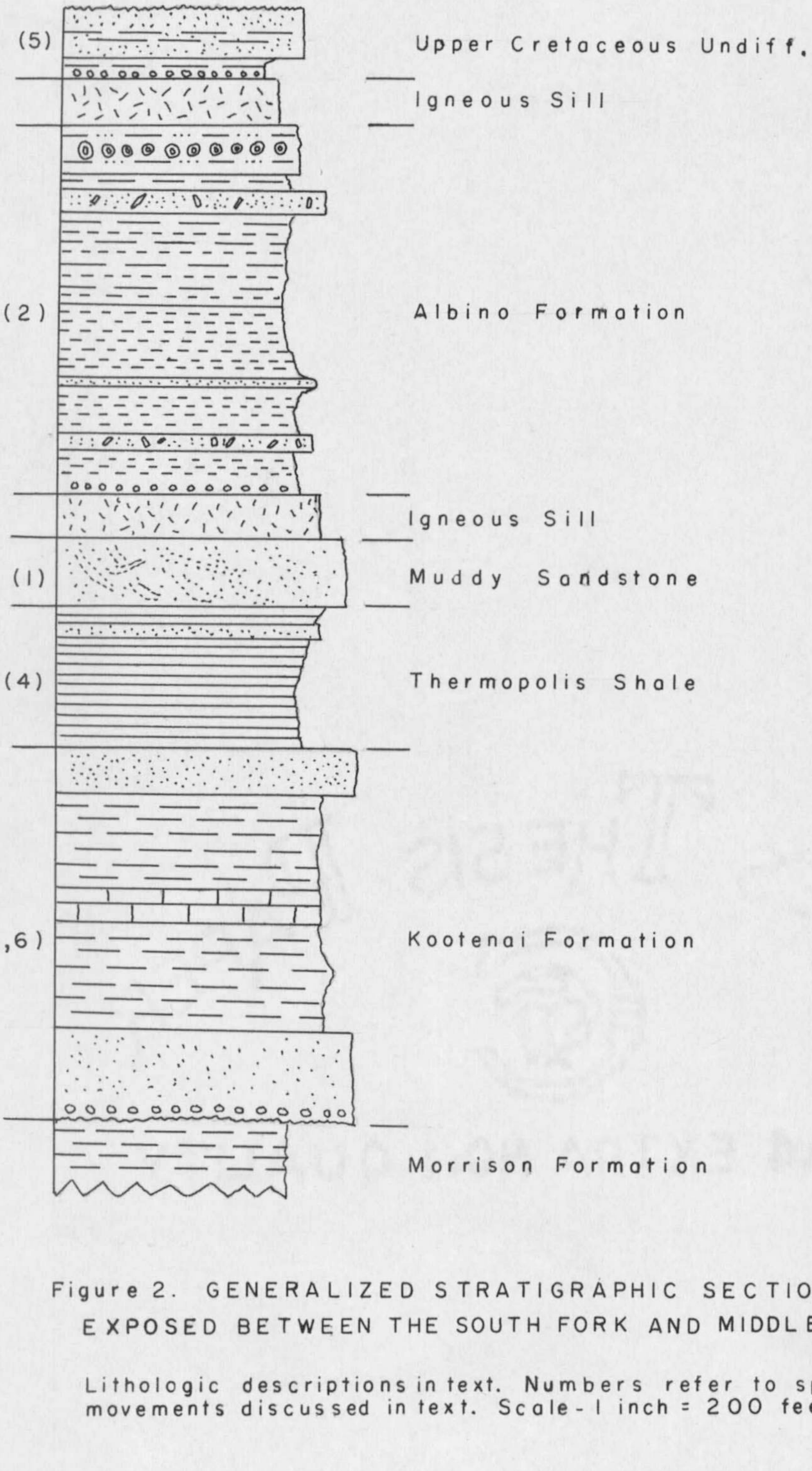


Figure 2. GENERALIZED STRATIGRAPHIC SECTION OF UNITS EXPOSED BETWEEN THE SOUTH FORK AND MIDDLE FORK

Lithologic descriptions in text. Numbers refer to specific mass gravity movements discussed in text. Scale - 1 inch = 200 feet.

the shale. The Morrison Formation is of little importance environmentally in this area due to its extremely small outcrop area.

KOOTENAI FORMATION

The Kootenai Formation of Early Cretaceous age, (Aptian according to Cobban and Reeside, 1952) rests unconformably on the Morrison Formation (Imlay, 1952). This unit is extremely important in the map area, forming almost the total outcrop area of the eroded surface of Andesite anticline, as well as being the unit through which the South Fork is presently flowing from Andesite anticline eastward to the lower plain. South of the map area, the exposures on the north flank of Buck Creek anticline are composed of the Kootenai Formation.

The Kootenai Formation was divided into three members in the Upper Gallatin region by Hall (1961, p. 64-66). His description of the units is partially reproduced below:

" 1. A lower member 80 to 150 feet thick consisting of coarse, massive, salt-and-pepper sandstone, often very conglomeratic near the base, cross bedded, with many light to dark gray chert grains and pebbles. In thin section the conglomeratic sandstone is composed of about 50 percent subangular to subrounded quartz grains and 50 percent subangular chert grains. Percentages of either the quartz and chert locally may increase up to 85, and many of the quartz grains show secondary quartz overgrowths on rounded antecedent grains. The chert is apparently largely derived from siltstone and fine sandstone, and the original fabric of the parent material can often be seen in the microscope . . .

2. A middle member, about 250 feet thick, consisting of yellowish tan to red or maroon nodular claystones, limestones, and limy siltstones below; 20-60 feet of fresh-water lime-

stones in the middle; and more red to maroon claystones, limestones, and limy siltstones above. The limy unit in the center of the sequence may have gradational contacts at top and bottom, but does have intraformational conglomerate beds occasionally. This unit is the "gastropod limestone" of other parts of western Montana and is probably equivalent to the "lacustrine limestone" of the "Moulton zone" of Cobban (1955, p. 108). The "gastropod limestone" is a noteworthy bed, characterized by a chalky appearance, and multitudes of small gastropod steinkerns and shells covering the bedding planes . . . Some beds contain ostracods by the millions, along with many small ooids like oolites without concentric structure. Other beds in the fresh-water limestone unit appear to have no fossils, but possess a peculiar assortment of fine clear calcite veinlets arranged in an angular "runic" (?) pattern. . . .

3. An upper sandstone member, about 50 feet thick, composed of well-sorted, fine-grained, clean, clear sparkling quartz arenite. . . Usually this upper sandstone member weathers to a distinctive dark red-brown due to a concentration of hematite cement in a layer about 1/8 to 1/4 inch deep on all exposed rock surfaces, and for this reason is called the "case-hardened sandstone" member of the Kootenai. . ."

The Kootenai Formation as a whole is the most resistant unit in the section. Of its three members, the lower sandstone-conglomerate and the upper sandstone form resistant ledges. The middle unit is less often found cropping out and usually can be recognized by its reddish soil and a tree-less open area, influenced by the impermeable nature of the shale. An example of the Kootenai weathering characteristics can be found on Andesite anticline. Here the dominant form of erosion is the downslope movement of large rectangular to cubical blocks of sandstone that are weathered from the bedrock.

The Kootenai Formation is here considered, in general, to be the most favorable lithologic unit for construction in the section studied.

This is concluded mainly from the type of mass-gravity processes which affect the Kootenai in this area. The Kootenai as a whole has a comparatively high resistance to downslope movement. The ability of a rock to withstand natural erosive processes is a good indication of its potential for utilization by man-made structures. The properties which contribute to this strength are its composition of quartz and chert, its coarseness and well-sorted grains, and its degree of consolidation and cementation. The shales, however, in the middle part of the formation, show a low resistance to erosion and therefore should be regarded as less favorable units for construction.

The potential of the Kootenai as a good acquifer is higher than the other units above due to its grain size, roundness and high degree of sorting, expecially in the upper sandstone. No studies, however, were made of groundwater production in the Kootenai in this report.

