AN ABSTRACT OF THE THESIS OF

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Title: STRATIGRAPHY AND STRUCTURE OF THE SNOWFLAKE RIDGE AREA, GALLATIN COUNTY, MONTANA

Abstract approved: ______________________
Dr. D. A. Bostwick

The thesis area, consisting of 50 square miles, is located in Gallatin County, Montana, and includes parts of the Madison and Gallatin Ranges. About 5,000 feet of sedimentary rocks, representing the late Paleozoic Mississippian, Pennsylvania, and Permian periods and all of the Mesozoic periods, and an undetermined thickness of Tertiary igneous and volcanic rocks are exposed in the area of study.

Most of the Paleozoic and Mesozoic sedimentary rocks were deposited in a stable shelf environment. The oldest rocks exposed belong to the Madison Group of Early Mississippian age. Pennsylvanian rocks are included in the Amsden and Quadrant Formations and Permian rocks in the Phosphoria Formation. Mesozoic formations include the Dinwoody and Woodside of Triassic age, the Rierdon, Swift, and Morrison of Jurassic age, and the Kootenai,

Thermopolis, Muddy, and Albino of Cretaceous age. The youngest pre-Laramide rocks are Late Cretaceous undifferentiated continental(?) sedimentary rocks.

The Laramide orogeny produced the main structures in the area, which consist of three anticlines and four synclines, all north-trending and asymmetric, and a high-angle reverse fault that is associated with the overturned east flank of the largest anticline in the area. Several normal faults of post-Laramide age occur in the thesis area.

Intrusion of a dacite porphyry laccolith and extensive erosion followed the Laramide orogeny. Pliocene welded tuffs were laid down on a Tertiary erosion surface and, locally, over high-level fluvial gravels.

Quarternary glaciation modified parts of the Madison and Gallatin Ranges, and glacial deposits are present in the thesis area. Post-glacial erosion has dissected the glacial deposits and at present is actively eroding the area. Minor local alluvial deposits are forming on some of the valley floors.

Stratigraphy and Structure of the Snowflake Ridge Area, Gallatin County, Montana

by

Timothy Campbell Lauer

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INTRODUCTION

Location and Accessibility

The Snowflake Ridge area is located in southern Gallatin County, Montana, along the West Fork of the Gallatin River (Plate 1). The area mapped, consisting of approximately 50 square miles, includes all of T. 9 S., R. 4 E., and part of T. 9 S., R. 5 E., and lies at the extreme southern edges of the Crown Butte and Sphinx Mountain quadrangles.

The thesis area lies completely within the Gallatin National Forest, and the eastern half of the area is in the Gallatin Game Preserve. The eastern boundary of the area coincides with a part of the western boundary of Yellowstone National Park. The Spanish Peaks Wilderness Area lies 14 miles to the north. West Yellowstone, Montana, the nearest town, is 30 miles to the south. There are several lodges and motels in the Gallatin River Canyon from which gasoline and food may be purchased.

Most of the area lies within the Madison Range, which is separated geographically from the Gallatin Range by the West Fork of the Gallatin River. Five square miles in the northeastern part of the area lie within the Gallatin Range.

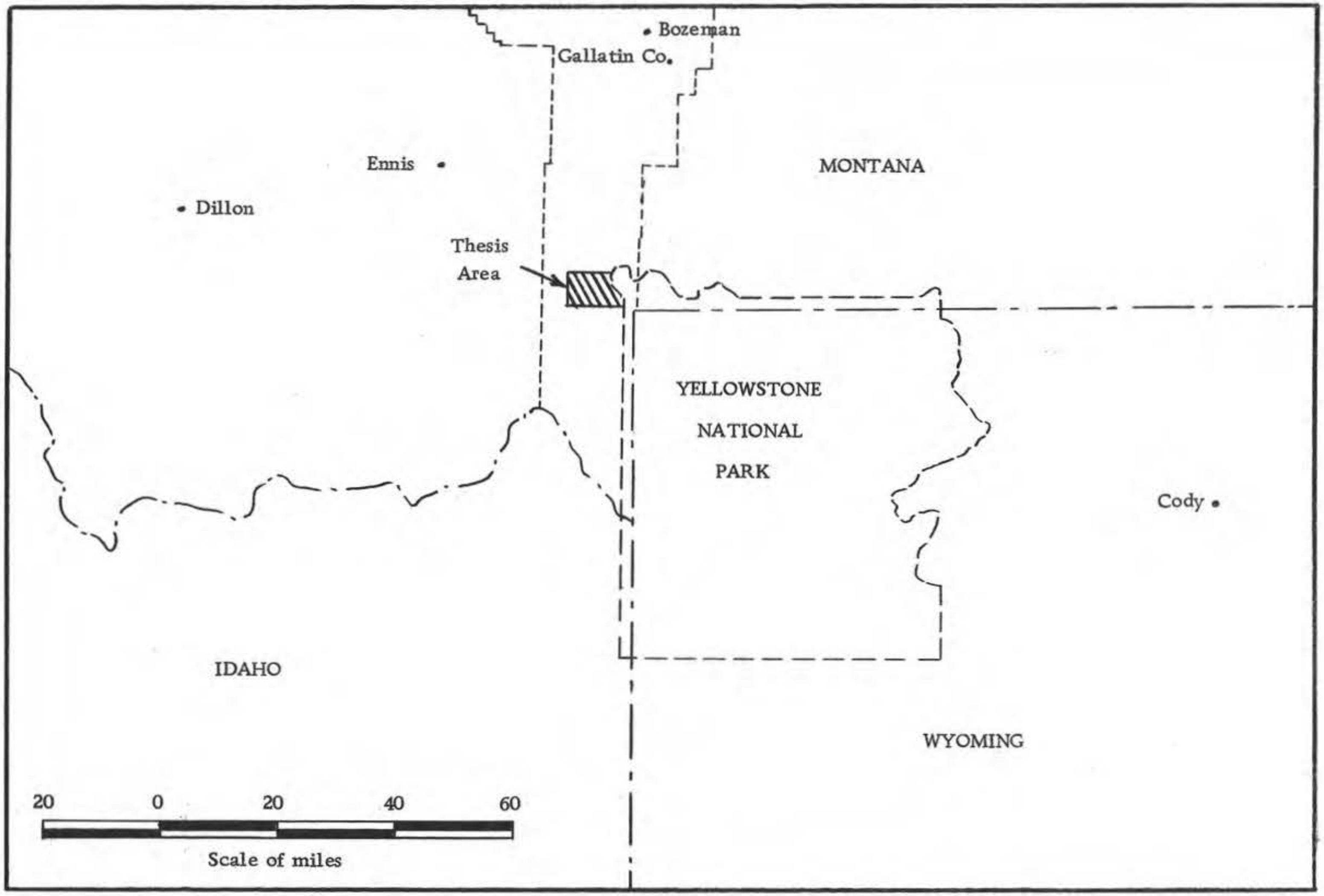


Plate 1. Index map showing location of thesis area.

U. S. Highway 191 provides the major access to the region and is the only road in the eastern part of the area. One good gravel road follows Taylor Fork west through the thesis area, and another gravel road--poor, but usually passable--extends southward 1.5 miles along Wapiti Creek at the western edge of the area. Dirt roads extend short distances up Sage and Monument Creeks to dude ranches but provide only limited access. Several jeep trails penetrate the area, but the best means of accessibility, owing to the high relief and thick vegetation, is by the numerous horse and foot trails.

Purpose and Method of Investigation

The primary purpose of this study was to produce a detailed geologic map of the Snowflake Ridge area and to measure and describe the lithologic variations of the formations within the area. Secondary objectives were (1) the determination of the position of the Snowflake Ridge area in relationship to the shelf edge of the geosyncline, and (2) to become more familiar with those sedimentary rocks typically found in the Rocky Mountains.

Owing to bad weather field work was not begun until the last week of June, 1965. The field investigation, completed September 26, 1965, lasted 13 weeks. The surface geology was plotted in the field on aerial photographs and topographic maps. A base map of the area was prepared from 15-minute quadrangle topographic maps of the

United States Geological Survey. With the assistance of Mr. Jimmie D. Ray, stratigraphic sections of 13 of the formations present in the area were measured.

Eighty-five thin sections were studied and 300 points per thin section were counted in determining modal analyses. Gilbert's classification of sandstones (81) and Leighton and Pendexter's classification of carbonate rocks (49) were used predominantly in expressing the results of modal analyses. Dolomite texture and fabric terminology follow the usage proposed by Friedman (32).

Fossils collected in the field were identified by the author.

Previous Work

The first geological investigation of the Snowflake Ridge area took place in the summer of 1872 when F. V. Hayden and his party ascended the Gallatin Canyon to the source of the Gallatin River. His account of this survey appears in the 6th Annual Report of the United States Geological Survey of the Territories (40, p. 77-81). In 1893, Peale (60) studied the geology of the Three Forks region to the north of the thesis area, and in 1896 a folio (61) of his maps was published.

Between the time of Hayden's survey and 1948 there were numerous geologic investigations throughout the region, especially in Yellowstone National Park. However, Wilsey (83), in the latter year, conducted the first detailed geologic work within the thesis area. Hall (38) mapped and studied the geology of the northern part of the thesis area and much more of the Upper Gallatin Valley region. Witkind (84) has recently completed a preliminary investigation of the Tepee Creek Quadrangle which lies immediately to the south of the Snowflake Ridge area.

Relief

The lowest elevation in the area of this investigation is 6,538 feet in the Gallatin River Canyon at the north boundary of the area. A maximum elevation of 9,319 feet occurs in the southern part of the area, west of Monument Creek. Thus, the maximum topographic relief is 2,780 feet. The local relief is greatest in the eastern part of the area, locally exceeding 1,700 feet (Figure 1). In the western part of the area the relief is considerably less and many of the slopes are dip slopes. Landslides are numerous in the extreme west and have produced an irregular, rolling topography of low relief (Figure 2). However, several high cliffs have been formed by landsliding.

Drainage

The Snowflake Ridge area is drained by numerous north-northeast-flowing streams that empty into the Gallatin River, which serves as the main drainage artery for the eastern half of the

Figure 1. View south up Sage Creek from top of Gallatin River Canyon. Relief is about 1,550 feet from top of canyon to the highway.

Figure 2. View southwest from Marble Point showing Wapiti Creek flowing into Taylor Fork Valley in the foreground.

Madison Range and the western half of the Gallatin Range (Figure 3). Taylor Fork and its major tributaries, Wapiti, Meadow, and Slide Creeks, drain most of the northern and western parts of the mapped area. Sage Creek and its three major tributaries, Canyon, Big Spring, and Little Spring Creeks, drain the central part of the area. Monument, Lodgepole, and Tepee Creeks drain directly into the Gallatin River and provide the drainage for the eastern part of the thesis area. Almost all the streams within the area flow the year around.

The northward-flowing Gallatin River has a gradient of about 44.5 feet per mile, which is the lowest stream gradient in the thesis area. A maximum gradient of approximately 720 feet per mile exists on the westward-flowing unnamed tributary to Big Spring Creek.

Climate

The nearest United States Weather Bureau stations are at West Yellowstone, Montana, 30 miles to the south, and Hebgen Dam, Montana, about 15 miles to the southwest. Both stations have nearly identical climates, and except for the higher elevations within the thesis area, which have lower average temperatures and greater amounts of precipitation, the climate at both of these stations is similar to that of the Snowflake Ridge area. Climatological data for the region is based on averages for the years 1931 through 1960 (79)

Figure 3. Gallatin River Valley. View south from Pulpit Rock.

at these two stations.

The annual mean temperature within the area is about 35° F. Winter temperatures seldom rise above freezing and temperatures below 0° F are of common occurrence. January is the coldest month with an average temperature of 11° F. July is the warmest month, with an average temperature of approximately 60° F. Summer temperatures rarely rise above 80° F. and often drop below freezing. During the fall and winter frequent rapid temperature changes are caused by warm, dry Chinook winds from the northwest, which may raise the temperature as much as 40° F. in 24 hours (78, p. 376-377).

Annual precipitation within the area is about 21 inches, and is more or less evenly distributed throughout the year. Winter precipitation is mostly in the form of snow, and thunderstorms provide much of the summer precipitation. A rainy season occurs during the first two to three weeks of June.

Vegetation

The diversified vegetation that covers the area has a zonation controlled by elevation (58) but has also been shown in general to correlate in location with the outcrop patterns of the formations. Within the thesis area there are several places that are so densely vegetated as to obscure the surface geology, making field work difficult.

Below 7,000 feet lodgepole and limber pine are associated with Rocky Mountain Douglas fir, but above this elevation the Douglas fir gives way to Engelmann spruce and subalpine fir in association with lodgepole and limber pine. Near the timber line (9,500 feet) subalpine fir becomes the important dominant, but whitebark pine is also found at or near the timber line. Localized patches of aspen occur on the numerous landslide areas and along streams. Willow thickets are found along the larger streams. Open areas support a luxuriant growth of grasses, sagebrush, sedges, and wildflowers.

STRATIGRAPHY

Rocks ranging in age from Precambrian to Quaternary are exposed in the Madison and Gallatin Ranges surrounding the Snowflake Ridge area. A short summary of these rocks is presented in the following section.

Regional Stratigraphy

Precambrian metamorphosed sediments are the basement rocks of the region. Excellent exposures occur in the high Madison Range six miles east of the Snowflake Ridge area and along the Gallatin River Canyon starting at a point about 13 miles north of the area of study. The metamorphic rocks also crop out on the east flank of the Gravelly Range, the west side of the Greenhorn and Snowcrest Ranges, in the Cherry Creek metamorphic complex south of Ennis, Montana, and in the area of the Madison River Canyon north of Ennis. These rocks consist of intricately folded and faulted gneisses, schists, amphibolites, quartzites, and phyllites. Locally the Precambrian rocks contain both acidic and basic intrusive bodies.

The Paleozoic rocks of southwestern Montana are predominantly marine sandstones, limestones, dolomites, and shales. Paleozoic rocks crop out in and around the Snowflake Ridge area, and the complete Paleozoic sequence is exposed north of the thesis area along the Gallatin River Canyon and west of the area of study in the high part of the Madison Range. In southwestern Montana the total thickness of the Paleozoic rocks is about 3,000 feet, but to the south and southwest the sequence becomes progressively thicker. The Paleozoic stratigraphy of southwestern Montana has been discussed by Sloss and Moritz (71).

Outcrops of Mesozoic rocks are numerous in southwestern Montana, but the thickness of these rocks is variable, especially in the lower half of the sequence. The lower part of the section consists mainly of marine sandstone, siltstone, mudstone, shale, limestone, and minor gypsum, and the upper part is composed of continental sandstones, siltstones, shale, claystone, and coal. The lower part of the marine sequence thickens rapidly westward into the geosyncline, where in southeastern Idaho the Triassic beds alone are more than 6,500 feet thick. To the east the marine section thins and intertongues with the continental sequence of the stable platform.

In southwestern Montana Tertiary rocks are both sedimentary and volcanic. With the close proximity of the Snowflake Ridge area to the Yellowstone Plateau, volcanic rocks are dominant in the thesis area. However, farther to the west and northwest, where the Sphinx Conglomerate (3,000 feet thick) and Livingston Formation (2,100 feet thick) are present, sedimentary Tertiary rocks are dominant. Dikes and sills of Tertiary age are numerous in the region.

Glacial, landslide, and alluvial deposits of Quaternary age cover much of the region. At higher elevations deposits of glacial moraine are numerous, and at least one tillite is also present. Landslide deposits are very abundant in the Madison and Gallatin Ranges and often are a significant part of the surface geology. All of the major stream and river valleys are blanketed by alluvial deposits of sand and gravel.

Thesis Area Stratigraphy

Sedimentary, volcanic, and igneous rocks ranging in age from Early Mississippian to Quaternary are exposed in the Snowflake Ridge area. In terms of thickness the sedimentary rocks are by far the dominant type, having an aggregate thickness of 4,000 to 5,000 feet. Table 1 gives a summary of the stratigraphic units, their thicknesses, general lithologies, and ages. A correlation chart (Table 2) is provided for stratigraphic comparison of rocks of the Snowflake Ridge area with those of surrounding regions. The following sections present the distribution and physiographic expression, detailed lithologies, fossil content, ages, sources, and depositional environments of the stratigraphic units in the Snowflake Ridge area.

Table 1. Summary of Stratigraphic Units

Age	Formation		Lithology	Thickness in feet
Quaternary			Alluvial valley fill.	
		Unconformity		
Quaternary			Landslide deposits.	
		Unconformity		
Quaternary			Tillite	
Quaternary			Glacial moraine and till.	
		Unconformity		
Tertiary			Welded tuffs.	?
		Unconformity		
Tertiary			High level gravels.	?
		Unconformity		
Tertiary			Dacite porphyry laccolith.	?
		Unconformity		
Cretaceous	Upper Cretaceous undifferentiated		Sandstones, siltstones, mudstones and shales; rocks commonly very siliceous.	0-1000?