## COLORADO GROUP

The remaining overlying part of the section in the area, consisting of approximately 700 feet of strata with interbedded igneous sills, is included in the Colorado Group. The four lithologic units present include, in ascending order, the Thermopolis Shale, the Muddy Sandstone, the Albino Formation, and an unnamed sandstone and shale unit. Cobban and others (1959) divided the Colorado Group in the Sawtooth Disturbed Belt area of northwestern Montana into two formations, the Blackleaf Formation of Early Cretaceous age, and the Marias River Shale of Late

Cretaceous age, each consisting of four members. Hall (1961) discussed the possibility of correlating the first four lithologic units above the Kootenai in the Upper Gallatin region with the four members of the Early Cretaceous Blackleaf Formation because of their many similarities. However, plant fossils collected by Hall from the Albino Formation were dated Late Cretaceous. Thus the correlation between these rocks and the Blackleaf Formation remains uncertain.

Thermopolis Shale

Above the Kootenai Formation are found approximately 150 feet of extremely non-resistant dark gray, fissile, carbonaceous shale, interbedded with thin slightly more resistant siltstone. This unit is regarded by Hall (1961, p. 66) as "the terrestrial or brackish water equivalent of the marine Thermopolis Shale of Wyoming."

Because of the non-resistant nature of this unit, it is very rarely exposed; in fact the only actual outcrop of the Thermopolis in the project area is found in the vicinity of Ousel Falls along the South Fork of the West Fork, (sec. 10, T. 7 S., R. 3 E.), beneath a glacial outwash deposit.

The Thermopolis Shale has just as distinctive a topographic expression as the Kootenai Formation. This unit forms a low swale between the Kootenai and the Muddy Sandstone. Subsequent streams generally develop along the strike of the Thermopolis. Another prominent characteristic of this unit is its association with mass-gravity movement. It is rarely exposed as bedrock. When it is present on a steep slope such as valley wall, slumping is common. The very narrow slide in the draw east of Andesite anticline on the Middle Fork was probably initiated by a downslope movement in the Thermopolis. Where the Thermopolis is found downslope from the Kootenai, as on an eroded anticline such as Andesite anticline, it provides a favorable base for downslope movement of the Kootenai float and talus.

Muddy Sandstone

The Thermopolis Shale passes gradationally upward into a sandstone unit approximately 50 feet thick which Hall (1961) has correlated with the Muddy Sandstone in Wyoming. This unit is thin to medium bedded, with well developed cross bedding, and weathers to a platy appearance in outcrop due to thin dark, fissile, shale layers interbedded with the sandstone. The composition of the sandstone is variable, ranging from a medium gray, moderately well sorted, fine to medium grained rock consisting of subangular to subrounded quartz grains, dark rock fragments, and feldspar grains, to a very argillaceous, greenish gray sandstone.

Contrasted with the weak Thermopolis, the Muddy Sandstone forms a resistant ledge along the South Fork, and a prominent thin hogback ridge bordering Andesite anticline. The float from the Muddy which accumulates on the talus slopes beneath the outcrop, consists of thin platy slabs. The Muddy for the same reasons as the Kootenai would provide a sound base for utilization in building. Its thinness restricts its potential somewhat in this respect.

Albino Formation

The remaining 500 or 600 feet of section represent, in the opinion of the writer, the Albino Formation named by Hall (1961), and part of the overlying unnamed sandstone and shale unit described by Hall (1961). This part of the section is very difficult to study in this area because of the extreme paucity of exposures. This is related to the weakness and incompetence of the rocks in general, which here leads to extensive mass-gravity action. In addition to this problem, these rocks have been intruded by igneous sills related to the Lone Mountain Intrusive Complex. It has not been proven in this study whether all of these sills are intruded parallel to bedding, or whether they cut across bedding at some small angle. The varying extent of these sills from their point of intrusion at Lone Mountain increases the difficulty of correlating the section in different locations.

The following discussion is a very limited outline of the Albino lithologies. The writer feels that any attempt at a detailed description of the Albino Formation in this area would not be justified because of the uncertainties in the field resulting from poor exposure of the units and the lack of lateral persistence of the lithologies present. The exact location of the upper contact of the Albino Formation, as mapped in Plate I, is uncertain because a distinct mapping criterion to place the contact was not recognized. The reasons for its position as mapped will be explained later.

The initial 20-30 feet of section directly over the Muddy sandstone is not exposed at any place in the area. The lower half of the Albino, perhaps 100-200 feet thick, consists of pastel colored claystone, mudstone, and shale. There is at least one approximately 5-foot thick sandstone bed in these soft rocks. There are also a few siliceous shale beds and hard brittle tuffs, both more resistant than the shale and claystone, in this zone. A very interesting conglomerate was found in the lower Albino in sec. 3, T. 7 S., R. 3 E. This conglomerate occurs as float in a slump block, hence it is not possible to determine its exact location in the section. Lithologically it is poorly sorted and cemented, and is composed of subangular coarse sand and pebble sized grains with a reddish, probably hematitic fine grained matrix. The rock has a distinctive reddish appearance in hand specimen.

In order to determine the clay mineralogy, two samples of the very loosely consolidated claystones were analyzed using X-ray diffraction. The silt and sand sized particles were first separated from the clay fraction and were not examined further. The clay was then saturated with several different cations to distinguish clay minerals in the resulting X-ray pattern. The clay fraction consists almost entirely of the smectite group of swelling clays. The clay is probably montmorillonite, a member of the smectites. These clay minerals are known for their ability to absorb water on the surfaces between their thin layers, which expands the structure of the mineral. This determination is in accord with the theory that volcanic ash is the parent material for bentonite. Montmorillonite is a known alteration product of volcanic ash in the Wyoming bentonites, also of Cretaceous age. Grim (1968) discusses this alteration process.

Above the very soft claystone, lie about 100 feet of black shale containing numerous shiny, well preserved fish scales. These are small, nearly circular, and ornamented with concentric rings. Fish scales are found in several black, homogenous shales in this part of the section. In these zones thin, gray and orange bentonite seams approximately 1 to 3 inches thick are interbedded with the shale.

The upper portion of the Albino Formation is considerably sandier and more resistant than the lower part. Especially resistant here is a 30-foot thick very well cemented salt-and-pepper sandstone. In thin section, this rock contains fine to medium sized, subangular to subrounded quartz grains. It also contains grains which appear gray or cloudy in plain light (possibly altered volcanic fragments), and a few plagioclase grains. The very small amount of fine material present is probably microcrystalline silica cement.

Above this sandstone, is about 20 feet of dark fissile shale. The remaining uppermost 40 to 60 feet of the Albino Formation as defined here, consists of gray siliceous shale with interbedded very hard, white, fine grained, homogeneous tuff or siliceous shale, grayish green argillaceous sandstone, and siltstone. One zone several feet this is notable for the abundance of its fossil material. One thin bed in this zone seems to consist almost entirely of a mass of plant leaves and stems, while other beds contain a combination of plant material and possibly nearshore marine pelecypods. Above the fossil beds, there are about 10 to 20 feet of undetermined covered material overlain by a prominent sill zone which will be described later.

This section of the Albino Formation has basic similarities to that described by Hall (1961), but there are also several differences. Hall found plant fossils in hard siliceous tuff 20 to 140 feet below the top of the Albino. In the section described above, if the upper contact of the Albino were placed at the contact with the sill, the fossil zone in my area would approximate the location of Hall's fossiliferous zone. On that basis, the Albino contact was mapped in this area. The fossils here, however, are found in different lithologies than were those of Hall. Although the hard tuffs are present in this zone, no organic remains were found in them. Another problem is that none of the bright red tuffs described by Hall were found in this zone or any other part of the section, with the exception of a few pieces found in float in various places. Thus the placement of the upper Albino contact is not made with much confidence, although the described position seemed the most reasonable horizon at which to place it. The sill mentioned above thins to the east and is not present in the section along the South Fork. In this location, additional black fissile shale lies above the sandy zone.