Table 1. (continued)

Age	Formation	Lithology	Thickness in feet
	Unconformity		
Cretaceous	Albino Formation	Varicolored tuffaceous, siliceous shales, claystones, siltstones, and sandstones; bentonites.	250
	Disconformity		
Cretaceous	Muddy Sandstone	Cross-bedded, calcareous, salt-and-pepper sandstone.	100
Cretaceous	Thermopolis Shale	Gray to black shale.	180
	Disconformity		
Cretaceous	Kootenai Formation	Conglomerates and conglomeratic feldspathic arenites, mudstones, fresh-water limestones, and quartz arenite.	430
	Disconformity		
Jurassic	Morrison Formation	Calcareous varicolored mudstones and quartz arenites.	320
Jurassic	Swift Formation	Oolitic-glauconitic calcarenites and conglomeratic sandstones.	60

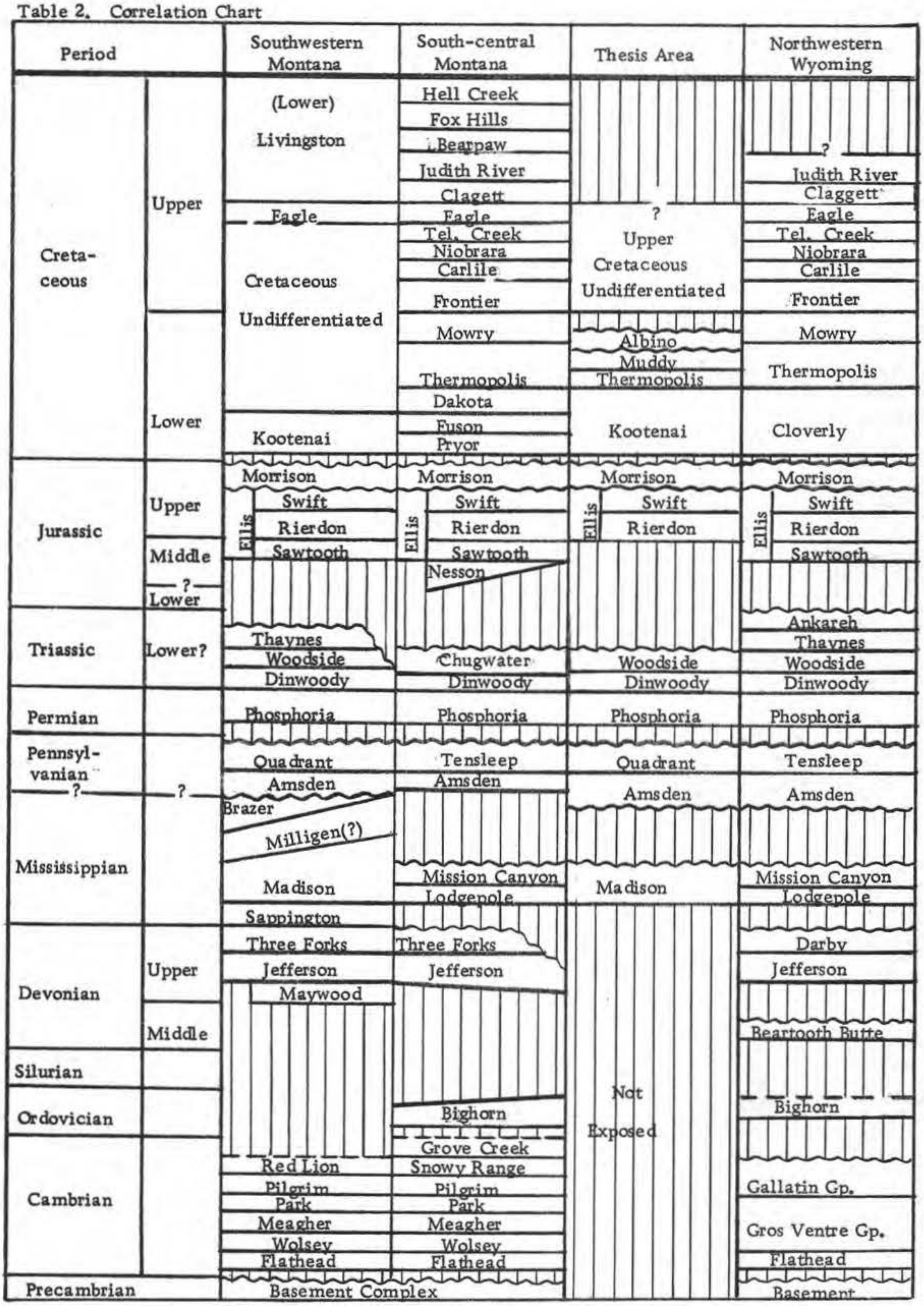
Table 1. (continued)

Age	Formation	Lithology	Thickness in feet
Jurassic	Rierdon Formation	Thin-bedded, fossiliferous, muddy limestones and limy mudstones.	120
	Disconformity		
Triassic	Woodside Formation	Red, slightly calcareous mudstone, subordinate thin interbedded siltstone, and very fine-grained sandstones.	130
Triassic	Dinwoody Formation	Thin gray to brown limestone, siltstone, and sandstone.	105
	Disconformity		
Permian	Phosphoria Formation	Gray brown, and orange, slightly calcareous quartz arenites, dark cherts, and phosphorite.	155
	Disconformity		
Pennsylvanian	Quadrant Formation	Very light gray, cross-bedded arenaceous limestone, calcareous quartz arenite, and quartz arenite.	260
	Disconformity		

Table 1. (continued)

Age	Formation	Lithology	Thickness in feet
Pennsylvanian	Quadrant Formation	Very light gray, cross-bedded arenaceous limestone, calcareous quartz arenite, and quartz arenite.	260
	Disconformity		
Pennsylvanian to Mississippian	Amsden Formation	Red detrital dolomite, mudstone, and limestone breccia.	100
	Disconformity		
Mississippian	Madison Group (Mission Canyon Limestone and Lodgepole Formation)	Thin-bedded to massive, fossiliferous limestones and dolomite; solution limestone breccia at top.	1320
	Base not exposed		

Table 2. Correlation Chart



Period		Southwestern Montana	South-central Montana	Thesis Area	Northwestern Wyoming
Creta-ceous	Upper	(Lower) Livingston Eagle Cretaceous Undifferentiated	Hell Creek Fox Hills Bearpaw Judith River Clagett Eagle Tel. Creek Niobrara Carlile Frontier	? Upper Cretaceous Undifferentiated	? Judith River Claggett Eagle Tel. Creek Niobrara Carlile Frontier
	Lower	Kootenai	Mowry Thermopolis Dakota Fuson Pryor	Albino Muddy Thermopolis Kootenai	Mowry Thermopolis Cloverly
Jurassic	Upper	Morrison Ellis Swift Rierdon	Morrison Ellis Swift Rierdon	Morrison Ellis Swift Rierdon	Morrison Ellis Swift Rierdon
	Middle	Sawtooth	Sawtooth Nesson		Sawtooth
	— ? — Lower				
Triassic	Lower?	Thaynes Woodside Dinwoody	Chugwater Dinwoody	Woodside Dinwoody	Ankareh Thaynes Woodside Dinwoody
Permian		Phosphoria	Phosphoria	Phosphoria	Phosphoria
Pennsyl-vanian ?—	?	Quadrant Amsden	Tensleep Amsden	Quadrant Amsden	Tensleep Amsden
Mississippian		Brazer Milligen(?) Madison Sappington	Mission Canyon Lodgepole	Madison	Mission Canyon Lodgepole
Devonian	Upper	Three Forks Jefferson Maywood	Three Forks Jefferson	Not Exposed	Darby Jefferson
	Middle				Beartooth Butte
Silurian					
Ordovician			Bighorn		Bighorn
Cambrian		Red Lion Pilgrim Park Meagher Wolsey Flathead	Grove Creek Snowy Range Pilgrim Park Meagher Wolsey Flathead		Gallatin Gp. Gros Ventre Gp. Flathead
Precambrian		Basement Complex	Basement Complex		Basement

Synthesized by T. Lauer from various sources.

Mississippian System

Madison Group

The oldest rocks mapped in the Snowflake Ridge area are part of the Madison Group, of Early Mississippian age. The name Madison limestone was used by Peale (60, p. 33-39) for exposures of limestone in the Madison Range near the center of the Three Forks Quadrangle, Montana. He divided the Madison into three types of limestone; from bottom to top, they are, the Laminated limestones, Massive limestones, and Jaspery limestones. The Madison limestones were raised to group status by Collier and Cathcart (17, p. 173) when they divided the Madison limestones into the Lodgepole and Mission Canyon Formations. These workers designated a section 550 feet thick in Lodgepole Canyon on the north side of the Little Rocky Mountains as the type section of the Lodgepole Formation. The Mission Canyon Limestone type section is in the canyon where Saint Paul's Mission is located, along the west flank of the Little Rocky Mountains, where it is approximately 300 feet thick.

Both Lodgepole and Mission Canyon Limestones are present in the Snowflake Ridge area, but at most outcrops it was not possible to distinguish between these two gradational units. For this reason these formations were mapped together as the Madison Group.

Moreover, because the lithologic character of these two formations is so similar in the Snowflake Ridge area, they are discussed collectively here as the Madison Group.

Distribution and Physiographic Expression

Exposures of Madison Group limestones are present over most of the eastern part of the Snowflake Ridge area. The best exposures are along the Gallatin River, Sage Creek, and Canyon Creek.

The Madison Group limestones are very resistant and generally form large, sheer cliffs or stacklike outcrops (Figure 4). However, areas where soil is developed on the limestones are heavily timbered.

Thickness and Lithology

The thickest exposure of the Madison Group in the Snowflake Ridge area occurs on the north side of the Gallatin River canyon from NW1/4SW1/4 sec. 12, T. 9 S., R. 4 E., up the steep canyon slide to the NE1/4NW1/4NW1/4 sec. 12, T. 9 S., R. 4 E. (Figure 4). At this location the Madison limestones are on the west flank of the Snowflake anticline, where up-folding and river erosion has caused almost the complete unit to be exposed in a section 1,318 feet thick. The base of the Lodgepole Formation is not exposed here, but comparison of the thickness of the section with a selection measured

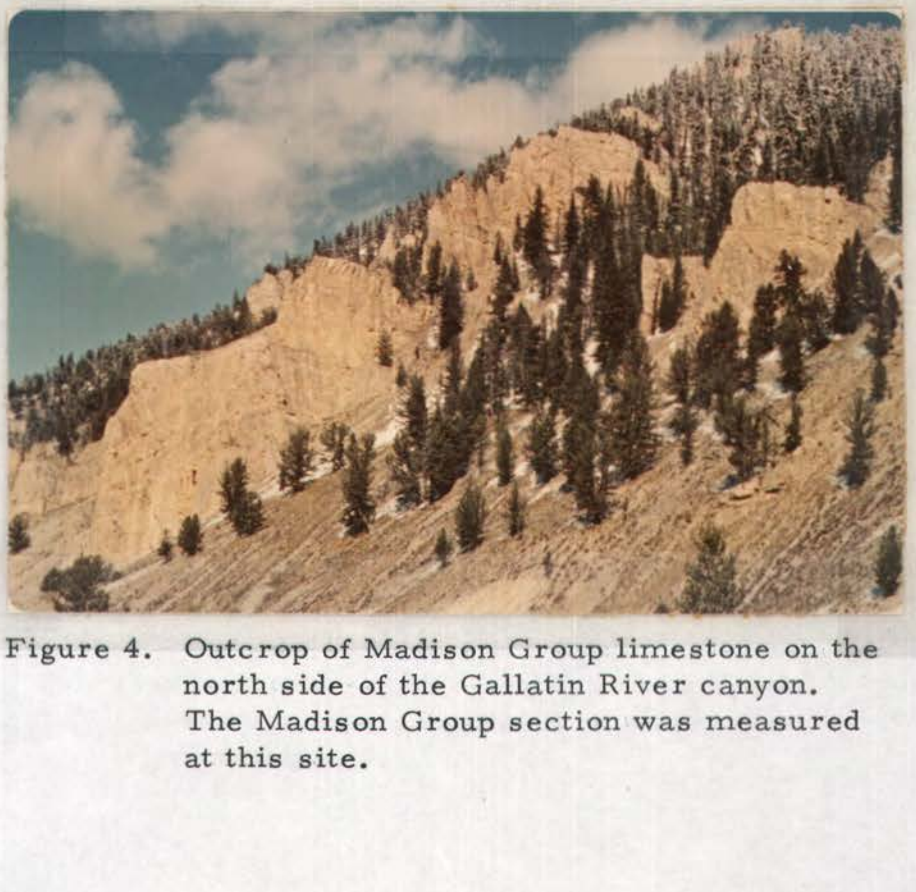


Figure 4. Outcrop of Madison Group limestone on the north side of the Gallatin River canyon. The Madison Group section was measured at this site.

by Hall (38) indicates that probably only 20 to 25 feet of basal Lodgepole beds are not exposed. The Madison section was sampled every five feet, and thin sections were cut from samples of each unit of the section. The petrographic information has been incorporated into the description of the stratigraphic section in Table 3. On the basis of field and petrographic evidence, the contact of the Mission Canyon Limestone with the Lodgepole Formation is placed at the top of unit 23.

Lodgepole Formation. In the Snowflake Ridge area the Lodgepole Formation consists of thin-bedded to massive, gray to brown, fossiliferous limestone (Figure 5). The upper part of the formation, which is the part most commonly exposed in the thesis area, becomes thick-bedded and indistinctly bedded. In the lower part of the formation beds range from 1/2 inch to 10 inches and are commonly 2 to 5 inches thick. Chert beds and chert stringers parallel to the bedding are common throughout the formation. The limestones of the Lodgepole Formation vary texturally from dense, very fine-grained to coarse-grained bioclastic. The reader is referred to Table 3, where each unit is named and described. A section of the Lodgepole Formation more than 870 feet thick was measured, but, because the base is not exposed, the total thickness of the formation is not known.

Mission Canyon Limestone. In the Snowflake Ridge area the Mission Canyon Linestone is made up of thick, indistinctly bedded

Table 3. Madison Group; stratigraphic section measured on the north side of the Gallatin River Canyon in the NW1/4 sec. 12, T. 9 S., R. 4 E.

Amsden Formation

Disconformity?: contact covered; top of Mission Canyon Limestone picked at break in slope above breccia zone.

Madison Group

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
33.	Limestone breccia: gray to yellowish-gray, according to clasts; increase in clast size upward from base; angular pebbles to angular boulders; mostly limestone boulders and chert pebbles in a matrix of finely crystalline limestone; massive cliff-forming unit with small caves and overhanging ledges. Top 10' covered.	95.6	1,318.7
32.	Covered section: probably same as unit 31.	11.0	1,223.1
31.	Dolomite: yellowish-gray (5Y 7/2), weathers pinkish-gray (5YR 8/1); beds 3' to 5' thick alternate with 2" beds; beds thin to 1' towards top and become less distinct. Thin sections 161 and 153.	51.1	1,212.1
30.	Dolomite: yellowish-gray (5Y 7/2), weathers pinkish-gray (5YR 8/1); dolomite rhombs less than 0.1 mm.; poorly bedded; highly fractured; unfossiliferous; numerous calcite veins filling fractures. Thin section 151.	11.1	1,161.1
29.	Dolomite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); poorly bedded to massive. Thin section 149.	5.0	1,150.1
28.	Covered section: talus and sparse outcrops indicate unit is same as unit 29.	195.0	1,145.1
27.	Oolitic limestone: light-olive-gray (5Y 6/1), weathers light-gray (N7); massive; oolites composed of concentric layers of micrite on a nucleus of a skeletal fragment; skeletal grains include echinoid spines, bryozoans, and crinoid columnals; some grains not coated. Thin section 147.	20.0	950.1

Table 3. (continued)

Unit	Description	Thickness (feet)	
		Unit	Total
26.	Limestone breccia: light-olive-gray (5Y 6/1), weathers light-gray (N7); bedding indistinct; contains white and brown angular chert pebbles and granules; angular limestone pebbles up to 3" long; crystalline limestone matrix; possible solution breccia.	25.0	930.1
25.	Dolomite: light-olive-gray (5Y 6/1); weathers light-gray (N7); bedding indistinct; euhedral dolomite rhombs with lenses of argillaceous carbonate and patches of recrystallized sparry calcite. Thin section 142.	10.0	905.1
24.	Dolomite: light-olive-gray, (5Y 6/1); weathers light-gray (N7); thinly laminated (less than 1/2"); contains microcrystalline mosaic of subhedral dolomite rhombs with a trace of authigenic quartz; subordinate crinoid stems. Thin section 137.	30.0	895.1
23.	Covered section: probably same as unit 22.	15.0	865.1
22.	Skeletal limestone: pale-yellowish-brown (10YR 6/2), weathers light-olive-gray (5Y 6/1); beds range from 1/2" to 2', average 14"; skeletal fragments of crinoids, brachiopods, and endothyrid foraminifers; sparry calcite cement. Thin section 133.	30.0	350.1
21.	Skeletal-oolitic limestone: pale-yellowish-brown (10YR 6/2), weathers light-olive-gray (5Y 6/1); massive; uncoated skeletal grains are crinoid columnals, brachiopod shells, echinoid spines, and tests of endothyrid foraminifers; most oolites have skeletal grains as nuclii; sparry calcite cement recrystallized from micritic lumps. Thin section 126.	25.0	820.1
20.	Calcite: white; 3" layer of calcite crystals 3/4" to 1" long and intergrown from the top and bottom of the layer.	0.25	795.1

Table 3. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
19.	Oolitic-skeletal limestone: pale-yellowish-brown (10YR 6/2), weathers light-olive-gray (5Y 6/1); 4' beds of oolitic limestone alternate with a series of 1" to 2" beds in 4' units; thin beds appear chalky; oolites subordinate, some with skeletal grains as nuclii; skeletal grains include crinoid stems, echinoid spines, and endothyrid foraminifers; cement is pore-filling sparry calcite. Thin section 123.	16.25	794.85
18.	Skeletal-oolitic limestone: pale-yellowish-brown (10YR 6/2), weathers light-olive-gray (5Y 6/1); massive; oolites formed of micrite around skeletal fragment nuclii; endothyrid foraminifers, echinoid spines, and ostracods; sparry calcite cement. Thin section 121.	13.5	778.6
17.	Skeletal limestone: pale-yellowish-brown (10YR 6/2), weathers medium-light-gray (N6); bedding in lower 70' ranges from 1" to 1', averages 3"; skeletal grains include crinoid stems, ostracods, bryozoans, and algal structures; lower 10' of unit is skeletal-dolomitic limestone to microcrystalline dolomite with a trace of detrital quartz. Thin sections 99 and 117.	108.0	765.1
16.	Skeletal limestone: brownish-gray (5YR 4/1), weathers pale-yellowish-orange (10YR 8/6); massive; echinoid spines, algal structures, and bryozoan fragments; sparry calcite cement; lower 5' is dolomite. Thin section 92 and 96.	28.0	657.1
15.	Micritic limestone: brownish-gray (5YR 4/1), weathers pale-yellowish-orange (10YR 8/6); thin beds (3" to 8") interrupted by layers of very thinly laminated (less than 1/4") micrite; euhedral dolomite rhombs are recrystallizing from micrite matrix; several skeletal grains of crinoid columnals present. Thin section 90.	57.0	629.1
14.	Skeletal-micritic limestone: colors same as in unit 10; laminated micritic limestone (less than 1/2") layers alternate with 2" to 5" skeletal limestone beds;		

Table 3. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
	micritic limestone has microscopic cut-and-fill structures with skeletal grains filling cuts in the micrite; skeletal grains are ostracods, crinoids columnals, echinoid spines, bryozoan fragments, algal structures, and endothyrid foraminifers; selective replacement of some skeletal grains by chert. Thin sections 73 and 77.	60.0	572.1
13.	Lump-skeletal limestone: colors same as in unit 10; lump composed of micrite; skeletal grains are ostracods, crinoid stems, and brachiopods; some skeletal grains replaced by chert. Thin section 66.	30.0	512.1
12.	Micritic-lump limestone: colors same as in unit 10; micritic layers (less than 1/16") alternate with 2" to 5" limestone beds; contains poorly preserved skeletal fragments; trace detrital quartz. Thin section 60.	25.0	482.1
11.	Micritic limestone: colors same as in unit 10; beds 2" to 5"; dense; patches of sparry calcite; micrite being recrystallized to euhedral dolomite rhombs. Thin section 55.	30.0	457.1
10.	Micritic-lump limestone: light-olive-gray (5Y 6/1), weathers moderate-yellowish-brown (10YR 5/4); thin bedded (1/2" to 4"); limestone interrupted by at least 60 repetitions of paper-thin (less than 1/16") micritic layers; micritic layers become less abundant near top; micritic lumps about 0.25 mm. in diameter. Thin section 51.	40.0	427.1
9.	Skeletal limestone: pale-brown (5YR 5/2), weathers grayish-orange (10YR 7/4); massive; contains skeletal fragments of brachiopods, algal structures, crinoids, bryozoans, echinoid spines, and ostracods; sparry calcite cement; minor replacement of crinoids by chert. Thin sections 39 and 44.	31.0	387.1
8.	Skeletal limestone: colors same as in unit 6: bedding ranges 3" to 10", averages 9"; skeletal grains are algal structures, bryozoans, crinoids, and brachiopods; cement is microsparrite; trace of authigenic quartz and chert replacing some crinoid fragments; trace detrital quartz. Thin section 34.	39.0	356.1