The age of the Albino is questionable. Ferns collected by Hall from the hard tuffs were dated as Late Cretaceous. However, Hall has described the similarity of the Albino to the Vaughn Bentonitic Member of the Blackleaf Formation as defined by Cobban (1959). This is also the "red speck zone" of the Colorado Shale named by Cobban (1951) for abundant minute grains of heulandite, a secondary zeolite found throughout the unit. Cobban (1951) considers the "red speck zone" or Vaughn Bentonitic Member of the Blackleaf Formation, to be equivalent to the Mowry Formation of Wyoming which contains fish scales and bones. The fish scales found in this area are one bit of substantiating evidence for this relation. If the Albino were determined to be equivalent to the Mowry, the upper sandy part of the Albino here described, may correlate with the Frontier Formation of early Late Cretaceous age in the Livingston area, reported by Roberts (1965).

The alternating weak and comparatively strong rocks of the Albino Formation present a classic situation for landsliding. In addition, the weaker clay and bentonite predominate in the lower portion of the section, with a greater percentage of sandstone near the top. Several samples of the almost unconsolidated clay in the lower part of the section were found to consist almost entirely of montmorillonite. The expandable nature of this clay mineral may be a contributing factor to the mechanism of sliding. Deeply buried clay horizons are likely to be saturated with water and should remain at a fairly constant state with respect to changes in volume. On the other hand, if the potential horizon of failure is located in the vicinity of the water table, fluctuations in the water table may initiate expansion and contraction which could tend to induce or support mass wastage.

Above the sill, which has a maximum exposed thickness of approximately 50 feet, are rocks which probably represent the unnamed sandstone and shale unit above the Albino as described by Hall (1961). This unit is mapped as Upper Cretaceous undifferentiated on Plate I, in the section of the map done by this writer. A very distinctive chert pebble conglomerate, 6 inches thick, is found several feet above the upper contact of the sill in the Middle Fork canyon. About 10 to 25 feet of shale with a few interbedded hard white tuff layers overlie this conglomerate. Above these rocks is a resistant sandstone and shale sequence about 50 feet thick which forms a prominent ledge at the rim of the Middle Fork canyon. These sandstone beds seem mostly nontuffaceous and containe some large pelecypods.

This unit overlying the Albino Formation is resistant to erosion. It would seem to provide a good base for construction. As it does overlie the Albino, however, it would participate in any large scale mass movements initiated in the Albino.

The stratigraphy of Lone Mountain involves alternating layers of andesitic sills and sedimentary rock. Much work remains to be done to correlate the sedimentary sequence of Lone Mountain with those in the basin. It is probable that the sedimentary layers represent still younger beds than those previously described.

# IGNEOUS ROCKS

Igneous rocks in the area consist of sills related to the Lone Mountain Igneous Complex. Their combined thickness is greatest at Lone Mountain, the center of the complex. Sills are also found throughout the map area at several reasonably persistent positions in the section, and at frequent non-persistent intervals.

The sills vary in lithology, ranging from basalt porphyry to latite porphyry in those types identified. The most common type, however, is andesite porphyry. A thin section of this rock shows altered plagioclase, K-feldspar, pyroxene, and biotite, and minor amounts of quartz and opaque minerals.

A thin section of a basalt porphyry sill contains phenocrysts of clinopyroxene in a groundmass of lath-shaped plagioclase and pyroxene. In outcrop, the mafic sills are commonly found as a disintegrated, unconsolidated soil-like mass of grains. In places, however, they are resistant enough to crop out as rock.

The lowest sill exposed in the section is andesite porphyry and is located above the Kootenai formation, and found cropping out on various portions of Andesite anticline, such as near Andesite Lookout Tower. This rock type is the one described above and is the most common type in the area.

The next major sill is a mafic rock intruded above or within the upper part of the Muddy Sandstone. This sill is 75-100 feet thick east of the plain bordering the South Fork (sec. 2, T.7 S., R. 3 E.).

This sill was found consistently throughout the area, however, it was never found with both its upper and lower contacts exposed. Thus it is not possible to define the specific position with regard to the Muddy Sandstone, into or above which the sill is intruded.

The uppermost prominent sill intrudes rocks above the Albino Formation. The base of this sill forms the upper contact of the Albino, as defined in this report. This sill is distinctive in lithology, consisting of elongated pink feldspar laths with orthopyroxene and biotite as the major mafic minerals. Most of the feldspar is potash feldspar, so that the rock should be classified as a latite or monzonite porphyry. Outcrops of this rock are found on Flatiron Mountain as well as in the same horizon in the section across the Middle Fork on the north side of the canyon wall.

Many other sills much too thin to map are located within the section. These are commonly of mafic composition and very highly weathered.

Although igneous rocks intruding Lone Mountain were not studied in detail, sills probably constitute about one half the thickness of the section, and half metamorphosed the sediments into which they were intruded. The resistant high topography of this mountain is a result of the thickening of the section due to the intrusion of the sills, as well as the strengthening or hardening of the country rock.

The igneous sills have quite varied weathering characteristics. Andesite sills break up by frost action into blocks 3 to 6 inches in length or diameter. Excellent spheroidal weathering features are found in the sills at the top of the Albino. These upper sills are less resistant than the andesitic lower sills mentioned above. The very thin mafic sills found in the section are extremely non-resistant. They are rarely seen in outcrop, and when found in road cut appear usually as an unconsolidated aggregate of grains.

## STRUCTURE

The general structural setting of the Madison Range is discussed by Hall (1961). The reader is referred to that paper for a review of the pertinent literature. Swanson mapped the area of the present report. No important corrections were deemed necessary in the structural interpretation of his map. A brief sketch of the structures present is given in the subsequent paragraphs.

The West Fork basin, or the "Lower Basin syncline" of Hall (1961), is a synclinal depression bounded on the north by the Spanish Peaks fault (McMannis and Chadwick, 1964). This fault is a high angle reverse fault trending N 60° W, of which thrusts Precambrian metamorphic rocks, which now form the Spanish Peaks, to the southwest. Paleozoic and Mesozoic strata on the northeast limb of the Lower Basin syncline are vertical to slightly overturned to the southwest along the footwall block. Hall (1961) considers the age of the Spanish Peaks fault to be post Late Cretaceous and possibly as young as Oligocene, depending on the age of tertiary volcanic rocks which overlap the fault to the southwest. McMannis and Chadwick (1964), however, dated the lower portion of the volcanic sequence as early Middle Eocene or latest Early Eocene, suggesting an older age for latest movement along the fault. These authors have proposed that the Spanish Peaks fault is related to the Gardiner fault, a similar thrust along the trend of the Spanish Peaks fault to the southeast. However, the intervening area between the two faults is buried by the Tertiary volcanis and the relations are thus obscured.

The Lower Basin syncline is bounded to the south by the Buck Creek anticline, the long axis of which parallels the Spanish Peaks Fault.

The area between the South Fork and Middle Fork of the West Fork has an anomolous structural pattern in that it consists of two synclines with an anticline between, trending about N. 40°E., approximately normal to the trend of the Spanish Peaks fault. Hall (1961) has suggested that these structures are possibly the result of the intrusion of the Lone Mountain Igneous Complex, which adjoins these structures to the west. This theory seems reasonable but no new evidence was discovered either to refute or prove it.

These structures are apparently fault-bounded on both the northeast and southwest, along the courses of the Middle Fork and South Fork, respectively. Swanson (1950) has mapped a strike-slip fault with left lateral displacement along the course of the Middle Fork (See Plate I), which displaces the anticlinal nose of Andesite anticline to the northwest. The structural trend of this anticline, however, continues on both sides of the Middle Fork. Andesite anticline is abruptly terminated to the southwest along the South Fork. No evidence was found here to indicate displacement or movement of this fault along the South Fork, if such a fault actually exists.

Andesite anticline, named for an intrusion which crops out along its axis, is the most prominent of the structures. It has been eroded down to the resistent Kootenai Formation in its core. Several remnants of a sill crop out on the flank of the anticline, and have been folded with the sediments on the southwest end of the ridge. Thus it appears that the sills were intruded before this particular structure was formed.