Table 3. (continued)

Unit	Description	Thickness (feet) Unit	Total
7.	Skeletal-lump limestone: colors same as in unit 6; 8" to 10" limestone beds alternate with micritic laminations (less than 1/16"); lumps composed of micrite; skeletal fragments are crinoid stems, horn corals, brachiopods and a few gastropods; brachiopods partially replaced by chert; micrite cement; some detrital quartz. Thin section 28.	18.0	317.1
6.	Crinoidal limestone: pale-brown (5YR 5/2), weathers grayish-orange (10YR 7/4); massive; composed dominantly of crinoid plates, some replaced by chert, and minor bryozoan fragments; medium- to coarsely-crystalline sparry calcite. Thin section 26.	5.0	299.1
5.	Dolomite: light-gray (N7); weathers grayish-orange (10YR 7/4); very finely crystalline dolomite rhombs; contains small (1/8" to 1/2" in diameter) circular hematite cemented patches which occur in this unit only; trace of authigenic quartz. Thin section 25a.	2.0	294.1
4.	Chert-skeletal limestone: 10" beds alternate with 1" layers of micritic limestone which increase to 2" near top; chert replaces skeletal fragments of brachiopods, horn corals, and crinoid stems; chert nodules elongate parallel to bedding. Thin section 23.	35.0	292.1
3.	Micritic-skeletal limestone: pale-brown (5YR 5/2), weathers grayish-orange (10YR 7/4); chert is olive-gray (5Y 4/1), weathers pale-yellowish-brown (10YR 6/2); chert layers thicken (up to 10") near top; skeletal fragments are crinoids, horn corals, bryozoans, ostracods, and brachiopods; most partly replaced by chert; matrix microsparrite to micrite. Thin section 18, 16, and 6.	69.6	257.1

Table 3. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
2.	Skeletal-micritic limestone: isolated chert layers and nodules 1/2" to 3" thick; skeletal fragments are bryozoans, horn corals, brachiopods, and crinoid stems, in micrite matrix; abundant chert replacement of skeletal fragments and matrix. Thin section 4.	0.9	187.5
1.	Skeletal limestone: light-olive-gray (5Y 6/1), weathers moderate orange-pink (5YR 8/4); chert beds ranging from 1/4" to 1 1/4" alternate with limestone beds 6" to 8"; skeletal fragments are bryozoans, ostracods, horn corals, and crinoid stems; chert replaces skeletal fragments in layers; lower 172' covered; isolated outcrops indicate lithology is the same. Thin sections 1 and 2.	186.0	186.0
	Total thickness.....	1,318.7	

Disconformity?: base of Madison Group not exposed, and character of contact with underlying unit unknown.

and massive gray dolomite, limestone, and limestone breccia. Stringers and lenses of chert parallel to the bedding are present but are not as abundant as in the Lodgepole Formation. The limestone breccia at the top of the Mission Canyon appears to be a solution breccia formed on a karst surface (Figure 6). The irregular contact with the underlying dolomite and the large angular clasts of limestone within the breccia indicate this unit was formed above sea level. The limestone breccia is composed of angular pebbles, cobbles, and boulders of limestone and angular pebbles and cobbles of chert in a finely crystalline limestone matrix. The unit forms large cliffs, which commonly have overhanging ledges and small caves. Microscopic descriptions of the Mission Canyon units are given in Table 3.

Fossils and Age

Beds of the Madison Group are very fossiliferous in the Snowflake Ridge area, especially those of the Lodgepole Formation. The following fossils were collected from the Madison limestones and identified by the author:

- Phylum Protozoa
    - Endothyra sp.
- Phylum Coelenterata
    - Syringopora sp.
    - Hapsiphyllum sp.
- Phylum Coelenterata (continued)
    - Lithostrotionella sp.
    - Horn coral, unidentified

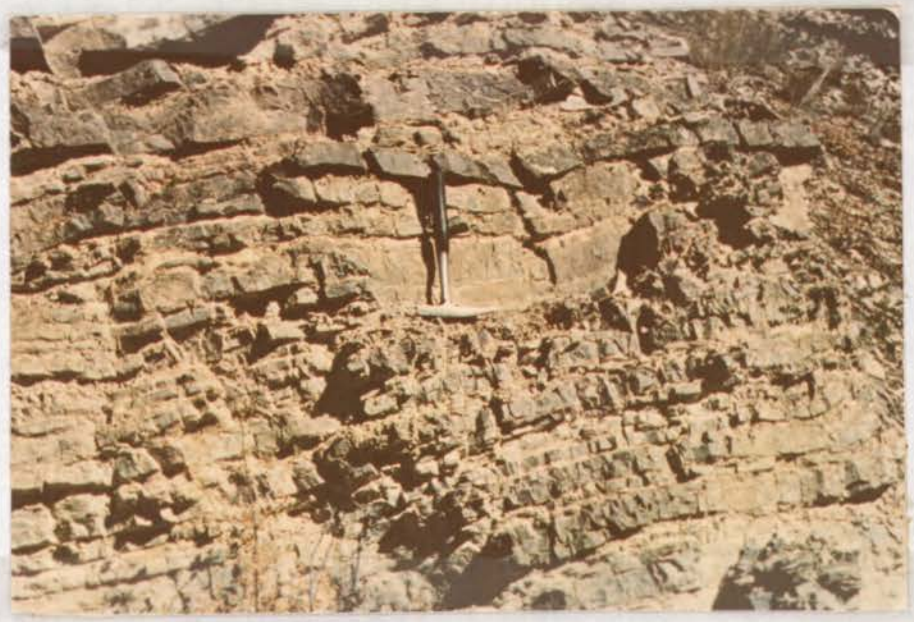


Figure 5. Typical thin-bedded limestone with limy mudstone partings of the Lodgepole Formation.

Figure 6. Mission Canyon solution breccia formed on a karst surface. Karst surface drawn in black.

Phylum Bryozoa
  Fenestrellina sp.
  Aulopora sp.
  Lioclema sp.
Phylum Brachiopoda
  Dictyoclostus sp.
  Linoproductus sp.
  Echinoconchus sp.
  Leptaena sp.
  Derbya sp.
  Schuchertella sp.
  Camarotoechia sp.
  Stegerhynchus (?) sp.
  Hustedia sp.
Phylum Brachiopoda (continued)
  Spirifer sp.
  Orthotetes sp.
  Atrypa sp.
  Composita sp.
  Dielasma sp.
  Schellwienella (?) sp.
Phylum Mollusca
  Platyceras sp.
Phylum Echinodermata
  Platycrinites sp.
  Crinoid calyx, unidentified
  Schizoblastus sp.

By reason of faunal, lithologic, and stratigraphic correlation with other dated sections in Montana the Madison Group of the thesis area is dated as Early Mississippian. The Lodgepole Formation is believed to have a Late Kinderhookian and Osagean age, and the Mission Canyon is considered to be of Osagean age (56, chart no 5).

Origin and Depositional Environment

Lodgepole Formation. The fauna and lithology of the Lodgepole Formation indicates deposition in a mid-neritic to shallow-neritic marine environment. The cyclic, thin-bedded limestones of the lower and middle part of the formation, as well as the detrital grains in the oolitic, lump, and bioclastic limestones, suggests deposition in a shallow water, agitated environment. Textures of these limestones indicate that both autochthonous and allochthonous calcite are present. Autochthonous carbonate is dominant, but allochthonous carbonate, probably derived from surrounding bottom sediments and benthonic faunas, is also present.

The thicker-bedded upper part of the Lodgepole Formation apparently represents a transition to a deeper marine environment, leading to the deep marine environment of the Mission Canyon Limestone. Detrital material is negligible, and the dense limestones probably originated beyond the zone of turbulence. The presence of skeletal limestones with benthonic faunas indicates deposition was still within the neritic zone.

Mission Canyon Limestone. The predominantly dolomitic, massive nature of the Mission Canyon indicates that deposition was in a deep marine environment, considerably west of the bordering landmass. The dolomites appear to have formed by diagenetic recrystallization of micritic limestones. Calcareous mud was probably deposited in relatively quiet neritic waters below the depth of wave action.

Pennsylvanian System

Amsden Formation

The Amsden Formation of Late Mississippian-Early Pennsylvanian age disconformably overlies the Mission Canyon Limestone in the Snowflake Ridge area. Darton (21, p. 394-401) first described the Amsden Formation as a sequence of red shales, white limestones, dolomites, and cherty and sandy limestones along the Amsden Branch of the Tongue River, west of Dayton, Wyoming. Scott (68, p. 1021) was the first to recognize the Amsden Formation in the Madison Range when he correlated beds that Peale previously had assigned to the Quadrant Formation with the Amsden Formation.

In the thesis area the Amsden Formation is very poorly exposed or absent. At Pulpit Rock, in sec. 3, T. 9 S., R. 4 E., on the west side of the Gallatin River Canyon, the Quadrant Formation directly overlies the Mission Canyon Limestone, but across the canyon the Amsden Formation is present. Amsden rocks are also absent along parts of the west side of Sage Creek Valley. Nowhere in the area is the contact of the Amsden Formation with the Quadrant Formation exposed, and the only good exposures of the Amsden Formation are outside of the area to the north. Where the section was measured, in sec. 4, T. 8 S., R. 4 E., the Amsden Formation appears to overlie the Mission Canyon Limestone disconformably and to be overlain disconformably by the Quadrant Formation.

Distribution and Physiographic Expression

The Amsden Formation crops out in the western half of the Snowflake Ridge area but is probably the worst exposed formation in the area.

Bright red and reddish-brown soils developed on the Amsden rocks are invaluable in mapping the formation. The general lack of resistance to weathering of the unit causes outcrops to be small and low-lying, and causes exposures to form gentle slopes between the more resistant Mission Canyon and Quadrant formations.

Thickness and Lithology

The Amsden Formation in the thesis area has a maximum thickness of 100 feet (Table 4), but the thickness of this unit is variable.

In the Snowflake Ridge area the Amsden Formation consists of a sequence of dolomites, sandy dolomites and sandstone. The basal unit is nearly pure limestone, but the formation becomes more dolomitic and sandy upward. The top bed of the formation is a slightly dolomitic quartz arenite. A dolomitic intraformational breccia, 5.5 feet thick, occurs near the top of the Amsden section.

Table 4. Amsden Formation; stratigraphic section measured on the east side of the Gallatin River Canyon, opposite Red Cliff Campground, in the SW1/4NE1/4 sec. 4, T. 8 S., R. 4 E.

Quadrant Formation

Conformable: contact appears gradational over an interval of about 5 feet.

Amsden Formation

Unit	Description	Thickness (feet)	
		Unit	Total
9.	Dolomitic quartz arenite: moderate-reddish-brown (10R 6/4), weathers pale-reddish-brown (10R 5/4); bedding indistinct; very finely crystalline, hypidiotopic dolomite cement; few detrital dolomite grains.	11.5	100.0
8.	Dolomitic intraformational breccia: massive; consists of angular fragments of yellow to white dolomite; fragments mostly 1/8" to 1/4", some to 1" long; matrix red arenaceous detrital dolomite. Sample MPa-6 taken 88' above base of formation.	5.5	88.5
7.	Arenaceous detrital dolomite: light-olive-gray (5Y 6/1), weathers light-gray (N7); thin-bedded (4" to 5"); hard and dense; detrital, worn, subhedral dolomite grains with euhedral overgrowths; fine-grained, angular to subangular, quartz and feldspar grains; hematite and authigenic, very finely crystalline, hypidiotopic dolomite cement.	10.5	83.0
6.	Arenaceous detrital dolomite: grayish-red (5R 4/2), weathers moderate-brownish-red (10R 4/6); except for color change same as unit 7. Sample MPa-5 taken 72' above base of formation.	2.5	72.5
5.	Arenaceous detrital dolomite: same as unit 7.	10.5	70.0
4.	Arenaceous dolomite: pale-reddish-brown (10R 5/4), weathers moderate-reddish-orange (10R 6/6); fine-grained, angular to subangular quartz and feldspar grains in nearly equigranular,		

Table 4. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
	very finely crystalline, hypidiotopic dolomite; hard and dense with siltstone partings; outcrop surface very bumpty (bumps up to 6" across). Sample MPa-4 taken 58' above base of formation.	3.0	59.5
3.	Detrital dolomite: light-olive-gray (5Y 6/1), weathers light-gray (N7); medium-bedded; hard; dense; medium-grained, euhedral, detrital dolomite and angular quartz silt-sized grains cemented by hematite; upper 25' stained moderate reddish-brown (10R 4/6) by overlying red beds. Sample MPa-3 taken 30' above base of formation.	43.3	56.5
2.	Dolomite: yellowish-gray (5Y 8/1), weathers grayish-yellow (5Y 8/4); laminated to thin-bedded (less than 1/2" to 4"), hard, dense, fractured, very finely crystalline, equagranular, hypidiotopic dolomite. Sample MPa-2 taken 13' above base of formation.	1.7	13.2
1.	Limestone: light-olive-gray (5Y 6/1), weathers light-gray (N7); massive, hard, dense, microsparrite. Sample MPa-1 taken 11' above base of formation.	11.5	11.5
	Total thickness.....	100.0	

Disconformity: contact slightly undulating owing to pre-Amsden erosion of the Mission Canyon surface.

Mission Canyon Limestone

Both fresh and weathered surfaces range from light shades of gray to red and reddish-brown.

The basal two units of the formation are composed of hard, massive to thin-bedded, fractured limestone and dolomite. Microscopically the dolomite is hypidiotopic, equigranular, very finely crystalline, and monomineralic. The limestone is very similar in appearance, but laboratory staining shows that little or no dolomite is present. A dolomite sequence more than 40 feet thick overlies the basal limestone and dolomite. This dolomite is thin-bedded (beds 4 to 5 inches thick) and hard; microscopically it is seen to be medium crystalline, nearly equigranular, and to consist of euhedral grains of detrital dolomite. Most of the voids are lined or filled with hematite; the euhedral rhombs of dolomite are rimmed with hematite, which imparts to the rock a distinctive reddish-brown color. Approximately five percent of the detrital dolomite is angular silt and very fine sand-sized quartz grains.

In the upper part of the Amsden Formation the detrital dolomite in the silty and arenaceous detrital dolomites and dolomitic sandstones is fine-grained and nearly equigranular. Authigenic dolomite like that of the dolomite near the base of the formation is also present. The grain size and quantity of detrital quartz and feldspar increase upward. Microscopically the clastic grains are angular to subangular and exhibit replacement of the quartz by the authigenic dolomite and interpenetration of the carbonate along the grain boundaries. Minor amounts of detrital muscovite and hematite are present.

Characteristics serving as criteria for the recognition of detrital dolomite are given by Amsbury (2, p. 8-14) and Strickler and Zeisloft (74, p. 74-76), and most of the characteristics listed by these authors were observed. Abraded subrounded grains of dolomite surrounded by rhombic to subrhombic overgrowths of dolomite in optical continuity with the original grains were common in the detrital dolomite units, as were angular to rounded dolomite grains separating sand-sized quartz grains. Dolomite overgrowths also occur on original euhedral grains, which show no signs of abrasion, and on original subhedral grains show only minor abrasion.

Unit 8 of the measured section (Table 4) is a dolomitic intraformational breccia. This unit consists of angular to subrounded fragments of yellow to white dolomite in a matrix of red arenaceous detrital dolomite. The clasts range in size from 1/8 to 1 inch long with most particles between 1/8 and 1/4 inch. Petrographic examination shows the fragments to be arenaceous dolomites, dolomitic sandstones, arenaceous micritic limestone, micritic limestone, and shale, in order of relative abundance. The matrix is composed of angular to subrounded, fine- to coarse-grained quartz and fine-grained crystalline, xenotopic, authigenic dolomite. In many places it is difficult to distinguish the matrix from the clasts, which are probably fragments from lower Amsden beds. Isolated patches of chalcedony and authigenic quartz rimmed by hematite are numerous, and inclusions of carbonate minerals commonly give these patches a light-browning tinge in unpolarized light.

Fossils and Age

No fossils were found in the Amsden Formation in the Snowflake Ridge area, and correlation is based on the formation's stratigraphic position between the Mission Canyon Limestone and the Quadrant Formation, as well as on lithologic similarities to Amsden beds described elsewhere. The section in the Snowflake Ridge area agrees particularly well with the upper part of the Amsden section described by Sloss and Moritz (71, p. 2159) in southwestern Montana. Most workers have considered that the Amsden Formation ranges in age from Late Mississippian through Early Pennsylvanian. However, on the basis of the close comparison of the section in the thesis area with that measured by Sloss and Moritz, the Amsden Formation in the Snowflake Ridge area is assigned a probable Early Pennsylvanian age.

In lithology and stratigraphic position the Amsden Formation of the thesis area is probably a partial equivalent of the Ranchester

Member of the Amsden Formation found in Wyoming which Mallory[1] has dated as Atokan in age. However, lithologic equivalents to the lower Horseshoe and Darwin members of the formation described by Mallory are absent in the thesis area.

Source and Depositional Environment

For the most part the Amsden Formation consists of varicolored detrital dolomites, arenaceous detrital dolomites, and dolomitic quartz arenites, which indicate the environment of deposition may have been terrestial rather than marine. The fact that the Amsden Formation appears to lie on a karst surface developed by erosion in the upper beds of the Mission Canyon suggests that the thesis area and surrounding region stood above sea level before deposition of the Amsden Formation. Strickler and Zeisloft (74, p. 77-78), commenting on the high percentage of detrital dolomite and the presence of vermiculite in the Amsden Formation in the area of Philipsburg, Montana, ". . . suggest the possibility that in this area, this formation represents a floodplain deposit or a series of coalescing deltas."

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[1] Mallory, W. W.; Distinguished Lecture, Am. Assoc. of Petroleum Geologists: "Pennsylvanian System in Wyoming": May 5, 1966, at Oregon State University.

The source material for the Amsden rocks is sedimentary. The silt and sand grains were probably derived from pre-existing sandstones and siltstones, and the detrital dolomite can be assumed to have come from pre-existing dolomitic rocks. Since the dolomitic source rocks broke down into detritus rather than dissolving, evidently mechanical weathering was dominant over chemical weathering, and the provenance had a semiarid to arid climate. Amsbury (2) shows that the grain size of the euhedral detrital dolomite is not an indication of the distance of transport, but actually represents the size of crystals in the dolomitic source rock.

Quadrant Formation

The Amsden Formation is disconformably overlain by the Middle Pennsylvanian Quadrant Formation, which was named by Peale (60, p. 39) for exposures of thin-bedded, cherty limestone and quartzite layers underlain by a red arenaceous limestone and varicolored shales in the Three Forks area. The term, as applied by Peale, included what are today the Amsden, Quadrant, and Phosphoria formations. Weed (35) designated a type locality for the Quadrant Formation at the southeast corner of Quadrant Mountain in Yellowstone Park. Scott (68) and Thompson and Scott (76) have redefined the type section of the Quadrant so that it now consists of Pennsylvanian rocks only.