The axis of the small syncline to the east of Andesite anticline trends about N 60 E, and has preserved some of the Albino Formation. This syncline is almost totally covered by landslide debris of various types, which has moved toward the axis of the structure. The nature of these mass-gravity movements will be treated in the section on geomorphology. The syncline to the west of Andesite anticline is bounded on the west by Lone Mountain. The Albino Formation is likewise preserved in the center of this structure. There is less landslide action here, however, and this may be due to proximity of the intrusive complex, which could have slightly metamorphosed and strengthened the weak units. Shales appear to be harder and more brittle than similar shale to the east.

The northeast-facing cirque of Lone Mountain has exposed a number of high angle faults of relatively small displacement. The environmental significance of these faults will be discussed later. No evidence of Recent movement was found.

# GEOMORPHOLOGY

## STREAM DEVELOPMENT

The two major streams in the area here considered, the South Fork and the Middle Fork of the West Fork of the West Gallatin River, are exceptions to the general pattern of drainage in the Gallatin and Madison ranges. The Gallatin River is thought to be superposed across major structural trends from a Mid-Tertiary surface of valley fill deposits and volcanic material during and after the Laramide Orogeny (McMannis and Chadwick, 1964; Hall, 1961). The major tributaries, including the West Fork, following synclinal axes and flow in weak rock units along the strike. The South Fork and Middle Fork of the West Fork, however, are transverse to a prominent structure, Andesite anticline. The South Fork, while not actually cutting through the anticline, lies at the southwest end of this northeast trending structure. These streams could possibly be superposed tributaries to the West Fork. However, a better explanation might be, as previously mentioned, that both streams may be flowing along fault trends, at least along a portion of their upper courses.

Drainage of the syncline east of Andesite anticline, is characterized by very poor adjustment, and numerous undrained depressions containing ponds or marshy areas caused by the almost complete coverage of the syncline by mass-gravity movement of various types. Along the portion of this syncline adjacent to Andesite anticline, streams not influenced by sliding follow the strike of the Thermopolis Shale, a very erodable unit.

MASS-GRAVITY MOVEMENTS

Mass-gravity movements in this particular area are perhaps the most important factor in the development of the present topography. The forms and processes responsible for these Quaternary features and their relationship to structure and stratigraphy will be described in this section. Numbered landslides in the text are related to the stratigraphic units in which they occur in Figure 2.

Following the classification of Sharpe (1938), mass-gravity movements were recognized representing three types of movement. These include slow flowage, rapid flowage and landsliding.

Slow Flowage

Slow flowage mass-gravity features including soil creep, talus creep (flow), and rock glaciers cover a large part of the area. For practical reasons, only talus creep (flow) and rock glaciers have been mapped.

Since most of the area is in slope, soil creep can be expected to affect practically all surficial material with the exception of resistant rock outcrops, and open slopes and cliffs which tend to lack a soil cover. Rock fall and talus are the dominant form of downslope movement in these cases. The facing of the slope, which determines in part the amount of moisture received and retained by the slope, is a very important factor in the amount of vegetative growth and amount of creep. Heavily vegetated slopes tend to have a heavy soil creep and/or a colluvial mantle. This is due both to the vegetation itself which anchors the soil somewhat, and to the moisture, which is responsible for the heavy vegetation on these slopes. Some more gentle slopes which lack tree growth, but have sage and grasses are influenced by the lithology upon which they are developed. The soil mantle here is often undergoing slow downslope movement.

Talus creep (flow) is present at several locations. Andesite point, the small intrusive cap of Andesite anticline, exhibits excellent examples of these features (Figure 3). The top of this point consists of a mass of broken, angular, disk-like blocks approximately 6 inches in diameter which have been produced by frost action. Surrounding this point, juding from the appearance of the landform, the talus has been, and probably is now, creeping down the slope. The terminus of movement consists of abrupt, well defined convex tongue-like lobes of material about 5 to 10 feet in width. The active nature of these tongues is indicated by turf rolls at the edge of each lobe. Larger examples of these features can be found along the lower edge of Lone Mountain where andesite crops out. This igneous rock, apparently because of its weathering characteristics, is the most widespread source for talus creep (flow). Talus creep is also found consistently below the outcrop of the Muddy Sandstone (1), along the north wall of the South Fork canyon.

Rock glaciers are the most spectacular form of slow flowage in the area. The best example is found in the northeast facing cirque high on Lone Mountain. This rock glacier is more than 1 mile in length and from 200 to 1000 feet wide.

Rock glaciers have been recognized since the beginning of this century. Many theories have been proposed for their origin. The literature on rock glaciers has been reviewed several times and will not be repeated here. The readers is referred to summaries by Wahrhaftig and Cox (1959), and Potter (1967). Only three important theories will be discussed here.

Sharpe (1938) considered rock glacier creep to be a specialized type of talus creep, caused by freezing and thawing of ice in the interstices of the talus debris, which would take place in cold temperature regions. This process quite likely could be the method of movement for the talus creep features described above. This type of movement does not require a permanent volume of ice in the rock glacier. If there is permanent ice at some depth in the Lone Mountain rock glacier, one of the following hypotheses would better explain the movement of this mass of debris. Wahrhaftig and Cox (1959) in a major study of approximately 200 rock glaciers in the Alaska Range, concluded that rock glaciers have a mantle of coarse material which is underlain by silt, sand, and fine gravel, cemented by interstitial ice. The velocity of the rock glacier which they measured was 2.5 feet per year. Wahrhaftig and Cox (1959) believe that the rock glaciers are not related to the late Wisconsin deglaciation, but began to form after the warm climatic maximum in post-Wisconsin time. They list three processes for the accumulation of ice in the debris including compaction of snow, freezing of melt water, and upward movement and freezing of groundwater in the debris.

Potter (1967) in a recent detailed study of a rock glacier in the Absaroka Range, came to a somewhat different conclusion regarding the formation of rock glaciers. The rock glacier which he studied was composed, in the upper two thirds, of a mantle of coarse debris, 1 to 1.5 meters thick which was underlain by relatively clean glacial ice, with little debris. He found the accumulation area (area in which there is a net gain of snow over the years) to be very small. This allowed the debris contributed to the rock glacier from the cirque to be transported past the zone of ice accumulation, thus never becoming a part of the glacial ice. The large size of the ablation zone (area in which there is a net loss of snow or ice over the years), in relation to the accumulation zone indicates the very low ablation rate of the glacial ice due to the insulating effect of the debris mantle. This could cause a substantial time lag between a climatic change and its effect on the glacial ice beneath the debris. From the fabric of the ice, Potter concludes that the freezing of meltwater is not a dominant process in the formation of ice in that particular rock glacier. He proposed the terms ice-cemented rock glaciers for the type described by Wahrhaftig and Cox (1959), and ice-cored rock glaciers for the type with a relatively clean debris-free ice core. The particular rock glacier which Potter studied had a maximum velocity of 6 cm. per year.

The rock glacier in the east to northeast facing cirque of Lone Mountain shown in Figure 4 appears to be a tonque-shaped rock glacier, as defined by Wahrhaftig and Cox (1959). Wisconsin glacial deposits which originated in the cirque terminate approximately 1 mile down valley from the maximum extension of the present rock glacier. The rock glacier heads in a small cirque which has been carved above the floor of the main cirque. It is possible that this cirque is related to the Temple Lake, Neo-glacial stage. The rock glacier does not fill the lower cirque, although it does expand in width as it leaves the upper cirque (See Plate I).

The rock glacier is divided into an inactive down-valley segment and an active segment near the head of the cirque, based on the following criteria.

(1) The bouldery surface of the inactive segment has considerable vegetative growth consisting of lichens and some grasses, while the active segment has little or no vegetation.

(2) The edges of the active segment are steeper and similar to talus slopes at their angle of repose, while the edges of the inactive segment are relatively subdued in comparison. Exceptions to this are on the south facing slopes in the center of the inactive portion where the rock glacier may be expanding laterally, possibly by creep into the main cirque or recently may have done so. These slopes are very unstable.

Material is supplied to the head of the rock glacier by rock fall and debris slide from the cirque walls surrounding the head of the rock glacier. It is also supplied to the central portion of the rock glacier from the long ridge forming the north wall of the cirque. The debris is formed by frost action and consists of platy andesite blocks and more rectangular to cubical blocks from the metamorphozed sediments. These fragments are generally several times larger than the andesite boulders. The walls of the cirque consist of numerous small couloirs with talus fans or cones at their base. There is a depression surrounding the edge of the active segment which prevents this material from reaching the top of the rock glacier, except at the very rear portion. However, with snow accumulation in the winter and spring this depression might be filled allowing material to move over snow onto the surface of the rock glacier.

A small amount of digging into the frontal scarp about 5 feet below the top, proved that much fine material is present underneath the boulder mantle. This would suggest that the rock glacier, if ice is present, is of the type described by Wahrhaftig and Cox (1959) and movement would occur by the flow of the interstitial ice. This zone in the scarp appeared to be wet, however, no ice was found. Mechanical equipment should be used to determine if ice is present in the rock glacier.

Since the time of the study extended through only one summer, no quantitative information could be gathered as to movement of the rock glacier, or of the amount of snow, if any, accumulating.

The microrelief of this rock glacier exhibits a pattern of longitudinal and transverse ridges and furrows which are approximately parallel to the margin of the glacier. Kettle-like depressions are also present. According to Wahrhaftig and Cox (1959), the above features can be explained by the accumulation and wastage of ice, and variable flow rates in the rock glacier.

Conclusive information relating to the type and history of the Lone Mountain rock glacier cannot be made here due to the limitations of the study. A study over a period of years would be needed to obtain information concerning accumulation, ablation, and present movement of the glacier. Without this information, it is only possible to speculate regarding its history. It is considered possible, however, that the inactive portion may correspond to the Temple Lake neo-glacial stage. Field work on the rock glacier was carried out with C. Montagne, and many of the conclusions and observations above were jointly derived.

Rapid Flowage

According to Hall (1961), earthflow, a type of rapid flowage, is the most important type of mass movement in the upper Gallatin region, in terms of area affected, with the exception of creep. Earthflow, in this region is probably gradational in velocity between creep and mudflow depending on the amount of water involved, the amount of slope, and the lithology in which it occurs. Earthflows are characterized by a crescentic headwall scarp, a constricted middle segment, and a lobate toe at the terminus (Hall, 1961). Their hummocky topography generally resembles that of glacial moraine, with irregular mounds and ridges, ponds, and marshy areas.

The amount of true earthflow in the map area is uncertain. The syncline east of Andesite anticline (2) is one area which might have undergone earthflow. The syncline is characterized by zones of typical hummocky topography, although the three-segment form mentioned above is not present. Other areas are found in the syncline which are surrounded by slides but in which rock seems to be in place. These were originally thought by the writer to be bedrock remnants that did not participate in the sliding. Scarps are found of varying age, both crescentic and linear in form.

Two theories are proposed for the history of mass gravity modification of this syncline. The first involves numerous overlapping earthflows of different ages which would tend to obscure the typical earthflow form. The undeformed areas must be considered to be bedrock islands which did not participate in the sliding. Slumping may be associated with the earthflows near the headwall scarps.

The second possible origin for the observed features could be related to a type of landslide phenomena. Landslides in general are discussed in the following section. This theory proposes that translatory movement of block glide occurred from both flanks of the syncline toward the axis. Translatory sliding was discussed by Hansen (1965), in connection with earthquake at Anchorage, Alaska in 1964. He also noted that translatory slides have been described without the triggering mechanism of an earthquake. These slides are commonly caused by failure of a weak, sensitive unit overlain by a more competent unit, along an almost horizontal plane. A prominent headwall scarp is formed at the initial point of movement. The tensional forces caused by the outward sliding of the mass results in the formation of a graben directly in front of the scarp. Blocks forward of the graben need not undergo significant deformation.

The prominent linear scarp found in sec. 3, R. 3 E., T. 7 S., (Figure 6), on the southeast flank of the syncline, is of this type. Outward and parallel to this scarp is a hummocky depression, possibly a graben, followed by a ridge exhibiting much less deformation, approximately equal in elevation to the top of the scarp. This pattern continues to the axis of the syncline (Figure 5). The outward moving blocks may rotate somewhat, instead of remaining parallel to their scarp, in order to become more normal to the maximum slope toward the axis.

The other flank of the syncline is thought to have undergone a similar history. The scarp here, is the south edge of Flatiron Mountain. The base of this steep scarp is now occupied by an extremely youthful stream which seems to substantiate the postulate of relatively recent gliding, possibly correlating to the youthful scarp on the southeast flank of the syncline. The series of ridges adjacent to the south side of Flatiron Mountain were originally thought to be islands of bedrock surrounded by slumping. However, they conform much better to a theory of blocks gliding outward from a scarp and being subjected to a slight rotation in order to move down the dip parallel to the axis.

If these movements occurred at the same time on opposite sides of the syncline, the movement would tend to be stopped by the collision of their toes at the axis of the syncline. The zone of failure was almost certainly one or several of the numerous weak claystones or bentonites in the Albino Formation.

Mudflow, a rapid water saturated type of flow is not a very significant process in this area. Only a few examples are known, two of them very small in area, located between Andesite anticline and Lone Mountain. These occur in the Albino Formation and are developed on somewhat steeper slopes than the typical earthflow.

An interesting mudflow occurs along the road to Andesite Lookout in sec. 32, R. 3 E., T. 6. S. (3). This flow consists, at its toe, of individual finger-like lobes. Large boulders from the Kootenai Formation are found on the surface of this flow indicating that it must have been very fluid. The zone of origin of this slide was not found, but it is possible that it began in the Thermopolis Shale with Kootenai talus boulders contributed from above, on Andesite anticline.

Landslide Phenomena

Landslides proper differ from the previously described types of mass-gravity movement in that they are relatively rapidly moving, have less water associated with them, and fail along a definite plane.