The formation disconformably overlies the Amsden Formation, or the Mission Canyon Limestone where the Amsden is not present, and is disconformably overlain by the Phosphoria Formation.

Distribution and Physiographic Expression

The Quadrant Formation crops out over much of the eastern part of the area. Exposures generally are very good, commonly taking the form of cliffs. The best exposures are along the Gallatin River northwest of Snowflake anticline, along Taylor Fork and Sage Creek Valleys, and west of Monument Creek in sec. 32, T. 9 S., R. 5 E. (Figure 7).

Thickness and Lithology

In the Snowflake Ridge area the Quadrant Formation is approximately 260 feet thick. A measured section of the formation is described in Table 5.

The Quadrant Formation in the thesis area consists of arenaceous limestones, calcareous quartz arenites, and quartz arenites. Although there is local variation in the amount of calcareous material present in the formation, beds generally become less calcareous from bottom to top. Weathered surfaces of outcrops are most commonly yellowish-gray to light-gray, but locally are pink. Fresh surfaces are very light-gray. Weathered and fresh surface

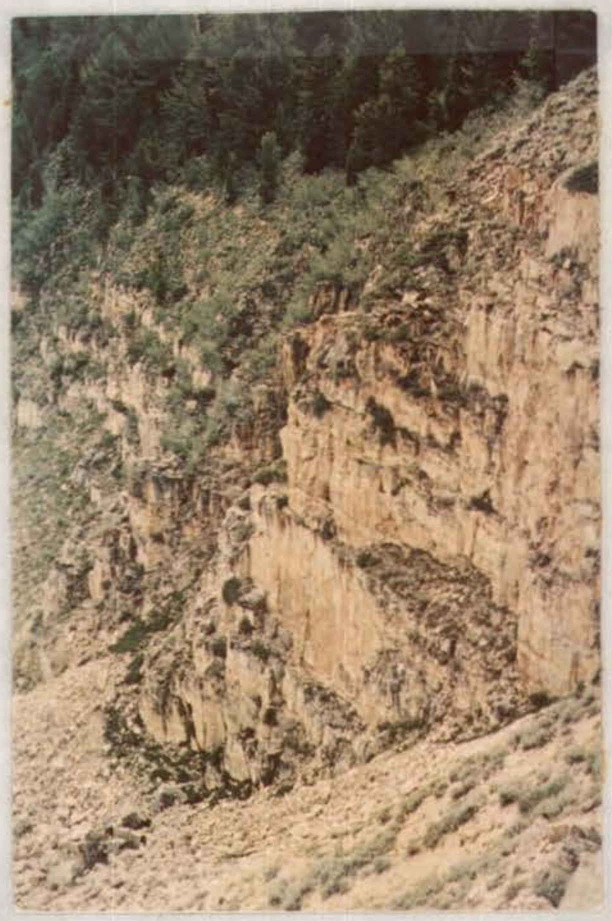

Figure 7. Outcrop of thin-bedded, cross-bedded, calcareous quartz arenite of the Quadrant Formation, west of Monument Creek in sec. 32, T. 9 S., R. 5 E.

Table 5. Quadrant Formation; stratigraphic section measured on the east side of the Gallatin River Canyon in the NW1/4 sec. 2, T. 9 S., R. 4 E., and the SW1/4 sec. 35, T. 8 S., R. 4 E.

Phosphoria Formation

Disconformity?: contact covered; picked by means of change in soil color, break in slope, and presence of large outcrop of Phosphoria sandstone only 10' above uppermost exposed Quadrant outcrop.

Quadrant Formation

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
9.	Covered section: probably same as unit 8.	5.0	263.5
8.	Calcareous quartz arenite: very-light-gray (N8), weathers yellowish-gray (5Y 8/1); laminated (less than 1/2"); highly cross-bedded; subangular to rounded, fine- to medium-grained quartz and chert cemented by sparry calcite and limonite; large patches with limonite cement only; large hematitic-limonitic concretions up to 1 1/2" long. Sample Pq-3 taken 258' above base of formation.	5.0	258.5
7.	Calcareous quartz arenite: same as unit 8 but without concretions; limonite specks occur throughout this unit and increase in number in upper 2'.	119.5	253.5
6.	Calcareous quartz arenite: very-light-gray (N8), weathers yellowish-gray (5Y 8/1); laminated (less than 1/2"); cross-bedded; angular to subrounded, fine- to very fine-grained quartz grains with overgrowths; some large rounded grains of quartz and feldspar; patches of finely crystalline dolomite; sparry calcite cement; vugs to 3" across filled by euhedral calcite crystals up to 1/2" long; arenite very porous. Sample Pq-2 taken 133' above base of formation.	5.5	134.0
5.	Calcareous quartz arenite: very-light-gray (N8), weathers yellowish-gray (5Y 8/1); laminated (less than 1/2"); highly cross-bedded; fine-grained, subangular quartz; limonite specks; outcrop fractures into large blocks.	5.0	128.5

Table 5. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
4.	Calcareous quartz arenite: very-light-gray (N8), weathers light-gray (N7); poorly bedded; fine-grained, subangular to angular quartz; sparry calcite cement.	23.0	123.5
3.	Calcareous quartz arenite: very-light-gray (N8), weathers light-gray (N7); laminated (less than 1/2"); multidirectionally cross-bedded; fine-grained, subangular to angular quartz; sparry calcite cement.	17.0	100.5
2.	Calcareous quartz arenite: same as unit 3 but thin- to medium-bedded (4" to 4') and not cross-bedded.	5.0	83.5
1.	Calcareous quartz arenite: very-light-gray (N8), weathers light-gray (N7); poorly bedded; angular to subrounded, fine-grained, overgrown quartz; sparry calcite cement; good porosity; crops out as small ledges; considerable talus cover. Sample Pq-1 taken 50' above base of formation.	78.5	78.5
	Total thickness.....	263.5	

Disconformity?: base covered; contact assumed at top of red Amsden soil.

Amsden Formation

colors vary but little. Bedding ranges from laminated to massive, and cross-bedding is very common throughout the unit.

The basal 20 to 30 feet of the formation are usually highly calcareous, and arenaceous limestones are the dominant rock type. When inspected microscopically these limestones are seen to be composed of subangular to subrounded grains of quartz cemented by medium to large crystals of sparry calcite. Quartz sand grains commonly make up to 40 percent of the limestones, but grains of chert and quartzite are noticeably lacking. Many types of inclusions were observed in the quartz grains.

Calcareous quartz arenite is the major rock type of the Quadrant Formation. The calcareous quartz arenites are all very well-sorted, and the grains are nearly equidimensional and of fine sand size. Well developed cross-bedding is common. These sandstones vary in the amounts of quartz and sparry calcite present. Detrital orthoclase and chert are present in small amounts, but the amount of feldspar never exceeds one percent, and the amount of chert never exceeds two percent. Sparry calcite acts as the cementing agent for the quartz grains, but porosity of these rocks is high. The quartz grains are angular to subrounded with rough, irregular edges due to attack and replacement by the calcite, but original subrounded to rounded grains of quartz are visible within the angular grains.

The upper part of the Quadrant Formation is for the most part composed of quartz arenites, but calcareous quartz arenites may be locally present. The sorting of the quartz arenites is excellent, but greater compaction of the quartz grains and precipitation of authigenic quartz in voids causes a decrease in porosity. The authigenic quartz filling the voids is not in optical continuity with the quartz overgrowths on the grains and probably is a second generation of quartz precipitate. Several of the grain contacts show incipient suturing, and interpenetration of grains is common. However, the rock is far from being a quartzite.

Heavy minerals observed in thin section included zircon, tourmaline, hematite, leucoxene, magnetite, rutile, and pyrite, in order of relative abundance. In all but one sample the heavy mineral suite accounted for an extremely small percentage of the rock.

Table 6 gives modal analyses of several samples of sandstone of the Quadrant Formation.

Fossils and Age

No fossils were found in the Quadrant Formation in the Snowflake Ridge area, and, thus, the assignment to this formation of a Middle Pennsylvanian age is based on stratigraphic position and comparisons with Quadrant sections at Quadrant Mountain (68, p 1017), Three Forks, Montana (6, p. 21), and the Madison Range, Montana (33, p. 65).

Table 6. Modal analyses of Quadrant Formation sandstone samples.

	Pq-3[1]	Pq-4[2]	Pq-5[3]	Pq-6[4]	Pq-7[5]
Detrital quartz	57	76	46	81	89
Detrital chert	Tr	Tr	2	Tr	1
Authigenic quartz	4	5	7	17	10
Carbonate	38	17	35	1	—
Feldspar	Tr	Tr	1	1	Tr
Limonite	—	1	9	—	—
Heavy accessory minerals	Tr	Tr	Tr	Tr	Tr

[1] Measured section of Quadrant Formation, NW1/4 sec. 2, T. 9 S., R. 4 E., and SW1/4 sec. 35, T. 8 S., R. 4 E., 50' above base of formation

[2] Same locality as above; 133' above base of formation

[3] Same locality as above; 258' above base of formation

[4] Measured section of Quadrant Formation above Pulpit Rock, SE1/4NE1/4 sec. 3, T. 9 S., R. 4 E., about 40' from top of formation

[5] Pulpit Rock section; top of formation

At the type section of the Quadrant Formation at Quadrant Mountain, Yellowstone National Park, Thompson and Scott (76, p. 350-353) found the fusulinid genera Wedekindellina and Fusulina in the upper part of the formation. The presence of these genera indicates the Quadrant Formation is Desmoinesian in age.

Source and Despositional Environment

Deposition of the Quadrant Formation, as indicated by the lithology and cross-bedding, was in a shallow neritic to littoral environment. The high degree of textural and mineralogical maturity indicated by the very high quartz content and excellent sorting of the sandstones and the very small heavy mineral suite suggest that the sand has gone through several cycles of sedimentation. A sedimentary provenance for the Quadrant detritus is obvious.

The abundance of cross-bedding indicates a high-energy environment, probably in the zone of wave turbulence. The high percentage of calcite cement coupled with the cross-bedding makes it seem most probable that the depositional environment for the Quadrant sediments was a near-shore marine environment. That part of the upper Quadrant that contains fusulines is certainly marine.

Permian System

Phosphoria Formation

The Permian Phosphoria Formation, which disconformably overlies the Quadrant Formation, was named by Richards and Mansfield (64, p. 683-689) in 1912 for exposures in Phosphoria Gulch, Bear Lake County, Idaho. At the type section two members are recognized: a lower phosphatic shale, about 180 feet thick, and the upper Rex chert, about 240 feet thick. In 1914, Stone and Bonine (73, p. 375) assigned the Permian strata of southwestern Montana to the Phosphoria Formation, but the light colored sandstones and dolomites of Montana differed greatly in lithology from the black shale, phosphorite, and bedded chert at the type section. Rocks previously asscribed to the Phosphoria Formation have now been broken down into three facies: (1) a black shale, phosphorite, and bedded chert facies called the Phosphoria, (2) a dolomite facies called the Park City, and (3) a sandstone facies called the Shedhorn. All three of these facies generally are not present in any one area. In the Yellowstone Park region and in the Snowflake Ridge area the Shedhorn facies is best developed, but for reasons of clarity, the author has chosen to retain the primary usage of Phosphoria Formation in place of Shedhorn Sandstone.

In the Snowflake Ridge area the Phosphoria Formation is disconformably overlain by the Triassic Dinwoody Formation. Cressman and Swanson (19) have observed local changes in the thickness of the upper member of the Shedhorn Sandstone and stringers of basal beds of the Dinwoody Formation extending down into joints in the upper Shedhorn Sandstone. The basal contact of the Phosphoria with the Quadrant Formation is exposed at the east edge of sec. 31, T. 9 S., R. 5 E. (Plate 2).

Distribution and Physiographic Expression

The Phosphoria Formation has good outcrops on the rim of the Gallatin River Canyon from Snowflake anticline to the north edge of the thesis area. Along Taylor Fork Valley a cliff of Phosphoria rocks can be followed upstream to a point where the formation dips underground. The Phosphoria is also exposed over much of the high area in the southeast part of the thesis area west of Monument Creek and along the west side of Sage Creek Valley.

The Phosphoria Formation in the thesis area, as a whole, is a very resistant unit, commonly forming cliffs. Outcrops weather a distinctive orange that aid greatly in identifying the formation from a distance.

Thickness and Lithology

A section of Phosphoria beds (Table 7) was measured in the SW1/4 sec. 35, T. 8 S., R. 4 E., where the formation is 156 feet thick.

Quartz arenites make up most of the Phosphoria Formation in the thesis area, and conglomerate, siltstone, phosphorite, and nodular and bedded chert make up a subordinate part of the section.

The Phosphoria Formation sandstones are yellowish-gray to yellowish-brown, very fine- and fine-grained quartzose sandstones. Microscopically the framework of these quartz arenites is seen to be composed of subangular to subrounded grains of quartz, chert, collophane pellets, phosphatic shell fragments, and sponge spicules. In the lower part of the formation sparry calcite acts as the cement, but rocks of the upper part of the unit are generally cemented with quartz overgrowths and authigenic microcrystalline quartz. Almost all the quartz grains have overgrowths on originally rounded grains. Chert stringers parallel and normal to bedding are common throughout the formation (Figure 8).

Another common occurrence throughout the Phosphoria Formation is vertical cylindrical sandstone structures 1/2 to 5 inches in diameter, up to six feet in length, and roughly circular in cross section. Individual columns may cut across beds of different

Table 7. Phosphoria Formation; stratigraphic section measured on the east side of the Gallatin River Canyon in the SW1/4 sec. 35, T. 8 S., R. 4 E.

Dinwoody Formation
  Disconformity: contact sharp

Phosphoria Formation

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
17.	Quartz arenite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); poorly bedded; subangular to subrounded, fine- to medium-grained; slightly calcareous; dark chert gives sandstone a dark salt-and-pepper appearance; unit contains thin chert stringers parallel to bedding.	11.0	156.0
16.	Chert and Quartz arenite: alternating beds of chert and sandstone; beds 1" to 2" thick; arenite same as unit 17.	10.0	145.0
15.	Quartz arenite: yellowish-gray (5Y 7/2), weathers light olive gray (5Y 6/1); poorly bedded; subangular to subrounded, fine- to medium-grained; slightly calcareous; appear salt-and-pepper owing to contrast of dark chert with light quartz.	15.0	135.0
14.	Chert and quartz arenite: alternating beds of chert and quartz arenite same as unit 15; beds 1" to 2"; chert stringers parallel to arenite beds; bottom 1' to 2' of interval contains vertical cylindrical structures composed of fine-grained quartz arenite, chert stringers and chert beds become less numerous towards top of unit with an accompanying increase in nodular chert only in quartz arenite matrix.	10.0	120.0
13.	Quartz arenite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); massive; hard, dense, slightly calcareous, fine-grained, angular to subrounded; salt-and-pepper appearance from contrasting dark chert and light quartz; upper 5' contains numerous vugs ranging from less than 1/8" to greater than 3" in diameter; vugs partly filled with white silica.	12.5	110.0

Table 7. (continued)

Unit	Description	Thickness (feet) Unit	Total
12.	Quartz arenite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); hard and dense; slightly calcareous; fine-grained, angular to subrounded quartz and chert; salt-and-pepper appearance; contains nodular chert and some vertical cylindrical sandstone structures which become more numerous in top 2.5' of unit.	8.5	97.5
11.	Quartz arenite: same as unit 12, but no nodular chert.	11.0	89.0
10.	Chert: yellowish-gray (5Y 7/2), weathers dark-yellowish-orange (10YR 6/6); nodular to bedded chert containing scattered, large vertical cylindrical sandstone structures; chert appears to have formed diagenetic reorganization of sponge spicules; fresh and relict spicules very numerous; scattered detrital quartz grains and phosphatic shell material; outcrop surface very knobby.	19.4	78.0
9.	Quartz arenite: same as unit 12; massive; contains vertical chert stringers up to 3' in length and 3" in diameter; top 2" to 3" of unit changes from massive to undulating laminations (less than 1/2").	3.5	58.6
8.	Interval of vertical cylindrical sandstone columns; extremely abundant; columnals composed of very fine- to fine-grained, angular to subrounded chert and quartz with some sponge spicules and phosphatic shell fragments; collophane pellets sparse; matrix for columnals is same as quartz arenite composing columnals; columns 3" to 4" in diameter and up to 5' long; some penetrate into underlying siltstone and overlying quartz arenite; unit also contains vertical chert stringers up to 3' in length and 3" in diameter. Sample Pp-4 taken 55' above base of formation.	2.2	55.1
7.	Siltstone: brownish-gray (5YR 4/1), weathers grayish-orange (10YR 7/4); very thinly laminated (less than 1/8"); platy.	5.0	53.0

Table 7. (continued)

Unit	Description	Thickness (feet) Unit	Total
6.	Phosphorite: pale-yellowish-brown (10YR 6/2), weathers moderate-yellowish-brown (10YR 7/4); medium- to coarse-grained, rounded collophane oolites and pellets in collophane cement; detrital quartz grains occur as nuclii for some of the oolites. Sample Pp-3 taken 48' above base of formation.	3.0	48.0
5.	Conglomerate: well-rounded chert pebbles to 1" diameter; matrix includes subangular to subrounded fine-grained quartz and chert, rounded collophane pellets, sponge spicules, and phosphatic shell fragments cemented by authigenic quartz and chert; slightly calcareous; dark, salt-and-pepper appearance. Sample Pp-2 taken 46' above base of formation.	1.0	45.0
4.	Nodular chert zone: nodules in very poorly bedded quartz arenite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); same as unit 3; contains layered columnal sandstone columns up to 6" in length and 1 1/2" in diameter; columnal sandstone same as quartz arenite of unit.	3.0	44.0
3.	Quartz arenite: yellowish-gray (5Y 7/2), weathers light-olive-gray (5Y 6/1); indistinctly bedded; angular, fine- to medium-grained quartz and chert and rounded collophane pellets cemented by authigenic silica overgrowths and microcrystalline quartz; some sponge spicules and phosphatic shell fragments; slightly calcareous; elongate vugs up to 2" long and 1/2" high, elongate to bedding in narrow 3" zones separated by 4' to 6' of non-vuggy sandstone; unit fractured. Sample Pp-1 taken 20' above base of formation.	26.0	41.0
2.	Quartz arenite: grayish-orange (10YR 7/4), weathers grayish-orange-pink (5YR 7/2); laminated (1/8" to 1/4"); quartz arenite same as that of unit 3, but contains widely scattered, subrounded to rounded chert pebbles up to 3/4" in diameter.	8.0	15.0
1.	Covered section: probably same as unit 2.	7.0	7.0
	Total thickness.....	156.0	

Disconformity?: contact covered; picked on change in soil color, break in slope, and large outcrop of Quadrant sandstone only 10' lower in section.

Quadrant Formation

lithology or, where numerous and tightly packed, the columns form a zone in which the surrounding matrix is subordinate (Figure 9). In the thesis area the sandstone composing the structures was exactly like that described above from the upper part of the formation. The origin and significance of these structures is unknown but Cressman and Swanson (19, p. 231) state that ". . . they probably represent the burrows of bottom-dwelling animals filled with sediment sufficiently different in character from the matrix so that the structures were preserved. Others may be fillings in cavities left by buried stems."