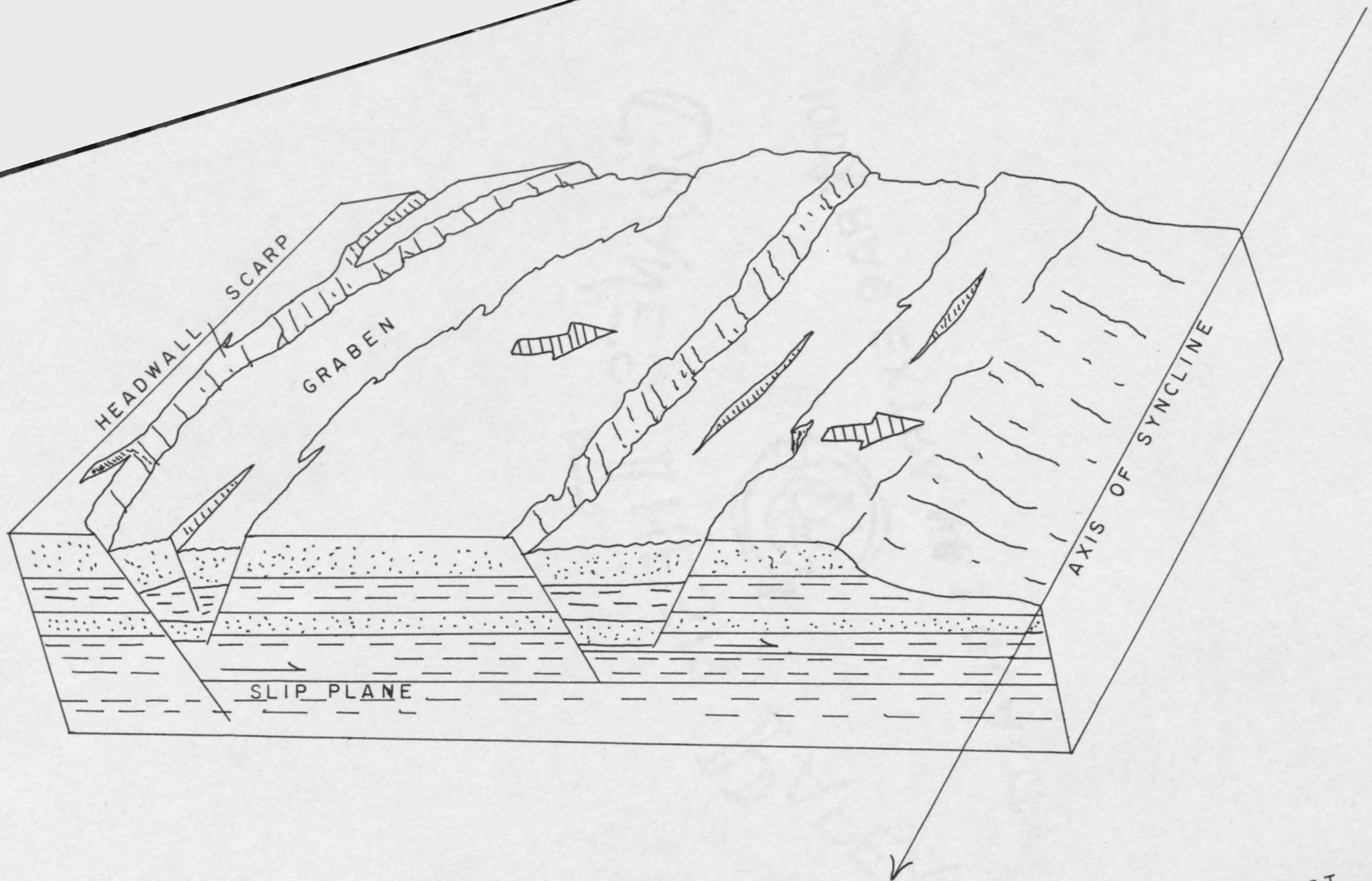


Figure 5. HYPOTHETICAL TRANSLATORY SLIDES IN SYNCLINE EAST OF ANDESITE ANTICLINE

Modified from Hansen (1965)

Slumping is the most prevelant example of landsliding in the map area. This phenomena is defined by Sharpe (1938, p. 65), as the "downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope from which it descends." These are found in the area exactly as described, showing rotational movement with the surface of the slump block tilted toward the headwall of the slump. They are most common on steep slopes such as youthful river valleys, and have a very close relationship to the stratigraphy. All stream valley slopes of a steep nature in the area sustain slumps when the Thermopolis Shale or Albino Formation are exposed. Examples of slumps occur along both the north wall of the South Fork canyon, and on both north and south facing slopes of Flatiron Mountain. The large slide mapped on the top of Flatiron Mountain (5) is probably mostly of slump origin. Commonly slumps are found near the headwall scarp of other types of mass movement such as earthflows and rockslides. Slumps have quite a range in size, from small blocks several feet wide to those the size of a house, and are not mapped in cases when they are very small.

The other type of landslide present is the rockslide. Sharpe (1938, p. 76), defines rockslides as "the downward and usually rapid movement of newly detached segments of the bedrock sliding on bedding, joint or fault surfaces, or any other plan of separation." This type of slide is probably an instantaneous movement with the detached segment of bedrock becoming broken into a mass of debris by the time it comes to rest at the base of the slope. The largest single mass movement in the area is probably a representative of this type. The slide is located along the South Fork of the West Fork on the east flank of Andesite anticline (6). A relatively large movement, this slide is approximately 1 mile in length and 3000 feet wide at its toe. The toe expands toward the terminus of the slide, but it is not a lobe-shaped form as in a flow. The primary indication that this slide broke away as a cohesive mass of rock in a rapid movement, is that it occurred mainly in the Kootenai Formation. The toe of this slide is a large mound of very large, angular, Kootenai material. Flow features were not found in the area, so it seems safe to assume that this slide failed along a definite plane. It has not been determined, however, what horizon did actually cause the movement. The Kootenai is both overlain and underlain by weak shale, and the Morrison could have been involved in this slide. Other possibilities cannot be ruled out, however, such as an undiscovered fault or the fact that the slide occurs near the point at which the strike of the previously discussed syncline changes from an east-west to a northeast orientation. Several large springs emanate from the toe of this slide.

GLACIATION

Quaternary glacial deposits cover a very small percentage of the area mapped for this report. The deposits that are present are thought to represent advance of valley glaciers in early and late Wisconsin time, which are known as the Bull Lake and Pinedale stade respectively. In addition the rock glaciers described previously are postulated to represent two recent stages of neo-glaciation.

Remnants of the early Wisconsin or Bull Lake, advance are found in two places in the map area. Resting on or just behind the gravel plain just north of the Ousel Falls campground is an eastward elongated subdued mound which is postulated to be a moraine related to this advance. The subangular to subrounded boulders on this deposit consist mainly of Kootenai sandstone and andesite. Few boulders are on the surface of the moraine. The gravel plain which caps the South Fork canyon at Ousel Falls is related to the Bull Lake glaciation as an outwash plain. These gravels merge to the east with the much larger gravel plain below. The source of the ice for these deposits is probably the upper South Fork drainage, as well as the Yellow Mule Creeks, which are three north flowing tributaries to the South Fork. Since the stream has cut through the outwash gravels as well as the bedrock in the canyon, the canyon must be no older than late Bull Lake. To the east of the above mentioned moraine, out of this map area, lies another morainal remnant which probably represents the maximum extent of the Bull Lake stage.

Deposits of early Wisconsin age are also found in portions of secs. 25, 30, and 29, R. 3 E., T. 6 S. These deposits are located along the creek bordering the west flank of Andesite anticline. They lie beyond a younger system of moraines and are modified by the outwash from the younger deposits. The obvious source of these materials is the cirque on Lone Mountain and is reflected in the andesite and shale boulders which are found on the moraines.

At the mouth of the Beehive Creek, two lateral moraines of probable Bull Lake age extend out and across the canyon of the Middle Fork. The ice responsible for these moraines apparently formed a temporary dam along the Middle Fork. A small lake was created behind the dam and fine grained silty and clayey materials were deposited in the open meadow through which the Middle Fork meanders. The Bull Lake deposits here correspond topographically to those of the Intermediate stage of Hall (1960a).

Evidence for glaciation of Pinedale or late Wisconsin age was found in only one place in the area, this being the system of moraines which lie within the Bull Lake material just described. These moraines can be distinguished from the Bull Lake on the basis of topography, soil development, and position. The topography is noticeably fresher in appearance than that of Bull Lake moraine, and consists of numerous mounds and kettles, and has a very abrupt ridge at the terminal moraine. Practically no soil has developed on the Pinedale features. A soil is found capping most Bull Lake deposits. Gravels extend outward from the terminal moraine to the fine grained deposits in the open marshy meadow through which the Middle Fork flows. Several springs also originate from this terminal moraine. Upstream from the meadow, along the Middle Fork, Pinedale ice apparently overrode or stopped at the edge of Bull Lake deposits which were formed by south flowing ice that originated in the Spanish Peaks area.

As previously mentioned, the inactive and active rock glaciers on Lone Mountain are tentatively dated as Temple Lake and Gannett Peak, respectively.

For a more complete discussion of glacial geology in this region, the reader should consult the report by C. Montagne, which was compiled as part of the Center's overall project.

## CONCLUSIONS AND ENVIRONMENTAL RECOMMENDATIONS

The present study, as previously mentioned, concerns those interrelationships of the various branches of geology, as well as climatic and biologic factors, which have produced the present landforms, drainage patterns, soils, and all other physical characteristics of the natural environment. This type of approach is becoming increasingly important as a result of man's need to better understand surficial materials and to plan more wisely his use and modification of the environment.