The chert-pebble conglomerate of unit 5 of the measured section consists of well-rounded pebbles up to 1 inch in diameter in a matrix of fine-grained quartz arenite of a salt-and-pepper appearance that is due to the presence of chert grains, collophane pellets, and phosphatic shell fragments. Sponge spicules are also present. At the site of the measured section this unit is not very fossiliferous, but in near by areas this conglomerate contains numerous specimens of Bellerophon sp. In some places these gastropods are so numerous that they become the "pebbles" of the conglomerate.

A phosphorite unit directly overlies the chert-pebble conglomerate. The phosphorite is about 85 percent collophane oolites and pellets, four percent detrital quartz grains, and 10 percent collophane cement. The collophane oolites and pellets are spherical

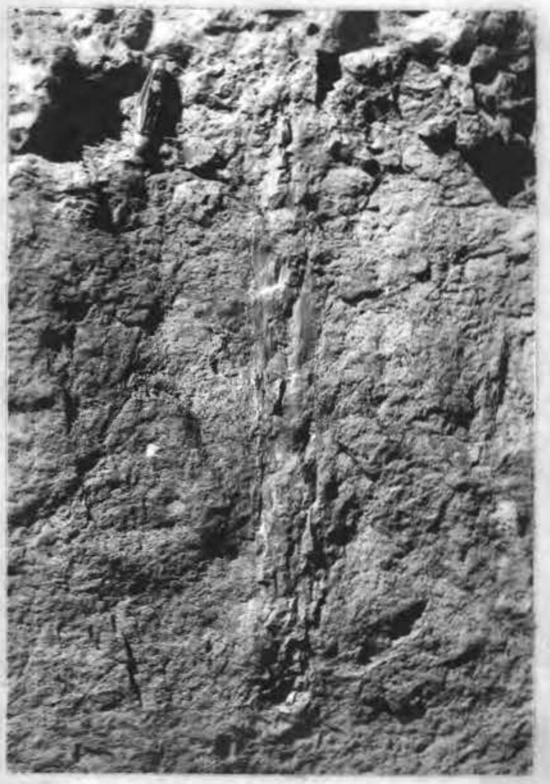

Figure 8. Vertical chert stringer in the Phosphoria Formation.

Figure 9. Zone of vertical cylindrical sandstone structures in the Phosphoria Formation. These structures are common throughout the formation.

to ovate. The oolites exhibit concentric layering and the pellets are structureless. About one percent of the rock is detrital chert, which forms the nuclei of some of the collophane grains.

The chert in the Phosphoria Formation, as represented by unit 10 of the measured section, is cryptocrystalline quartz that contains numerous sponge spicules, phosphatic shell fragments, collophane grains, and detrital quartz grains. Numerous relict spicules are visible in the thin sections, and the chert appears to have formed by the reorganization and crystallization of the opal of the sponge spicules. Unit 10 of the section probably represents the Tosi Chert Tongue of the Phosphoria Formation (19, p. 227).

Fossils and Age

The only identifiable fossils found in the Phosphoria Formation were Bellerophon sp. Age determination is based on stratigraphic position and lithologic similarity to the sections measured by McKelvey *et al.* (51) (52) in Montana.

The Permian age of the Phosphoria Formation has been noted by Frenzel and Mundorff (31, p. 676-679), who identified late Wolfcampian(?) fusulinids from the basal beds of the Phosphoria near Three Forks, Montana; Miller, Furnish, and Clark (54, p. 1057, 1059), who described Leonardian ammonites from the Phosphoria Formation in the Wasatch Mountains and in Idaho; and

Miller and Cline (53, p. 282-286), who described cephalopods of the Phosphoria Formation in the northwestern United States.

According to the Permian Subcommittee of the National Research Council's Committee on Stratigraphy (25, chart 7) the Phosphoria Formation in Montana is Guadalupian in age.

Source and Depositional Environment

From the various lithologies of the Phosphoria Formation of the thesis area it seems evident that the depositional environment was marine, but it is also evident that the depth of water varied during deposition. The mineral and textural maturity of the Phosphoria sandstones suggests deposition in a shallow water, high energy environment. Cressman (18, p. 25) and Eardley (26, p. 672) show the source of detritus in southwestern Montana to be dominantly Mississippian and Pennsylvanian rocks to the east. This coincides well with the mineralogical evidence of the sandstones--that the chert came from the Madison Group and that quartz grains with overgrowths came from the Quadrant Formation.

The conglomerate of unit 5, with its well rounded chert pebbles and clean, quartzose sandstone matrix, also suggests a near-shore, shallow-water environment. The presence of specimens of Bellerophon in this interval is supporting evidence for such an environment.

The origin of the chert beds in the Phosphoria has been in controversy for many years, but it is the author's opinion that the chert of unit 10 has been largely formed by diagenic reorganization and crystallization of sponge spicules that accumulated in a moderately deep and quiet marine environment. Relict sponge spicules are much more numerous than unaltered spicules, and a progression from fresh to completely cherty relict spicules can be observed in thin sections.

The oolitic-pelletal phosphorite was probably deposited in shallow, turbulent water where the oolites and pellets could accrete phosphatic material.

Triassic System

Dinwoody Formation

The Early Triassic Dinwoody Formation was named and described by Blackwelder (8, p. 425-426) for beds in Dinwoody Canyon on the northeastern slope of the Wind River Mountains, Wyoming. The type section is composed of 200 feet of gray and olive shaly siltstones and shales and thin brown limestones near the base; this section is bounded below by the Quadrant Formation and above by the red-bed Chugwater Formation.

Kummel (47) (48, p. 233) and Moritz (55) have recognized a twofold division of the Dinwoody Formation; a lower shale member and an upper member of interbedded calcareous siltstones, silty limestones, and gray crystalline limestones with some interbedded gray to buff shales.

In the Snowflake Ridge area the Dinwoody Formation disconformably overlies the Permian Phosphoria Formation, but is conformably overlain by the Early Triassic Woodside Formation. The relationship between the Dinwoody and Woodside formations is an intertonguing one, with the Dinwoody tonguing out eastward into the eastward thickening Woodside and Chugwater formations.

Distribution and Physiographic Expression

The Dinwoody Formation in the thesis area is very poorly exposed, forming gentle slopes with low lying ledges above the cliff-forming Phosphoria Formation. The best outcrops of the formation are high on the east side of the Gallatin River Canyon in sec. 2, T. 9 S., R. 4 E., and on the steeply dipping east flank of the Snowflake anticline near the south end of Snowflake Ridge.

Thickness and Lithology

No complete section of the Dinwoody Formation is present in the thesis area, but a section was measured above the mouth of

Buck Creek in sec. 5, T. 8 S., R. 4 E., north of the thesis area (Table 8).

In the Snowflake Ridge area the Dinwoody Formation has a twofold division; a lower dolomite division and an upper division of arenaceous limestone and very fine-grained, calcareous, ripple-marked sandstone (Figure 10). The lower shale member recognized by Kummel and Moritz in other parts of southwestern Montana and Idaho is not present in the area.

Forty feet of finely crystalline, hard, medium-bedded (3 to 8 inches thick), Lingula-bearing dolomite composes the lower division of the Dinwoody Formation. Weathered surfaces are pinkish-gray, and fresh surfaces are very pale orange. Some Lingula shells have been dissolved, leaving lath-like voids. In thin section the lower dolomite is seen to be very finely crystalline and has a hypidiotopic fabric. Most of the Lingula shells have been recrystallized to hypidiotopic dolomite, but commonly pieces of shell still exhibit the original chitinophosphatic layered structure. Irregular small masses of collophane occur throughout the slide, and rims of collophane occur around the edges of some Lingula shells. The collophane was formed from the decomposition of the phosphatic brachiopod material. Several silt-sized quartz grains are present in the dolomite of the thin sections examined.

Table 8. Dinwoody Formation; stratigraphic section measured above the mouth of Buck Creek in the SW1/4NE1/4NE1/4 sec. 5, T. 8 S., R. 4 E.

Rierdon Formation

Disconformity: at site of section measurement pre-Jurassic erosion or local nondeposition has caused absence of the Woodside Formation.

Dinwoody Formation

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
4.	Calcareous quartz arenite: yellowish-gray (5Y 7/2), weathers pale-yellowish-brown (10YR 6/2); bedding indistinct; angular to subrounded, very fine- to fine-grained quartz; *Lingula* shell fragments; cement is microsparrite; trace glauconite; ripple-marked.	15.0	105.0
3.	Calcareous quartz arentite: pinkish-gray (5YR 8/1), weathers very-pale-orange (10YR 8/6); bedding indistinct; angular to subangular, very fine-grained quartz in micrite and microsparrite cements; *Lingula* shell fragments; unit poorly exposed. Sample Trd-3 taken 75' above base of formation.	20.0	90.0
2.	Arenaceous limestone: yellowish-gray (5Y 8/1), weathers very-pale-orange (10YR 8/2); thin-bedded (2" to 6"); angular to subrounded, very fine-grained quartz in microsparrite; *Lingula* shell fragments. Sample Trd-2 taken 45' above base of formation.	30.0	70.0
1.	Dolomite: very-pale-orange (10YR 8/2), weathers pinkish-gray (5YR 8/1); thin-bedded (3" to 8"); stylolites along some bedding planes; very finely crystalline, nearly equagranular, xenotopic dolomite; *Lingula* shells; shell-shaped pore spaces formed by removal of Lingula shells. Sample Trd-1 taken 5' above base of formation.	40.0	40.0
	Total thickness.....	105.0	

Disconformity: contact partly covered.

Phosphoria Formation

Figure 10. Ripple-marks on steeply dipping bed of the Dinwoody Formation near the south end of Snowflake Ridge on the east flank of Snowflake anticline.

The arenaceous limestone and calcareous sandstones of the upper Dinwoody Formation resemble each other closely and differ mainly in the amounts of quartz and carbonate present. The arenaceous limestone consists of angular to subrounded, very fine sand-sized grains of quartz and chert, rounded grains of detrital dolomite, fragments of Lingula shells, and rounded fragments of micritic limestone in a microsparrite cement. Most of the quartz grains appear to have once been subrounded to round, but attack and replacement by the calcite cement has made them irregular and angular. Many types of inclusions are present in the quartz grains. The detrital grains of dolomite show up in thin sections as individual rounded rhombs that have a reddish-brown rim and an overgrowth of dolomite that is in optical continuity with the rhombs. Many fragments of Lingula shells are present, but most have been recrystallized to microsparrite and show relict outlines only. However, many chitinophosphatic fragments are present, and there is a crude alignment of both relict and unaltered brachiopod shell fragments parallel to the laminations. Very minor amounts of collophane are associated with the Lingula shell fragments. The grains of micritic limestone that occur in the microsparrite cement are rounded and range from fine to very coarse sand size. Magnetite and zircon are the dominant heavy minerals.

The sandstones at the top of the Dinwoody Formation are calcareous quartz arenites composed of angular, fine- to very fine-grained quartz and chert and rounded grains of dolomite in a very finely crystalline microsparrite. Fossils are very sparse in this well-sorted sandstone. All quartz and chert grains have very irregular boundaries where the carbonate cement has replaced and penetrated the quartz, and the quartz grains show many types of inclusions.

Fossils and Age

Assignment of an Early Triassic age to the Dinwoody Formation in the thesis area is based on correlation with the same facies of the Dinwoody that contains abundant *Lingula borealis* in southeastern Idaho designated by Newell and Kummel (57).

In southwestern Montana Kummel (48, p. 236) found two ammonite faunas in the Dinwoody; one at Frying Pan Gulch, Beaverhead County, and another at Dalys Spur, 13 miles south of Dillon, Montana. These faunas he dated as early Scythian (very Early Triassic) in age.

Source and Depositional Environment

The position of the Snowflake Ridge area at the edge of the Wyoming shelf on the eastern margin of the geosyncline suggests a marine depositional environment for the Dinwoody Formation; this is supported by the ripple-marked, calcareous, Lingula-bearing sediments of the formation. The clean, well-sorted sandstones and specimens of Lingula indicate a shallow water environment, probably in the littoral zone. Moritz (55, p. 1800) concluded that the Dinwoody Formation indicates mildly unstable shelf conditions on which repeated ". . . shifts from lagoonal or littoral environmental conditions to normal neritic conditions" took place.

The source area for the detrital material was probably to the east. The abundant quartz and minor chert suggest a sedimentary provenance. The inclusions in the quartz indicate that metamorphic and plutonic rocks once contributed clastic material to the sedimentary provenance from which the Dinwoody sediments were derived.

Woodside Formation

The Dinwoody Formation in the area of study is conformably overlain by the Early Triassic Woodside Formation, which was named by Boutwell (9, p. 446) for exposures of maroon and red shaly siltstones at Woodside Canyon in the Park City mining district of northeastern Utah. At the type section the Woodside Formation is approximately 1,000 feet thick, and lies between the Permian Phosphoria Formation and the Triassic Thaynes Formation.

Tracing the Woodside Formation over northern Utah, western Wyoming, southeastern Idaho, and southwestern Montana, Kummel

(46) found that it interfingers westward in southeastern Idaho and southwestern Montana into the upper part of the Dinwoody Formation. In the thesis area, however, the Woodside is overlain disconformably by the Late Jurassic Rierdon Formation. If any Dinwoody beds were deposited on the Woodside they were removed before deposition of Rierdon sediments.

Distribution and Physiographic Expression

The Woodside Formation is very poorly exposed in the Snowflake Ridge area, and in most localities it was necessary for mapping purposes to combine the Dinwoody and Woodside formations into one unit of undifferentiated Triassic rocks. The nonresistant beds of the formation weather to gentle slopes but produce a red soil that greatly aids in mapping.

Thickness and Lithology

A complete section of the Woodside Formation exposed east of Monument Creek in the SW1/4SW1/4NE1/4 sec. 28, T. 9 S., R. 5 E., was measured and described. In the thesis area the unit is about 133 feet thick. A description of the measured section is presented in Table 9.

The Woodside Formation in the thesis area consists of an alternating sequence of mudstones and sandstones. The mudstones,

Table 9. Woodside Formation; stratigraphic section measured on the east side of a small ridge in the SW1/4SW1/4NE1/4 sec. 28, T. 9 S., R. 5 E.

Rierdon Formation

Disconformity: contact sharp; contact placed in the sandstone at change in color from red-orange of Woodside to gray of Rierdon.

Woodside Formation

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
6.	Quartz arenite: very-pale-orange (10YR 8/2), weathers pale-yellowish-brown (10YR 6/2); laminated to thin-bedded (less than 1/2" to 4"); slightly calcareous; very fine-grained.	8.1	113.5
5.	Mudstone: dark-reddish-brown (10R 3/4); calcareous; alternates rhythmically every 4' to 5' with 4" to 6" layers of quartz arenite; pale-olive-green (10Y 6/2), weathers pale-brown (5YR 5/2); thinly laminated (less than 1/4"); calcareous; very fine-grained; some sandstone layers undulate slightly. Samples Trw-3 and Trw-2 taken 125' and 96' above base of formation, respectively.	83.3	125.4
4.	Quartz arenite: pale-olive-green (10Y 6/2), weathers pale-brown (5YR 5/2); laminated (1/4" to 1/2"); calcareous; very fine-grained. Sample Trw-1 taken 42' above base of formation.	3.1	42.1
3.	Mudstone: dark-reddish-brown (10R 3/4); slightly calcareous, highly fractured, and brittle.	1.3	39.0
2.	Quartz arenite: greenish-gray (5GY 6/1), weathers moderate-brown (5YR 3/4); soil dark reddish-brown (10R 3/4); laminated (less than 1/2"); slightly calcareous; very fine-grained.	2.5	37.7
1.	Covered section: digging through soil cover exposed red mudstone and very fine-grained sandstone layers.	35.2	35.2
	Total thickness.....	133.5	

Disconformity?: base covered; contact assumed at break in slope at tree line.

Dinwoody Formation

which compose most of the unit, are dark reddish-brown, hard, and brittle. Repeated every 4 to 5 feet in the section are units 4 to 6 inch thick of greenish-gray, very fine-grained, laminated to thin-bedded, slightly calcareous sandstones. The sandstones are composed of angular to subangular grains of quartz and plagioclase, calcite cement, and minor detrital muscovite, biotite, and dark argillaceous material. Heavy mineral grains are numerous and include hematite, zircon, tourmaline, magnetite rutile, sphene, and apatite, in order of relative abundance. The sandstones appear to be calcareous quartz arenites. However, a large part of the argillaceous matrix material is removed during grinding of the thin sections, and the sandstones may actually be calcareous quartz wackes.

Fossils and Age

No fossils were found in the Woodside Formation in the Snowflake Ridge area, and, thus, assignment of an Early Triassic age to the Woodside Formation is based primarily on its relative position in the sequence and on its lithologic similarity to Woodside beds of other areas. Kummel (48) has dated the Woodside Formation as Early Triassic in southwestern Montana.

Source and Depositional Environment

The origin of the "red-beds" of the Woodside, Chugwater, and Ankareh Formations, all of Triassic age, has been in controversy for many years. Darton (23), Schuchert (67), Moritz (55), and Tomlinson (77) have advocated a continental origin for these formations, but Branson (11, 12) and Reeside (62) contend the formations are of marine origin. Since exposures of the Woodside Formation were limited and little time was available for study of this problem, no strong argument can be offered for origin of the beds in the Snowflake Ridge area. However, the author believes that in the Snowflake Ridge area the well-sorted, very fine-grained sandstones, the even bedding, and the calcareous nature of the formation suggests a marine rather than a continental origin. Such an environment seems the more probable since the area lies at the edge of the Wyoming shelf.

Jurassic System

Rierdon Formation

Cobban (13, p. 1277) was the first to use the name Rierdon Formation when he raised the Ellis Formation to group status and subdivided it into the Swift, Rierdon, and Sawtooth Formations. Originally the Ellis Formation was named by Peale (60) in 1893 for all rocks between the Quadrant Formation and the Dakota Sandstone in the Three Forks area.

The Late Jurassic Rierdon Formation, as described by Cobban at the type section in Rierdon Gulch, Pondera County, Montana, consists of gray calcareous shales that are locally sandy.

The Sawtooth Formation is absent in the Snowflake Ridge area, and the Rierdon Formation disconformably overlies the Woodside Formation. The contact between these formations is exposed at two places in the thesis area; on the north side of Taylor Fork Valley in the NW1/4SE1/4, T. 9 S., R. 4 E., and on the small ridge just southeast of Black Butte Ranch in the SW1/4NE1/4 sec. 28, T. 9 S., R. 5 E. The conformable contact with the overlying Swift Formation is also exposed on the north side of Taylor Fork Valley.

Distribution and Physiographic Expression

The Rierdon Formation crops out along Taylor Fork Valley, along the east flank of Snowflake anticline, and east of Monument Creek near the Black Butte Ranch.

Outcrops of the Rierdon Formation take the form of gently sloping, grass-covered slopes. Exposures weather a distinctive cream-white, and small fossilized pelecypods are common in the float material. The best exposures in the area are found on the north side of Taylor Fork, where the section was measured, and at the exposure of the overturned beds of the Rierdon in the Snowflake anticline on the north side of U. S. Highway 191 (Figure 27).

Thickness and Lithology

The Rierdon Formation is 120 feet thick on the north side of Taylor Fork Valley in the NW1/4SE1/4 sec. 9, T. 9 S., R. 4 E. (Table 10).

In the Snowflake Ridge area the Rierdon Formation is dominantly limestone and mudstone but contains one sandstone unit at the base. Both the mudstone and sandstone are highly calcareous.

The basal sandstone of the Rierdon is a calcareous quartz arenite, and it rests disconformably on the uppermost red sandstone of the Woodside Formation throughout the area. The sandstone is very light-gray, weathers pale orange, and is laminated, soft, friable, very fine-grained, and commonly platy. Microscopically the sandstone is seen to consist of angular to subrounded grains of quartz, chert, plagioclase, microcline, muscovite, biotite, and heavy accessory minerals cemented by medium crystalline sparry calcite. The heavy mineral suite includes tourmaline, zircon, sphene, and magnetite. Table 11 gives a modal analysis of this sandstone.

Overlying the basal calcareous quartz arenite is a sequence of micritic, micritic-skeletal, and oolitic limestones. Within this

Table 10. Rierdon Formation; stratigraphic section measured on the north side of Taylor Fork Valley in the NE1/4SE1/4 sec. 9, T. 9 S., R. 4 E.

Swift Formation

Conformity: top of Rierdon Formation placed at top of oolitic limestone that does not contain glauconite.

Rierdon Formation

		Thickness (feet)	
Unit	Description	Unit	Total
6.	Oolitic limestone: pinkish-gray (5YR 8/1), weathers drak yellowish-orange (10YR 6/6); massive; hard; contains pelecypods and gastropods; several hematite cemented areas 1/4" to 1/2" across and several inclusions of unknown affinity. Sample Jr-4 taken 118' above base of formation.	4.0	120.0
5.	Micritic limestone: light-olive-gray (5Y 5/2), weathers pale-greenish-yellow (10Y 8/2); scattered pelecypod shell fragments.	31.6	116.0
4.	Mudstone: light-olive-gray (5Y 5/2), weathers yellowish-gray (5Y 7/2); laminated to thin-bedded (1/4" to 1/2"); calcareous; scattered pelecypod shell fragments; transitional upward into micritic limestone.	20.1	84.4
3.	Micritic limestone: dark-yellowish-brown (10YR 4/2), weathers very-pale-orange (10YR 8/2); thin-bedded (1/2" to 4"); hard with concoidal fracture; abundant pelecypods and gastropods. Sample Jr-3 taken 35' above base of formation.	32.8	64.3
2.	Micritic-skeletal limestone: pale-yellowish-brown (10YR 6/2), weathers grayish-orange (10YR 7/4), massive; hard, brittle, with concoidal fracture; abundant *Graphaea*, *Astartella*, *Ostrea*, and other pelecypods and gastropods. Sample Jr-2 taken 10' above base of formation.	26.5	31.5
1.	Calcareous quartz arenite: very-light gray (N8), weathers very-pale-orange (10YR 8/2); laminated (less than 1/2"); angular to subrounded, very fine-grained quartz, feldspar, and chert grains in medium crystalline sparry calcite cement; soft and friable; often platy. Sample Jr-1 taken 4' above base of formation.	5.0	5.0
	Total thickness.....	120.0	

Disconformity: contact sharp; unit 1 rests on fine-grained, platy sandstone of the Woodside Formation.

Woodside Formation

sequence of limestones is a calcareous mudstone unit, about 20 feet thick, that grades into micritic limestones above and below. The mudstone is light olive-gray, weathers yellowish-gray, and contains scattered pelecypod and gastropod shell fragments.

Table 11. Modal analysis of basal Rierdon Formation sandstone sample.

	Jr-1[1]
Detrital quartz	64
Detrital chert	1
Plagioclase	3
Microcline	1
Carbonate	30
Heavy accessory minerals	1

[1] Measured section of Rierdon Formation, NW1/4SE1/4 sec. 9, T. 9 S., R. 4 E., 2' above base of formation

The limestones, which make up most of the Rierdon Formation, are commonly various shades of light-gray and weather cream-white. Fossil pelecypods and gastropods are very abundant in some of the limestones, and shell fragments occur to some extent in all the limestones. A micritic skeletal limestone directly overlies the basal sandstone. This limestone is composed of approximately 70 percent micrite and 30 percent skeletal grains of pelecypods, gastropods and bryozoans. Most of the original shell material has been replaced by barite, but some sparry calcite shell material is also present. At the top of the formation an oolitic limestone, which is more resistant than the rest of the formation, contains about one percent skeletal material and is cemented by microsparrite. The oolites all exhibit concentric structures in most of which nuclei are not visible. However, quartz grains as nuclei are present in a few of the oolites observed. Several cubes of authigenic(?) pyrite were observed in the upper part of the oolitic limestone.

Fossils and Age

The Rierdon Formation is highly fossiliferous in the Snowflake Ridge area, and a composite collection of fossils from several localities has been identified by the author. The collection includes specimens of *Ostrea* sp., *Trigonia* sp., *Pleuromya* sp., *Pecten* sp., *Pholadomya* sp., and unidentified bryozoans and gastropods. This fauna closely resembles a generic representation assemblage dated by Imlay (43, p. 496) as early Callovian (earliest Late Jurassic).

Source and Depositional Environment

The basal calcareous quartz arenite of the Rierdon Formation probably had a dual source. A sedimentary provenance is indicated by the high amount of quartz and chert, and an acid igneous provenance is indicated by the plagioclase, microcline, muscovite, and biotite. The sedimentary provenance was the main donor of detritus for this sandstone, a conclusion that would concur with Imlay's statement that ". . . most of the sandstones of Middle Jurassic and Callovian age were derived from the east or southeast and were probably reworked from older sandstones" (43, p. 492). Deposition of the detritus for the calcareous quartz arenite was probably in the high-energy littoral zone, as indicated by the good sorting and calcite cement.

The mudstone and micritic limestone of the middle Rierdon Formation probably accumulated in a marine environment of deeper water and lower energy, where sorting of the sediment could not occur. Many of the shell fragments in these rocks were probably washed into the deeper environment from closer to shore, but where complete fossil shells are abundant it seems probable that the environment could not have been deeper than shallow neritic (43, p. 496).

The oolites found at the top of the formation indicate aggregation and deposition in the shallow, warm, agitated, marginal parts of the sea. Oolites are considered by Imlay (43, p. 493-494) to be especially representative of the beginning and ending of marine transgressions.

Figure 11. Moderately steep dipping beds of the Swift Formation just east of the east flank of Snowflake anticline.

probably from the limestone that also contributed the oolitic limestone fragments to the calcarenite. These reworked oolites can generally be distinguished from the primary oolites by the indistinct, partly destroyed structure and micritic composition of the former.

Table 12. Swift Formation; stratigraphic section measured on the north side of Taylor Fork Valley in the NW1/4SE1/4 of sec. 9, T. 9 S., R. 4 E.

Morrison Formation

Conformity: contact sharp; non-glauconitic limestone of Morrison Formation overlies the glauconitic calcarenite of the Swift Formation.

Swift Formation

		Thickness (feet)	
Unit	Description	Unit	Total
1.	Calcarenite: dusky-yellow (5Y 6/4), weathers yellowish-gray (5Y 7/2); six cross-bedded calcarenite beds from 1' to 8' thick alternate with six oolitic-skeletal limestone beds from 1' to 9' thick; calcarenite contains fine- to coarse-grained oolites, rounded quartz, angular to subrounded chert, volcanic glass fragments, glauconite, heavy minerals, and limestone, sandstone, and siltstone fragments in calcite cement; oolitic-skeletal limestones; olive-gray (5Y 4/1), weathers pale-yellowish-brown (10YR 6/2); medium-grained oolites; skeletal grains include bryozoans, echinoid spines, and pelecypods; subordinate detrital grains of subangular to rounded quartz, chert, and glauconite; calcite cement. Samples Js-1, Js-2, and Js-3 taken 8', 25' and 36' above base of formation, respectively.	60.6	60.6
	Total thickness.....	60.6	

Conformity: contact sharp; glauconitic-oolitic-skeletal limestone of Swift Formation overlies non-glauconitic, oolitic limestone of the Rierdon Formation.

Rierdon Formation

The framework for the interbedded oolitic-skeletal limestones consists of medium-grained oolites and fine to coarse skeletal grains of pelecypods, gastropods, bryozoans, crinoid stems, echinoid spines, and belemnoids, with minor angular to subangular detrital quartz, chert, plagioclase, heavy accessory minerals, and fragments of limestone, sandstone, and siltstone. Glauconite is present in amounts up to five percent in many of the limestones and occurs as green subrounded grains that impart a green color to some of the limestones. Fine- to coarse-grained recrystallized sparry calcite cements the framework. In thin section the oolites appear to be both spherical and ovate and show radial, concentric, and radial-concentric structure. Most of the oolites have no identifiable nuclei, but, where present, nuclei are made up of quartz and shell fragments. All primary oolites are stained bright reddish-brown by limonite, but reworked oolites and fragments of oolitic limestone have not been observed to be stained.

Fossils and Age

The Swift Formation, though not as fossiliferous as the Rierdon Formation, yielded a suite of marine fossils that includes specimens of *Astrocenia* sp., *Ostrea* sp., columnals of *Pentacrinus* sp., echinoid spines, belemnoid guards, and unidentifiable fragments of pelecypods and gastropods.

The faunal assemblage of the Snowflake Ridge area resembles much of the composite fauna described by Imlay (43, p. 497-498) from the western interior of the United States. Imlay dated the fauna as being Oxfordian (early Late Jurassic) in age. Cobban (13, p. 1286) also has dated a similar fauna in the Sweetgrass Arch, Montana, as Late Jurassic. Because of faunal and lithologic similarities, the beds of the Swift in the Snowflake Ridge area are considered to be approximately the same age as those dated by Imlay and Cobban.

Source and Depositional Environment

The oolitic limestone fragments, reworked oolites, chert, and sandstone and siltstone clasts of the Swift Formation suggest a sedimentary provenance. The quartz grains and sandstone fragments probably came from a pre-existing sandstone, and the chert, reworked oolites, and limestone fragments were derived from a pre-existing limestone or limestones.

The presence of oolites, abundant detrital material, shallow water fossils, cross-bedding, and the absence of micrite, suggests that deposition of the Swift Formation was in the shallow, agitated, littoral zone. The presence of glauconite further indicates a marine environment provided it has not been recycled into the rock from some outside source. The source area of detritus was probably to the east of the area of study.

Morrison Formation

Eldridge (27) was the first to use the name Morrison Formation, which he applied to an essentially fresh water sequence of shales and dirty sandstones near Morrison, Colorado, but he did not designate a type section. In 1944 Waldschmidt and LeRoy (80) designated and described a type section approximately two miles north of the town of Morrison. Since then fresh water deposits of very Late Jurassic age have been included in the Morrison Formation in Colorado, Wyoming, and Montana.

The basal contact of the formation appears to be conformable with the Swift Formation. This contact is best exposed on the north side of Taylor Fork Valley, where a section of Morrison beds was measured. The overlying basal conglomerate of the Kootenai Formation rests unconformably on the uppermost sandstones of the Morrison.

Distribution and Physiographic Expression

In the Snowflake Ridge area the non-resistant Morrison Formation is usually poorly exposed. Some of the light-colored sandstone lenses in the formation form small outcrops rising several feet above the gently sloping, grass-covered slopes formed on the softer shales and mudstones.

The Morrison Formation crops out along the east flank of the Snowflake anticline, but the best exposures of the formation are on the north side of the valley of Taylor Fork and on the west side of Monument Creek Valley in the Monument Creek structural complex.

Thickness and Lithology

A section of the Morrison Formation was measured on the north side of Taylor Fork Valley in the center of sec. 9, T. 9 S., R. 4 E. (Table 13), where it is about 320 feet thick.

In the Snowflake Ridge area the Morrison Formation consists of a sequence of alternating mudstones and sandstones, in almost equal proportions.

The mudstones of the Morrison Formation are dominantly grayish-olive green and weather various shades of green, brown, gray, and yellow. The mudstone intervals range in thickness from less than seven feet to greater than 40 feet. The mudstones are all calcareous and generally contain silt to fine-sized sand quartz grains.

A gray, hard, massive, highly-fossiliferous, micritic limestone, 2.5 feet thick, is present in the lower part of the formation. The fossils were not identified, but include fresh-water pelecypods, gastropods, and ostracods. Microscopically the limestone is seen

Table 13. Morrison Formation; stratigraphic section measured on the north side of Taylor Fork Valley in the center of sec. 9, T. 9 S., R. 4 E.

Kootenai Formation

Disconformity: basal conglomeratic sandstone of the Kootenai Formation rests on uppermost sandstone of the Morrison Formation.

Morrison Formation

		Thickness (feet)	
Unit	Description	Unit	Total
14.	Quartz arenite: light-olive-gray (5Y 6/1), weathers light-brownish-gray (5YR 6/1); thin-bedded (1" to 4") and commonly flaggy; cross-bedded; subangular, very fine- to fine-grained quartz, chert, and feldspar; numerous black carbonaceous flakes and plant debris. Sample Jm-8 taken 295' above base of formation.	28.5	319.6
13.	Quartz arenite: yellowish-gray (5Y 7/2), weathers moderate-brown (5YR 3/4); laminated (less than 1/2"); cross-bedded; lithology like unit 14; unit contains coarse-grained subfeldspathic lithic arenite and pebble lenses and scour-and-fill structures averaging 4" thick.	37.5	291.1
12.	Quartz arenite: moderate-orange-pink (5YR 8/4), weathers moderate-brown (5YR 3/4); laminated (less than 1/2".); cross-bedded; subangular to subrounded, medium-grained quartz, chert, and siltstone; grades upward into fine-grained, laminated (less than 1/2"), cross-bedded quartz arenite: yellowish-gray (5Y 7/2), weathers moderate-brown (5YR 3/4). Samples Jm-7 and Jm-6 taken 260' and 220' above base of formation, respectively.	36.0	253.6
11.	Covered section: in part quartz arenite as in lower part of unit 12.	59.0	217.6
10.	Covered section: in part mudstone: grayish-brown (5YT 3/2), weathers moderate brown (5YR 3/4); calcareous.	24.0	158.6
9.	Quartz arenite: grayish-orange (10YR 7/4), weathers grayish-orange-pink (5YR 7/2); massive; calcareous; very fine-grained. Sample Jm-5 taken 125' above base of formation.	11.6	134.6

Table 13. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
8.	Mudstone: grayish-olive-green (5GY 3/2), weathers grayish-red (5R 4/2); calcareous.	43.9	123.0
7.	Quartz arenite: grayish-orange (10YR 7/4), weathers grayish-orange-pink (5YR 7/2); massive; calcareous; very fine-grained. Sample Jm-5 taken 125' above base of formation.	8.1	79.1
6.	Mudstone: same as unit 8.	32.5	71.0
5.	Micritic limestone: medium-gray (N5), weathers light-brownish-gray (5YR 6/1); massive; hard; abundant fossils of fresh-water pelecypods, gastropods, and ostracods. Sample Jm-3 taken 37' above base of formation.	2.5	38.5
4.	Mudstone: grayish-olive green (5GY 3/2), weathers dusky-yellow-green (5GY 5/2); calcareous.	6.4	36.0
3.	Quartz arenite: pale-yellowish-orange (10YR 8/6), weathers dark-yellowish-orange (10YR 6/6); laminated (less than 1 cm.); cross-bedded; soft and friable; angular to subangular quartz; sparry calcite cement. Sample Jm-2 taken 25' above base of formation.	7.2	29.6
2.	Mudstone: grayish-olive green (5GY 3/2), weathers dusky-yellow-green (5GY 5/2); non-calcareous.	16.6	22.4
1.	Quartz arenite: light-olive-gray (5Y 6/1), weathers dark-yellowish-orange (10YR 6/6); massive; subangular, fine-grained quartz and chert; sparry calcite cement. Sample Jm-1 taken 2' above base of formation.	5.8	5.8
	Total thickness.....	319.6	

Conformity: contact sharp

Swift Formation

to be composed of coarsely crystalline calcite skeletal fragments, oolitic limestone clasts, and micritic calcite containing silt and very fine sand sized grains of quartz and plagioclase. The limestone fragments are now composed of micrite, but relict oolities with sparry calcite nuclei are recognizable. The micritic limestone is cut by numerous microveinlets of sparry calcite.

The sandstones of the Morrison Formation include beds that are laminated to thin-bedded (less than 1/2 inch to 4 inches thick) and beds that are massive. The laminated and thin-bedded sandstones are cross-bedded and locally contain scour-and-fill structures of medium- to coarse-grained sandstone. Modal analyses of the sandstones of the measured section showed all except the coarser grained scour-and-fill sandstones to be quartz arenites, some of which are calcareous. Fresh surfaces are various shades of gray, green, pink, and orange, and weathered surfaces are generally shades of brown and orange. Microscopically, the quartz arenites are seen to consist of angular to subrounded grains of quartz, chert, and heavy minerals cemented together by calcite and hematite or by microcrystalline quartz. Overgrowths on rounded quartz grains are common, but the present grains are generally angular owing to replacement around the edges by the carbonate cement and interpenetration by compaction along grain boundaries. Sparry calcite may be totally absent or comprise up to 35 percent of the quartz arenites. Authigenic hematite and its alteration product, limonite, are present in most of the thin-sections and commonly stain the calcite red. The hematite fills voids between grains and acts as a cementing agent. In the noncalcareous quartz arenites the compaction of grains is always greater than in the calcareous sandstones. The grains are bonded together by interpenetration of grains along grain boundaries and by authigenic microcrystalline quartz. Minor amounts of quartzite, plagioclase, microcline, zircon, tourmaline, and magnetite are usually present.

Petrographic examination of the medium- to coarse-grained, scour-and-fill sandstones, which occur in the upper part of the unit, shows them to be subfeldspathic lithic arenites. Quartz, chert, quartzite, siltstone clasts, and volcanic rock fragments make up most of the framework in these sandstones, with minor amounts of feldspar and heavy mineral grains. Bonding of the grains is by authigenic microcrystalline quartz, hematite, and by welding together by interpenetration of grains. However, the coarser grained sandstones have good porosity despite their greater than normal degree of compaction. Many of the quartz grains have overgrowths.

Table 14 gives the modal analyses of the sandstone samples collected from the measured section. Sample Jm-6 is a scour-and-fill sandstone taken from unit 12 of the section.

Table 14. Modal analyses of sandstones from the measured section of the Morrison Formation.

	Jm-1	Jm-2	Jm-6	Jm-8
Detrital quartz	58	63	45	50
Chert and quartzite	4	2	22	11
Carbonate	25	35	—	8
Authigenic microcrystalline quartz	—	—	15	20
Hematite	12	—	3	6
Limonite	Tr	—	Tr	2
Feldspar	Tr	Tr	Tr	2
Fine-grained rock fragments	—	—	15	—
Heavy accessory minerals	1	Tr	Tr	1

Fossils and Age

Age determination for the Morrison Formation is based on correlation by stratigraphic position and lithologic similarity with adjacent regions in the northern Cordillera. No identifiable fossils were found other than the fresh water pelecypods, gastropods, and ostracods.