This study has shown that the topography in the West Fork Basin has undergone a complex history. Since the intense period of folding, faulting, and volcanic activity in early Tertiary time, (McMannis and Chadwick 1964), the region has been experiencing constant uplift and erosion. Climate played a great role in this erosional history. However, the present landforms are probably no older than the Pleistocene epoch, in which a colder and wetter climate was responsible for several advances of valley glaciers into the West Fork Basin. The warmer climates present during the retreat of these glaciers probably initiated periods of intense mass wasting related to the increased water available from the melting glaciers. The most recent history has been characterized by reduced activity of landsliding as a result of the dryer and warmer climate. That the mass-gravity phenomena have not ceased, however, has been brought out in this paper. The future of this area involves man's interaction with the geologic and climatic processes. With that prospect in mind, recommendations are included with the following conclusions. These recommendations are not an attempt to dictate design and construction. They are deductions from the information gathered in this study.

From a geologic standpoint, the stratigraphy is the most important factor that should be taken into consideration when development is planned. As has been emphasized, most of the units in this area are extremely undesirable for construction. The topographic expression is used as an index to define their suitability. The sequence of these particular units consisting of interbedded shale, sandstone and claystone, has proven to be unstable from its past geomorphic activity. The alternation of permeable and impermeable beds is the most important property in their failure. A period of heavy rainfall can increase the pore pressure in the rocks causing decrease of the shearing strength. The slides can be activated by failure along one of the weak clays. The Thermopolis Shale, and the Albino Formation almost without exception have undergone flowage or slump activity. The units which would provide a good base for construction, including the Kootenai Formation, the Muddy Sandstone, and the sandstone and shale sequence above the Albino, are also involved in various landslides, although these are probably related to more unusual factors, such as earthquakes or the presence of faults.

In addition to the inherrently poor engineering properties of the sediments, these units have in some cases, been uplifed to relatively high elevations, and dissected by narrow steep-walled valleys. That the region is still undergoing tectonic movement, is attested to by periodic earthquake shocks. With recognition of these facts before development, and with careful design and construction, the geologic problems described can be overcome. Three specific points warrant mention concerning stratigraphy and landslides.

It is recommended that construction be limited to the Kootenai Formation out crops whenever possible. In this regard, the proposed ski lift to the top of Andesite anticline is well placed.

Old landslides are [illegible]stable [illegible] at the present time. However, if their natural equilibrium is altered without precautions to allow for this, slides could again become active. It is hoped that the map accompanying this report will be helpful in locating these areas.

If conditions were changed, areas which have not undergone landslides could begin to slide. The entire section above the Kootenai is a case in point. One example will suffice to illustrate this idea. Flatiron Mountain is a body of mostly intact bedrock which is bounded on three sides by landslides and on the other by a steep canyon with slumping walls. Slumps, in fact, encircle Flatiron Mountain. The hill is composed mainly of the Albino Formation dipping downstream (east) along the Middle Fork at about 20 to 30 degrees. Present plans included a dam to be constructed on the Middle Fork above the plain, on old landslide deposits. This will create a lake along the present course of the Middle Fork and will raise the local water table. With the increase of pore water pressure in the sediments, thus created, the probability of slumping and sliding into the lake from Flatiron Mountain would be increased. An unpleasant but not necessarily dangerous effect of slumping into the lake will be the probable silty or muddy nature of the water.

The only portion of the area mapped in this report that is scheduled for immediate development is the cirque of Lone Mountain. A ski lift is planned to extend onto the active portion of the rock glacier. Several statements can be made in regard to this location.

The movement, if any, of the rock glacier should be studied before structures are permanently anchored to it. It should be determined if ice exists in the rock glacier, and if so, in what form. Potter (1967) has predicted the following possible problem for construction of roads on rock glaciers. In the present climate, the ice exists in rock glaciers due to the insulating effect of the overlying mantle of debris. If this cover is removed, as by the construction of a road, it could cause local melting of the ice and collapse of the road. The active slopes or scarps should be avoided in construction because of their lack of stability. These can be recognized by their lack of vegetative growth in comparison to the inactive portions, and their steeper inclination.

The faulting in the cirque walls presents a different type of threat to development. There are two types of shale present in the cirque walls. A reddish weak shale that weathers into small pebbles or cobbles and moves downslope by frost action and debris slide. The other type is a considerably more resistant darker colored shale. This can move downslope by the failure of a large mass of such material. The boulders thus produced can measure 3 to 5 feet in diameter and momentum can move them a considerable distance. One such rockslide mapped had broken loose from the north wall of the cirque and moved out across the entire rock glacier in a narrow path. Another mass of this rock is faulted into an overhanging position nearby as shown in Figure 8. Differential erosion of the weaker shale will tend to remove support from the mass of resistant rock. Although this mass, if it should fail, would be likely to do so under freeze and thaw conditions in the spring or fall when the lifts are not in operation, it could cause damage to the lift line. Of course, an earthquake shock, common in this region might serve to trigger a slide at any time. Blasting might prove to be a useful preventative measure for this situation.

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APPENDIX

## APPENDIX

### Glossary of Geological Terms

ablation - The portion of a stagnant or retreating glacier or rock glacier that sustains a net loss of ice by melting.

andesite - A light to gray colored igneous rock composed of large light colored feldspar grains, and dark colored pyroxene and biotite (mica) grains surrounded by a matrix of very small grains.

anticline - A type of fold in which the rocks are bowed up along an axis.

basalt - A dark colored igneous rock composed of dark colored pyroxene and sometimes olivine grains, and gray feldspar grains.

Bull Lake stade - The early Wisconsin period of advance of valley glaciers ending approximately 70,000 years ago.

Cretaceous Period - The period of geologic time from about 130 million years to 60 million years ago.

fissile - A rock which easily splits into small pieces along parallel planes.

graben - An area which has been downdropped relative to adjacent topography due to a fault or landslide.

high angle reverse fault - A fault in which the plane of movement is highly inclined to the horizontal. The rocks above the fault plane are pushed up and over the rocks below.

igneous sill - A thin layer of igneous rock which was intruded as hot magma into sedimentary rocks parallel to the sedimentary layers.

Jurassic Period - The interval of geologic time from 180 to 130 million years ago.

kettle - A depression in a glacial deposit formed when a mass of stagnant ice melts and allows the overlying rock and soil to collapse into the space created.

mass-gravity movement - Any downslope movement of rock or soil caused mainly by the action of gravity on the mass of material.

Mesozoic Era - The period of geologic time between 220 and 60 million years ago. This includes the Triassic, Jurassic and Cretaceous periods.

metamorphism - Alteration of rocks by heat, pressure, and chemical activity.

moraine - A glacial deposit of rock and soil carried or pushed by a glacier and dropped at some period in its history.

outwash - Sands and gravels deposited by streams emanating from a glacier.

Paleozoic Era - Ther period of geologic time from approximately 600 million years to 220 million years ago.

Pinedale stade - The most recent period of major valley glaciation ending about 10,000 years ago.

Pleistocene Epoch - A recent period of geologic time from about 1 to 2 million years ago to 10,000 years ago. This epoch included many periods of valley and continental glaciation.

Quaternary - The period of time from the beginning of the Pleistocene Epoch to the present time.

scarp - A usually steep cliff or slope from which movement along a fault or landslide has occurred.

superposed - Streams that were forced to cut a channel in resistant rock because they once flowed on a surface of weaker sediment which covered the hard rock below. When this weak rock was removed by erosion, the stream had established its course and could not avoid cutting a channel into the resistant rock beneath the soft cover.

syncline - The opposite type of fold from an anticline. The rocks have been folded (bowed) down along an axis.

talus - A mass of rocks at the base of an outcrop of bedrock. The pebbles or boulders weather and fall away from the outcrop and come to rest on the slope below.

Temple Lake sub-stade - A small recent advance of valley glaciers ending about 1000 years ago.

Tertiary Period - The interval of geologic time from 60 million years to about 2 million years ago.