Early workers assigned an Early Jurassic age to the Morrison Formation, but Simpson (70), in a thorough paleontological study of the fauna, has dated the Morrison as Late Jurassic. Imlay (42, chart 8C) also assigns the Morrison a Late Jurassic age.

Source and Depositional Environment

The absence of marine fossils and the presence of current cross-bedding and scour-and-fill structures in the Morrison Formation suggests a fluvial depositional environment. From a study of the stratigraphy of the Morrison Formation in southwestern Montana, Moritz (55, p. 1811-1812) concluded that:

> Following the withdrawal of the Jurassic sea this region was a low plain, on which the widespread fluvial deposits of the Morrison formation were deposited. Relatively large rivers meandered across this plain of low relief. The geographic conditions during Morrison time over such a vast area have no counterpart in the present landscape. The courses of these rivers were constantly changing and shifting, accounting for the rapid facies changes that the formation exhibits. Ephemeral lakes sometimes developed on the broad flood plains, and the fresh-water limestones were deposited in them. The thickness and nature of the clastic material in the sediments indicate that this region remained stable during late Jurassic time, but the presence of a few 'salt-and-pepper' sandstones (subgraywackes), which become very abundant in the Cretaceous, suggests a transition from stable conditions to geosynclinal conditions. The axis of the geosyncline remained west of this region.

Mineralogical evidence suggests that the many Late Jurassic rivers that eroded and transported the clastic debris deposited as the Morrison Formation probably passed through areas of sedimentary, igneous, volcanic, and metamorphic rocks, all of which contributed to the river detritus. However, winnowing during transport, especially of the less resistant minerals, makes it impossible to tell which provenance might have been the principal donor.

Cretaceous System

Kootenai Formation

The Kootenai Formation disconformably overlies the Jurassic Morrison Formation. In 1885 Dawson (82, p. 1119) described a sequence of Lower Cretaceous conglomerates, sandstones, shales, and thin coal beds to which he applied the name Kootenie in Alberta, Canada, but he did not designate a type section. The present spelling of Kootenai was introduced by Fisher (29), who used the name Kootenai Formation for beds in Montana and part of Wyoming that he correlated with the Kootenie beds of Dawson in Alberta. At Three Forks, Montana, Berry (6) referred 1,500 feet of sandstone, shale, and fresh-water limestone, originally designated the Dakota Sandstone by Peale (61), to the Kootenai Formation.

A disconformity between the Morrison Formation and the basal conglomerate of the Kootenai Formation is exposed along the north side of Taylor Fork within the thesis area, but the best exposure of this contact occurs at the locality where the Kootenai section was measured, in sec. 21, T. 7 S., R. 4 E., about 7 miles north of the Snowflake Ridge area (Figure 12).

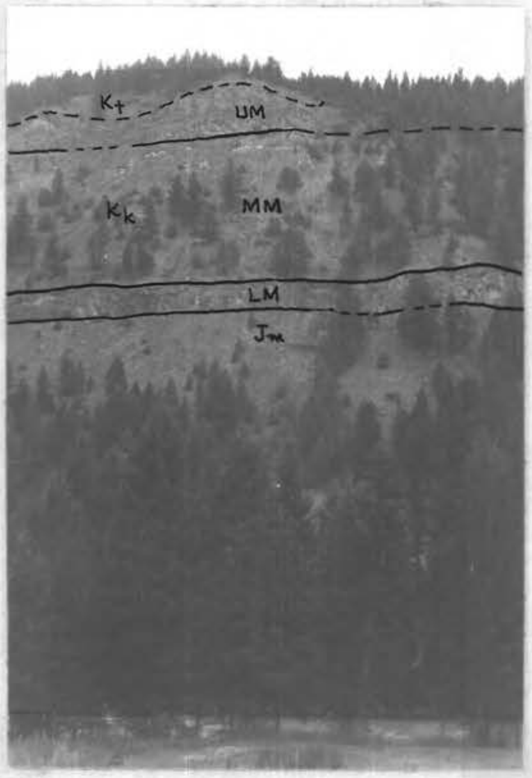

Figure 12. Kootenai Formation on east side of Gallatin River, sec. 21, T. 7 S., R. 4 E. Lower cliff is Lower Member, tree covered slope is Upper Member. Top of the slope is capped by beds of the Thermopolis Shale.

Distribution and Physiographic Expression

The Kootenai Formation is the most widespread outcropping unit in the thesis area. The formation crops out along the east flank of Snowflake anticline, from which exposures trend southeast into the structural complex on the west side of Monument Creek Valley. Kootenai rocks also crop out along the valley of Taylor Fork and over much of the southwestern part of the Snowflake Ridge area (Plate 2).

Exposures of the Kootenai Formation, on the whole, are good, but at no one place within the thesis area is the complete Kootenai section exposed. The lower conglomerates and sandstones of the formation commonly form ledges and small cliffs, but the middle beds of mudstones, siltstones, and limestones and the upper beds of sandstone generally produce grassy slopes and gently rolling topography. Slopes that lie below the conglomerates and sandstones generally are strewn with large angular blocks, many of them greater than 10 feet in diameter (Figure 30).

Thickness and Lithology

A complete stratigraphic section of the Kootenai Formation was measured about 7 miles north of the thesis area, where the thickness of the formation is 430 feet (Table 15). Estimates of thickness of

Table 15. Kootenai Formation; stratigraphic section measured on the east side of the Gallatin River Canyon in sec. 21, T. 7 S., R. 4 E.

Thermopolis Shale

Disconformity: contact sharp

Kootenai Formation

		Thickness (feet)	
Unit	Description	Unit	Total
Upper Member			
46.	Quartz arenite: pale-yellowish-brown (10YR 4/4); thinly laminated (less than 3/16"); cross-bedded; parts into 2" to 18" layers; angular to subrounded, very fine-grained quartz, chert, and K-feldspar grains; framework bonded by quartz overgrowth, authigenic microcrystalline quartz, and interpenetration of grains; grain size increases upward to fine-grained; widely scattered chert pebbles near base. Sample Kk-14 taken 414' above base of formation.	21.0	430.1
Middle Member			
45.	Siltstone to very fine-grained arenite: colors same as in unit 43; poorly laminated (less than 1/2"); mottled; limonite stained; quartzose; widely scattered chert pebbles; becomes harder, cleaner, and better laminated upwards. Sample Kk-13 taken 400' above base of formation.	15.0	409.1
44.	Quartz arenite: colors same as in unit 43, laminated (less than 1/2"); hard; dense; blocky, subangular, fine-grained quartz and chert; limonite spots from alteration of hematite.	5.0	394.1
43.	Siltstone: light-gray (N 7), weathers brownish-gray (5YR4/1); laminated (less than 1/2"); tending toward platiness; hard; dense; blocky; bedding undulates; peaty mudstone partings; iron concretions.	14.9	389.1
42.	Siltstone: dark yellowish-orange (10YR 6/6); weathers grayish-red (5YR 4/2); tectonic zone of extreme shattering and discoloration of siltstone; bed-on-bed gluiding and highly contorted bedding.	2.1	374.2
41.	Quartz arenite: colors same as in unit 40; laminated (less than 1/2"); hard; dense; blocky; angular to subrounded, fine-grained quartz and chert cemented by overgrowths, authigenic microcrystalline quartz, and		

Table 15. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
	hematite; appears salt-and-pepper owing to small hematite pods altering to limonite. Sample Kk-12 taken 365' above base of formation.	11.5	372.1
40.	Siltstone: light-gray (N 7), weathers brownish-gray (5YR 4/1); drag folded zone; laminated (less than 1/2") to thin-bedded (less than 2"); platy; 1" dusky red (5R 3/4) laminated (less than 1/2") layer in middle of unit weathering dark reddish-brown (10R 3/4).	4.5	360.6
39.	Arenite: probably quartz arenite; colors same as in unit 38; laminated (less than 1/2"); hard, very fine-grained; upper 1' limonitic.	4.0	356.1
38.	Mudstone: dark reddish-brown (10R 3/4); weathers grayish-red (10R 4/2); fractured.	3.0	352.1
37.	Quartz arenite: colors same as in unit 36; laminated (less than 1/2"); symmetrical ripple-marks with wave length of 2.5" and amplitude of 1/2"; subangular to subrounded, very fine-grained quartz and chert. Sample Kk-11 taken 349' above base of formation.	5.0	349.1
36.	Siltstone: moderate-brown (5YR 4/4), weathers grayish-orange (10YR 7/4); thinly laminated (less than 3/16"); platy; becomes thin-bedded (less than 2"), less platy, and grades upward to very fine-grained, crossbedded quartz arenite.	6.3	344.1
35.	Siltstone: light-gray (N 7), weathers pale-yellowish-brown (10YR 6/2); massive, hard, dense; highly fractured.	4.1	337.8
34.	Siltstone: brownish-black (5YR 2/1), weathers dusky-brown (5YR 2/2); hard, dense.	2.5	333.7
33.	Siltstone: light-gray (N 7), weathers pale-yellowish-brown (10YR 6/2); thin-bedded (less than 1/2"); hard, dense, highly fractured. Sample Kk-10 taken 324' above base of formation.	12.0	331.2

Table 15. (continued)

Unit	Description	Thickness (feet) Unit	Total
32.	Mudstone: olive-gray (5Y 3/2), weathers grayish-red (5R 4/2); massive, highly fractured; calcareous; poorly exposed.	12.0	319.2
31.	Gastropod limestone: pale yellowish-brown (10YR 6/2), weathers moderate yellowish-brown (10YR 5/4); massive; hard; micritic cement with micritic replacement of shell material; gastropods small (all less than 3/4" long); some oolites.	8.0	307.2
30.	Siltstone: yellowish-gray (5Y 8/1), weathers pinkish-gray (5YR 8/1); laminated (less than 1/2") to thin-bedded (less than 4"); hard; dense; highly fractured; calcareous.	8.9	299.2
29.	Gastropod limestone: same as unit 31, but contains numerous small lenses of gray to black siltstone up to 1' long and 1" thick. Sample Kk-9 taken 290' above base of formation.	1.0	290.3
28.	Siltstone: olive-black (5Y 2/1), weathers olive-gray (5Y 4/1); massive, hard, dense, highly fractured; cut-and-fill structure by overlying gastropod limestone.	1.5	289.3
27.	Shaly limestone: black (N 1), weathers yellowish-gray (5Y 8/1); one bed; strong fetid odor.	0.7	287.8
26.	Gastropod limestone: same as unit 31.	7.5	287.1
25.	Micritic limestone: medium-dark-gray (N 4), weathers pinkish-gray (5YR 8/1); hard; dense.	1.5	279.6
24.	Gastropod limestone: same as unit 31. Sample Kk-8 taken 275' above base of formation.	4.0	278.1
23.	Covered section: talus and soil cover; soil color change from red to yellow-tan upward; probably becomes more calcareous upward.	41.0	274.1
22.	Mudstone: olive-gray (5Y 3/2), weathers grayish-red (5R 4/2); massive; fractured; nondular; becomes less calcareous upward. Sample Kk-7 taken 198' above base of formation.	40.0	233.1

Table 15. (continued)

Unit	Description	Thickness (feet) Unit	Total
21.	Quartz arenite: dusky-brown (5YR 2/2), weathers grayish-brown (5YR 3/2); massive; subrounded, fine-to medium-grained quartz and chert, and small square green flakes of unknown composition. Sample Kk-6 taken 180' above base of formation.	19.0	193.1
20.	Siltstone: pale-red (10R 6/2), weathers dark-yellowish-orange (10YR 6/6); massive; hard; very dense; highly fractured; tuffaceous and calcareous; contains small irregular to lathlike inclusions of mudstone. Sample Kk-5 taken 130' above base of formation.	50.0	174.1
19.	Mudstone: dusky-red (5R 3/4), weathers blackish-red (5R 2/2); poorly bedded.	19.0	124.1
18.	Micritic limestone: dark-reddish-brown (10R 3/4), weathers pale-reddish-brown (10R 5/4); hard; some calcite veinlets; scattered chert pebbles ranging in size from less than 3/16" to 1 1/2" long in top 5' of unit. Sample Kk-4 taken 94' above base of formation.	16.0	105.1
17.	Limy mudstone breccia: pale-yellowish-brown (10YR 6/2), weathers grayish-orange (10YR 7/4); massive; mudstone contains small angular fragments of underlying and surrounding siltstone; contact with underlying siltstone appears to be a relief surface with limy mudstone breccia penetrating 4" to 5" into underlying siltstone; outcrop highly fractured and nodular; grades upward into limestone of unit 18. Sample Kk-3 taken 84.5' above base of formation.	5.5	89.1
16.	Siltstone: dusky-red (5R 3/4), weathers dark-reddish-brown (10R 3/4); poorly bedded; fractured; contains sand grains of quartz and chert and small chert pebbles.	5.5	83.6
Lower Member			
15.	Arenite: probably either a quartz arenite or a feldspathic arenite; yellowish-gray (5Y 8/1), weathers grayish-orange (10YR 7/4); poorly bedded; highly fractured; salt-and-pepper, pebbly, subangular to subrounded, fine - to medium-grained quartz, chert, and feldspar; chert pebbles range from less than 3/16" to greater than 1/2"; contact		

Table 15. (continued)

Unit	Description	Thickness (feet) Unit	Total
	with underlying quartz arenite is gradational over approximately 3'.	8.0	78.1
14.	Quartz arenite: colors same as in unit 12; massive; subangular, very fine-grained quartz and chert cemented by authigenic microcrystalline quartz. Sample Kk-2 taken 64' above base of formation.	17.6	70.1
13.	Conglomerate: colors same as in unit 12; chert pebbles in matrix of medium-grained, salt-and-pepper feldspathic arenite; scour-and-fill structure.	0.7	52.5
12.	Feldspathic arenite: yellowish-gray (5Y 7/2), weathers moderate-brown (5YR 4/4); massive; salt-and-pepper; subangular to subrounded, medium-grained quartz, chert, and K-feldspar.	5.8	51.8
11.	Quartz arenite: colors same as in unit 3; massive; pebbly; same as unit 14.	1.7	46.0
10.	Conglomerate: colors same as in unit 3; massive; chert pebbles 1/4" to 1/2" long in matrix of fine-grained, salt-and-pepper arenite.	0.3	44.3
9.	Arenite: colors same as in unit 3; fine-grained, salt-and-pepper, and quartzose.	1.1	44.0
8.	Conglomerate: colors same as in unit 3; chert pebbles less than 1/4" in diameter in a fine-grained matrix of salt-and-pepper quartz arenite.	0.2	42.9
7.	Feldspathic arenite: colors same as in unit 3; laminated (less than 1/2") to thin-bedded (up to 4"); subangular to rounded, very coarse-grained quartz, chert, and K-feldspar; salt-and-pepper and pebbly; grades upward into coarse-grained feldspathic arenite.	11.1	42.7
6.	Rhymically alternating feldspathic arenite and quartz arenite: colors same as in unit 3; laminated (less than 1/2") to thin-bedded (up to 4"); subangular to rounded, very coarse-grained, pebbly, salt-and-pepper feldspathic arenite alternating with subangular to subrounded, fine-grained, salt-and-pepper quartz arenite.	3.0	31.6

Table 15. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
5.	Conglomerate: colors same as in unit 3; scour-and-fill structure; chert pebbles up to 1/2" in diameter in a coarse-grained matrix of salt-and-pepper, feldspathic arenite.	0.9	28.6
4.	Feldspathic arenite: colors same as in unit 3; laminated (less than 1/2") to thin-bedded (up to 1/2"); cross-bedded subangular to rounded, very coarse-grained quartz, chert, and K-feldspar; tuffaceous; several lenses of pebbly feldspathic arenite in lower 5'.	19.7	27.7
3.	Conglomerate: pinkish-gray (5YR 8/1), weathers light-brown (5YR 6/4); chert pebbles up to 1/2" in diameter in a coarse-grained, tuffaceous, salt-and-pepper feldspathic arenite; grades upwards from largest to smallest pebbles.	1.0	8.0
2.	Feldspathic arenite; massive; subangular to rounded, very coarse-grained quartz, chert, and K-feldspar; tuffaceous; salt-and-pepper; contains 1" to 2" graded chert pebble layers about 1.5' apart; pinches out to west.	4.5	7.0
1.	Basal conglomerate: pinkish-gray (5YR 8/1), weathers light-brown (5YR 6/4); pebbles and cobbles of Morrison sandstone and pebbles of tan, red, brown, gray, and black chert in matrix of feldspathic arenite: subangular to rounded, coarse-grained quartz, chert, and K-feldspar; tuffaceous; salt-and-pepper. Sample Kk-1 taken 1' above base of formation.	2.5	2.5
	Total thickness.....	430.1	

Disconformity: contact sharp

Morrison Formation

outcrops in the Snowflake Ridge area and rough calculations of thicknesses based upon the geologic map compare well with the thickness of the section. Lithologies of the measured section are closely similar to those within the thesis area, indicating that there is little or no facies change between the area of the thesis and the site of the measured section.

Three distinct lithologic members are present in the Kootenai Formation in the region studied. For descriptive purposes the formation is here divided into a Lower Member of conglomerates and sandstones, a Middle Member of mudstones, siltstones, and limestones, and an Upper Member of sandstone.

Lower Member: Approximately 80 feet of coarse-grained, salt-and-pepper sandstones and chert-pebble conglomerates make up the Lower Member of the Kootenai Formation. Weathered surfaces are predominantly shades of dark brown. Fresh surfaces are lighter and more variable in color, depending upon the relative amounts of pebbles, sand, and iron oxides. The commonest colors of the fresh rocks are pinkish- and yellowish-gray. Bedding ranges from massive to laminated. Grain size is the most important factor controlling the development of bedding. Interlensing of the conglomerates and sandstones is common in the Lower Member. Scour-and-fill structures were observed but appear to be less common. Graded bedding and crossbedding are the only sedimentary structures present. The ledges and cliffs made up of this Lower Member are generally highly fractured into large blocks.

The basal conglomerate of the Kootenai Formation is 2.5 feet thick and lies disconformably on the uppermost sandstone of the Morrison Formation. Fresh surfaces of the conglomerate are pinkish-gray but are light-brown where weathered. The unit appears to be uniform in thickness and to have wide lateral continuity. The conglomerate consists of subrounded to angular pebbles and cobbles up to 6 inches in diameter of Morrison sandstone and subordinate white, tan, red, brown, gray, and black well rounded to rounded chert pebbles set in a matrix of coarse-grained, salt-and-pepper sandstone.

Microscopic inspection of the basal conglomerate shows a variety of types of chert pebbles. Besides the usual microcrystalline chert there are also pebbles of microgranular and chalcedonic chert. Small pebbles of basalt are also present in the conglomerate. The matrix is a mixture of medium- to coarse-grained, angular to subangular, detrital quartz, chert, and basalt fragments and interstitial, partly devitrified, volcanic glass. Minor detrital accessory minerals include K-feldspar, magnetite, zircon, and green hornblende. Authigenic microcrystalline quartz and hematite are present. The hematite rims many of the grains, aiding in cementing the framework together and adding to the color of the rock.