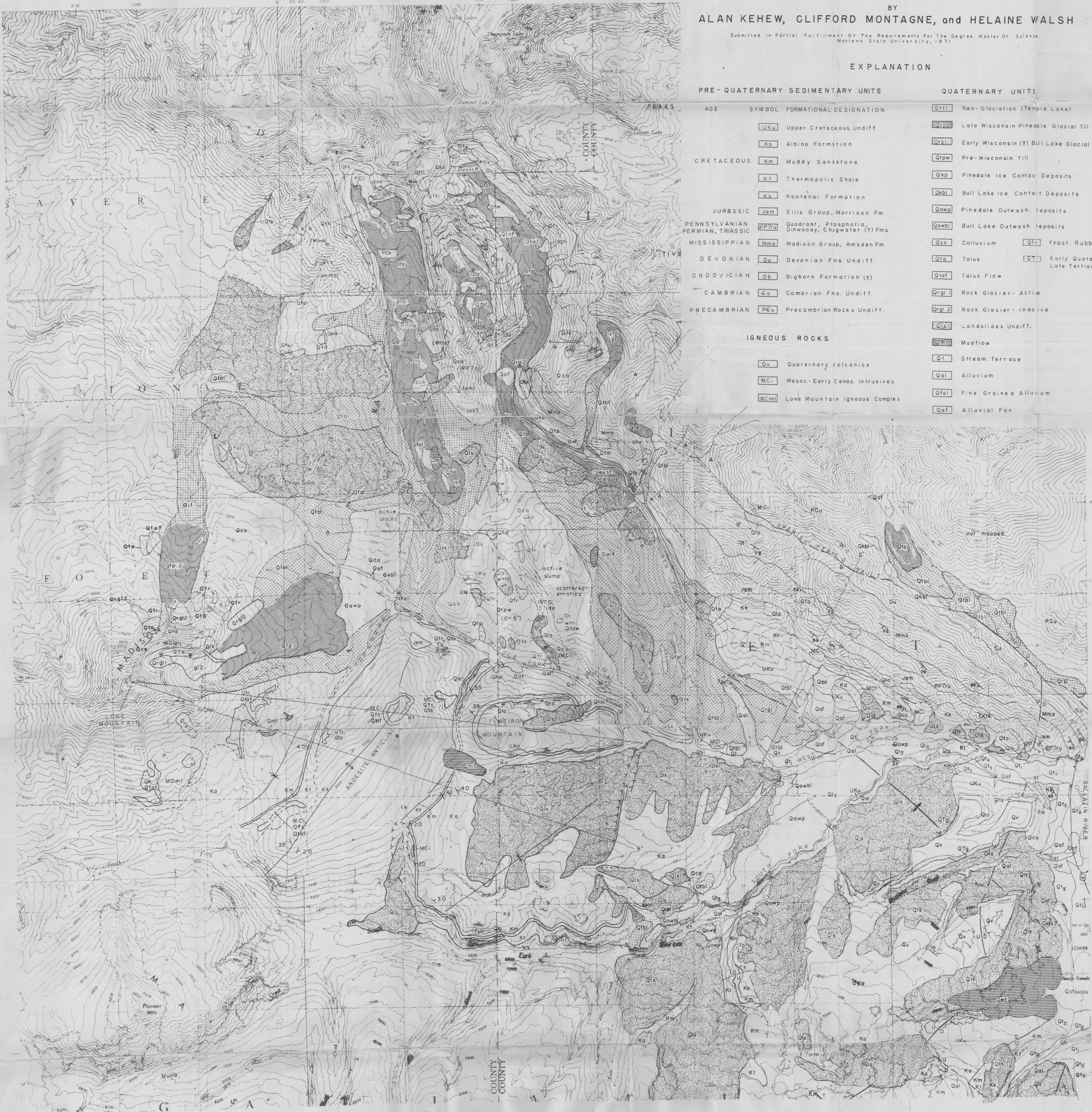
tuff - A rock composed of compacted volcanic ash.

Wisconsin Age - The latest part of the Pleistocene Epoch, including the Bull Lake and Pinedale glacial advances.

# ENVIRONMENTAL GEOLOGY OF THE WEST FORK BASIN
# GALLATIN COUNTY, MONTANA

BY
ALAN KEHEW, CLIFFORD MONTAGNE, and HELAINE WALSH

Submitted In Partial Fulfillment Of The Requirements For The Degree Master Of Science
Montana State University, 1971




## EXPLANATION

### PRE-QUATERNARY SEDIMENTARY UNITS

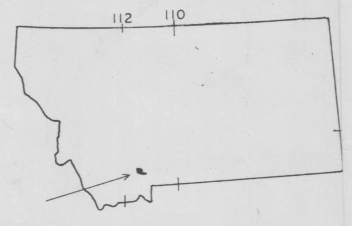
| AGE | SYMBOL | FORMATIONAL DESIGNATION |
|---|---|---|
| | UKu | Upper Cretaceous Undiff. |
| | Ka | Albino Formation |
| CRETACEOUS | Km | Muddy Sandstone |
| | Kt | Thermopolis Shale |
| | Kk | Kootenai Formation |
| JURASSIC | Jem | Ellis Group, Morrison Fm. |
| PENNSYLVANIAN PERMIAN, TRIASSIC | PPTru | Quadrant, Phosphoria, Dinwoody, Chugwater (?) Fms. |
| MISSISSIPPIAN | Mma | Madison Group, Amsden Fm. |
| DEVONIAN | Du | Devonian Fms. Undiff. |
| ORDOVICIAN | Ob | Bighorn Formation (?) |
| CAMBRIAN | Ꞓu | Cambrian Fns. Undiff. |
| PRECAMBRIAN | PꞒu | Precambrian Rocks Undiff. |

### IGNEOUS ROCKS

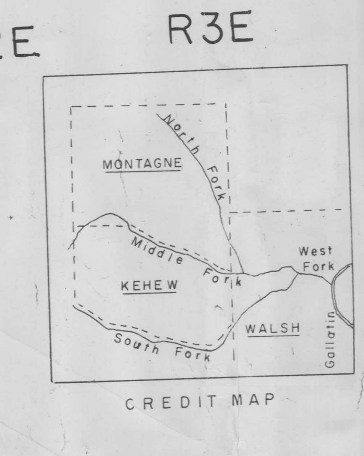
| | |
|---|---|
| Qv | Quaternary Volcanics |
| MCi | Mesoz.-Early Cenoz. Intrusives |
| MCIml | Lone Mountain Igneous Complex |

### QUATERNARY UNITS

| | |
|---|---|
| Qttl | Neo-Glaciation (Temple Lake) |
| Qtp | Late Wisconsin Pinedale Glacial Till |
| Qtbl | Early Wisconsin (?) Bull Lake Glacial Till |
| Qtpw | Pre-Wisconsin Till |
| Qkp | Pinedale Ice Contac Deposits |
| Qkbl | Bull Lake Ice Contact Deposits |
| Qowp | Pinedale Outwash Deposits |
| Qowbl | Bull Lake Outwash Deposits |
| Qco | Colluvium |
| Qta | Talus |
| Qtaf | Talus Flow |
| Qrgl 1 | Rock Glacier - Active |
| Qrgl 2 | Rock Glacier - Inactive |
| Qls | Landslides Undiff. |
| Qmf | Mudflow |
| Qt | Stream Terrace |
| Qal | Alluvium |
| Qfal | Fine Grained Alluvium |
| Qaf | Alluvial Fan |
| Qfr | Frost Rubble |
| QT | Early Quaternary - Late Tertiary Gravels |



MAP LOCATION




CREDIT MAP

SCALE 1:24,000

0 2000 4000 6000 8000 10,000 FEET

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

Bedrock Geology Modified From Swanson (190)
Base Map - U.S. Department of Interior Bureau of Reclamtion, Missouri Basin Project Sheets 116, 126

GN 0°16' MN 18°1/2

### SYMBOLS

- Formation and Surficial Unit Boundary
- Inferred or Uncertain Boundary
- Landslide Scarp (Hachures Point Downhill)
- Landslide Flow Direction
- A Snow Avalanche Path
- Ice Flow Direction
- U Upthrown Block
- Fault (Dashed Where Obscured)
- D Downdropped Block
- A—A' Location of Cross Section
- Morainal Form
- Anticlinal Axis
- Synclinal Axis
- Pre-Quaternary Bedrock Boundary Within A Surficial Unit

PLATE I