Overlying the basal conglomerate is a sequence of lenticular sandstones and subordinate conglomerates. The lenses vary in both lateral and vertical extent. On a whole, pebbles decrease in abundance upward in the section. The conglomerate lenses have essentially the same composition as the basal conglomerate, but the lenses contain no pebbles and cobbles from the Morrison Formation.

The sandstones of the Lower Member of the Kootenai Formation are predominantly medium- to coarse-grained, salt-and-pepper sandstones. However, there are several fine-grained, clean, calcareous, quartzose sandstone beds in the Lower Member.

The coarse-grained, salt-and-pepper sandstones in composition and texture are much like the matrix of the conglomerates. The fine-grained sandstones are composed of well-sorted, angular to subrounded grains of quartz and orthoclase. Minor constituents are chert, volcanic glass, muscovite, garnet, tourmaline, and zircon. Authigenic calcite is an important constituent of these fine-grained quartzose sandstones and authigenic microcrystalline quartz and hermatite are also commonly present. A modal analysis of one thin section from a fine-grained quartzose sandstone is given in Table 16.

Quartz is by far the most abundant detrital mineral. It is generally colorless but may appear gray where many inclusions occur. Both regular and irregular shaped inclusions are present. Many of the grains are strained, showing undulatory extinctions. The feldspar, which is nearly all orthoclase, occurs as gray, cloudy grains. Most of the feldspar grains show minor alteration.

Table 16. Modal analysis of Kootenai Formation Lower Member sandstone sample.

	Kk-2[1]
Detrital quartz	48%
K-feldspar	10
Carbonate cement	27
Authigenic microcrystalline quartz	13
Chert	1
Plagioclase	Tr
Hematite	Tr
Heavy accessory minerals	Tr

Sample location:

[1] Measured section of Kootenai Formation, sec. 21, T. 7 S., R. 4 E., 64 feet from base of formation.

The sandstones, though moderately porous, are well cemented by carbonate minerals and microcrystalline quartz and are highly compact. Interpenetration of grains along contact boundaries is common, and sutured grain contacts are being developed. Calcite and minor amounts of siderite are present in patches around the grains and replace the quartz and feldspar. Authigenic microcrystalline quartz has been precipitated between and around the detrital grains in small, scattered, and irregular masses.

These fine-grained quartzose sandstones are classified as calcareous quartz arenites. The coarse-grained, salt-and-pepper sandstones with which the calcareous quartz arenites are associated are classified as tuffaceous feldspathic arenites.

Middle Member: Overlying the lower conglomerates and sandstones are about 330 feet of reddish- to yellowish-brown mudstones, siltstones, and limestones, some of which are tuffaceous. The mudstones and siltstones are commonly calcareous.

In thin section some of the siltstones are seen to be predominantly composed of quartz fragments. Partially devitrified volcanic glass with relict shards is commonly present. Ankerite is the principle carbonate mineral, but calcite is usually present in minor amounts. The carbonate mineral content ranges from about 1 percent up to 45 percent, and most slides examined contain at least 10 percent.

Most of the limestones of the Middle Member are in the upper part. They are predominantly yellowish-brown to yellowish-gray, vary in thickness from slightly over one foot to 8 feet, and are generally separated from one another by several feet of calcareous siltstone. Four distinct limestones, each containing more than 50 percent gastropod shell material, occur in the upper part of the member, but nonfossiliferous, hard, dense limestones are also present.

The limestones are composed of microcrystalline to finely crystalline calcite, micrite, or sparry calcite, or a mixture of these. Except in the highly porous gastropod limestones, fossil material is absent. Several vaguely-defined structures were observed that possibly are of fossil origin, but recrystallization of the limestones has obliterated the evidence. The gastropod shell material appears to have been replaced and is now composed of micrite. Coarsely-crystalline sparry calcite, micrite, and chalcedonic quartz act as cementing agents for the gastropod shells, which commonly are filled with microcrystalline calcite or chalcedony.

A disturbed zone, slightly over 5 feet thick, occurs near the top of the Middle Member in the measured section. This zone is noted by its extreme shattering and discoloration of the siltstone beds of which it is composed. Apparently extensive bed-on-bed gliding has resulted in highly contorted bedding (Figure 13).

Upper Member: The Upper Member of the Kootenai Formation is a very fine- to fine-grained, clean, well-sorted, sparkling quartz arenite that weathers to a reddish-brown. This quartzose sandstone member is approximately 20 feet thick. Very widely scattered pebbles, all less than half an inch in diameter, are present in the beds of the base of the member. The sandstone is generally laminated to thin-bedded, with a maximum bedding thickness of 18 inches. Bedding is poorly developed in places. Crossbedding is prevalent in several zones within the unit. Like the Lower conglomerate and sandstone member, the Upper Member is fractured into blocks.

Figure 13. Highly contorted and shattered beds in Middle Member of Kootenai Formation at site of measured section.

Small limonite spots up to 1/4 inch in diameter, derived from alteration of hematite, occur on the outcrop surfaces.

Petrographic analyses show the Upper sandstone member to be composed of very well-sorted, angular to subrounded grains of quartz and chert. Minor accessory minerals include K-feldspar, quartzite, muscovite, green hornblende, garnet, tourmaline, and zircon. Authigenic minerals include microcrystalline quartz, hematite, and limonite. Table 17 shows modal analyses of two thin sections from the Upper Member of the Kootenai Formation.

Table 17. Modal analyses of Kootenai Formation Upper Member sandstone.

	TCL-40[1]	Kk-14[2]
Quartz	67%	64%
Chert	15	12
K-feldspar	9	7
Authigenic microcrystalline quartz	8	13
Quartzite	Tr	2
Hematite	1	2
Heavy accessory minerals	Tr	Tr

Sample locations:

[1] Along east side of Little Wapiti Creek, 3/4 mile above sharp turn in dirt road to Wapiti Creek Ranger station.

[2] Measured section of Kootenai Formation, sec. 21, T. 7 S., R. 4 E., 414 feet from base of formation.

Colorless, strained grains of quartz with regular and irregular inclusions are the major constituent of the sandstone. The feldspar is predominantly orthoclase and shows a slight alteration. The chert grains, gray, and composed of microcrystalline quartz, are highly compacted, and many are completely enclosed by other grains of chert and quartz. Except for the heavy minerals, the grains are of nearly equal size and shape. Many grains have sutured contacts, and most grains are seemingly so intergrown as to lock themselves together. The heavy mineral grains are generally smaller and better rounded than other grains of the detrital framework. Microcrystalline quartz has formed in the voids. Because of the high degree of compaction and the filling of the voids with microcrystalline quartz, this sandstone has very little pore space. Hematite, which rims some of the grains, also helps to render this sandstone nonporous.

Age and Fossils

The Kootenai Formation in Montana is considered to be Early Cretaceous in age (16). Age determination for the formation in the thesis area is based upon the stratigraphic position of the beds and lithologic comparison of the section with that of other sections reported in the literature. Other than the gastropods within the gastropod limestones, no fossils were found in the formation. The gastropods are not well enough preserved or have distinctive enough character to allow classification and use in age determination.

Klepper (44) briefly described the Kootenai Formation in the Ruby River Valley and Snowcrest Range, but did not include within the formation the upper sandstone beds present there. Hall (38), however, does include the upper sandstone beds (Upper Member of this study) as part of the Kootenai in the upper Gallatin River Valley. The transitional contact between the Middle and Upper members of the Kootenai, and the sharply defined contact between the Upper Member and the overlying black shale of the Thermopolis Shale are the reasons for including the quartz arenite as part of the Kootenai Formation in the thesis area.

Source and Depositional Environment

The primary depositional environment of the Kootenai Formation is a continental lacustrine one, but a fairly high, though variable, energy zone of fluvial deposition is also indicated by the interlensing conglomerates and coarse-grained sandstones, graded conglomerates, and scour-and-fill structures. Grain roundness, good sorting, and the nearly monomineralic nature of the pebbles suggests that a moderate to high amount of transport of the detritus took place during which the less resistant material has been removed. The very high amounts of chert and quartz indicate a sedimentary provenance for the detrital constituents. The chert probably came from the

Lodgepole, Mission Canyon, and Phosphoria formations, or similar Paleozoic rocks, and the detrital quartz was probably derived from quartzose sedimentary rocks of the Quadrant, Phosphoria, or lower Paleozoic formations. The textures of the Lower Member are dominantly fluvial in character. However, the unusual amount of volcanic glass found in the conglomerates and sandstones points to fairly intense volcanic activity at the time of deposition.

The Middle Member of mudstones, siltstones, and limestones is a sequence representing much lower energy depositional requirements than the Lower Member. Fresh-water fossils, especially in the limestones, have been noted by several workers (72, 61, 6, 44). Shallow, warm lake waters were probably the sites of accumulation for these deposits. It is probable that these lake waters had high carbonate contents, and calcium carbonate precipitated from the waters and was deposited along with the clastic sediment.

The Upper sandstone member and the several sandstones near the top of the Middle Member indicate an increase in coarser detritus as well as an energy increase in the depositional environment. The excellent sorting in the Upper Member is supporting evidence for this energy increase. Symmetrical ripple marks in the sandstone indicate wave action. The significant amount of hematite contained in this sandstone would most likely form in an environment of high oxidation potential. For these reasons a shallow, warm, well-aerated marine environment is proposed as the depositional environment for this sandstone.

Thermopolis Shale

The Lower Cretaceous Thermopolis Shale, which disconformably overlies the Upper Member of the Kootenai Formation, was named by C. T. Lupton (50) in 1916 for exposures near the town of Thermopolis, Wyoming. The formation consists of dark-colored shale containing one or more lenticular beds of sandstone.

East of the Snowflake Ridge area in Stillwater and Rosebud Counties, Montana, the Muddy Sandstone was originally mapped as a member within the Thermopolis Shale, but in the thesis area no beds of Thermopolis Shale were found above the Muddy Sandstone. The distinct lithologic character and significant thickness of the Mowry Shale, and the recent practice of mapping all shale immediately above the Muddy Sandstone as part of the Mowry Shale has led the author to map the Muddy Sandstone as a separate unit.

Distribution and Physiographic Expression

Exposures of Thermopolis Shale are small and poor in the Snowflake Ridge area. Outcrops of the shale are best along the valleys of Taylor Fork and Wapiti Creek near the confluence of the two streams. The only other outcrops occur in the north part of the area in the E1/2 sec. 4, T. 9 S., R. 4 E. (Plate 2). The Thermopolis Shale section was measured north of the thesis area in sec. 31, T. 7 S., R. 4 E.

Gently sloping grass-covered slopes form on the Thermopolis Shale. A dark-gray to black soil layer is generally present, and fresh shale must be exposed by digging.

Thickness and Lithology

In the Snowflake Ridge region the measured thickness of Thermopolis Shale is 180 feet (Table 18).

Most of the Thermopolis Shale consists of olive to dark-gray shale. A siltstone unit, 40 feet thick, is present near the middle of the formation.

Outcrops are composed of hard, slightly calcareous, dark-gray shale and siltstone weathered to an olive-gray. The siltstone is laminated, platy, and calcareous. No microscopic examinations of Thermopolis samples were made.

Age and Fossils

The Early Cretaceous age of the Thermopolis Shale has been based on fossil material and stratigraphic position. No microfossils or megafossils were found in the formation in the thesis area, but one ammonite, several pelecypods, and numerous plant fragments were collected from exposures of Thermopolis Shale along the West Fork of the Gallatin River, 16 miles north of the thesis area. The ammonite, Douvilleiceras sp., and pelecypods, Inoceramus sp. and Unio sp., were identified by the author.

Table 18. Thermopolis Shale; stratigraphic section measured on the east side of the Gallatin River Canyon in sec. 21, T. 7 S., R. 4 E.

Muddy Sandstone

Conformity: contact covered; assumed from change in soil color, definite break in slope; next outcrop is Muddy Sandstone.

Thermopolis Shale

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
4.	Covered section:	10.0	180.0
3.	Shale: dark-gray (N 3), weathers olive-gray (5YR 4/1); laminated (less than 1/4"); slightly calcareous; contains many impressions of unknown affinity which are branching, approximately 1/8" wide and up to greater than 1" long; contains scattered small concretions. Sample Kt-1 taken 95' above base of formation.	90.0	170.0
2.	Siltstone: same colors as in unit 3; laminated (less than 1/2") platy (plates 1/4" to 1/2"); calcareous; forms small, low-lying ledges above shale.	40.0	80.0
1.	Shale: same colors as in unit 3; contains same branching structures as in unit 3, but lacks concretions.	40.0	40.0
	Total thickness.....	180.0	

Disconformity: contact sharp

Kootenai Formation

Source and Depositional Environment

Deposition of the Thermopolis sediments, as indicated by the lithology and fossils, was in a moderately deep marine environment. Its transitional contact with the overlying Muddy Sandstone indicates a progressively shallowing marine environment.

Since microscopic stüdy of the shale was not undertaken no evidence of source rocks was obtained.

Muddy Sandstone

The Early Cretaceous Muddy Sandstone overlies the Thermopolis Shale in the thesis area. The contact is conformable and gradational over approximately 4 feet.

Hintze (82, p. 1448) first used the name Muddy Sandstone for beds whose sands upon drilling became muddy from the soft shale above and below. Thus, there is no type section for this formation.

On Lincoln Mountain and in the northwest corner of the thesis area the Muddy Sandstone is disconformably overlain by the local Albino Formation, but in the eastern part of the area undifferentiated Upper Cretaceous rocks disconformably overlie the formation.

Distribution and Physiographic Expression

The best exposures of Muddy Sandstone are in the northwest part of the thesis area at the base of Lincoln Mountain and along the north edge of the large earthflow in sec. 4 and 5, T. 9 S., R. 4 E. (Figure 31). A section of Muddy Sandstone was measured on the north side of Taylor Fork Valley at the base of Lincoln Mountain in the center of sec. 7, T. 9 S., R. 4 E. (Figure 14).

Outcrops of Muddy Sandstone generally form ledges and small cliffs between the less resistant Thermopolis and Albino formations in the northwest part of the area. The best exposures commonly form the headwall or sidewall cliffs of landslides. In the eastern part of the area exposures are extremely poor, forming gentle grass-covered slopes.

Thickness and Lithology

The Muddy Sandstone, as measured in the thesis area, is about 100 feet thick (Table 19), but the thickness of the unit ranges from a few feet to more than 100 feet in Montana and Wyoming (34).

The Muddy Sandstone in the Snowflake Ridge area is generally a gray, laminated to thin-bedded (less than 1/4 to 3 inches thick), platy, cross-bedded, fine-grained, calcareous, salt-and-pepper sandstone that weathers a dirty brown. Scour-and-fill structures and

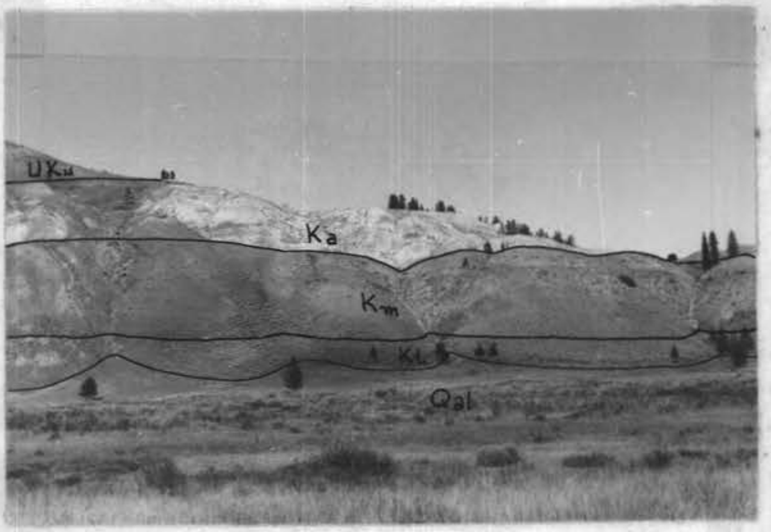

Figure 14. Light colored beds of the Albino Formation overlie the Muddy Sandstone at the southeast corner of Lincoln Mountain.

lenses of chert-pebble conglomerate and medium- to coarse-grained sandstone are present, making lateral variation of the formation common.

Table 19. Muddy Sandstone; stratigraphic section measured on the north side of Taylor Fork Valley west of Meadow Creek near the base of Lincoln Mountain in the SE1/4NW1/4, sec. 7, T. 9 S., R. 4 E.

Albino Formation

Disconformity: contact assumed at top of last calcareous sandstone of the Muddy Sandstone.

Muddy Sandstone

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
1.	Lithic arenite to subfeldspathic lithic arenite: light-gray (N 7), weathers pale-yellowish-brown (10YR 6/2); thinly laminated to thin-bedded (less than 1/32" to 3"); cross-bedded and scour-and-fill structures abundant throughout formation; angular to subrounded, very fine- to medium-grained quartz, feldspar, chert, quartzite, sandstone, devitrifying volcanic glass, basic fine-grained volcanic rock fragments (basalt?), and argillaceous rock fragments cemented by sparry calcite, authigenic nontronite, chlorite, and other alteration clay minerals; dark chert and fine-grained volcanic rock fragments give the sandstone a salt-and-pepper appearance; chert-pebble beds (pebbles up to 1" in diameter) and plant debris are common near top of the formation. Samples Km-1 and Km-2.	99.5	99.5
	Total thickness.....	99.5	

Conformity: contact gradation; gradational contact partly covered, but base was selected at break in slope and soil color change.

Thermopolis Formation

Modal analyses of Muddy Sandstone samples show that the sandstones range from subfeldspathic lithic arenites to lithic arenites. Microscopically, the sandstone is seen to be composed of detrital quartz, chert, quartzite, plagioclase, orthoclase, and clasts of siltstone, shale, phyllite, argillite, and fine-grained volcanic rock fragments in a matrix of either medium- to coarse-grained sparry calcite or brown devitrifying volcanic glass. Grains of microcline, glauconite, biotite, muscovite, leucoxene, magnetite, zircon, tourmaline, and authigenic pyrite make up a minor part of the detrital framework. The grains are angular to rounded but average subangular, owing to replacement by calcite and interpenetration of some grains along their mutual boundaries. Sorting of the sandstone is moderate to good, depending upon the beds sampled. Table 20 gives the modal analyses of two Muddy Sandstone samples.

Fossils and Age

Darton (22) (23), Hintze (82) and other early workers considered the Muddy Sandstone to be Late Cretaceous. However, in 1951 Crowley (20) found and described an Early Cretaceous microfauna in the Newcastle Sandstone (Muddy Sandstone equivalent in south-central Montana and north-central Wyoming), and placed the Early Cretaceous-Late Cretaceous time boundary at the top of the Muddy Sandstone. Because of Early Cretaceous ammonites found in the

Mowry Shale in Wyoming, which generally overlies the Muddy Sandstone, Cobban (14) and Cobban and Reeside (15) raised the Early Cretaceous-Late Cretaceous boundary to its present position at the top of the Mowry Shale.

Table 20. Modal analyses of Muddy Sandstone samples.

	TCL-37[1]	Mont. 15[2]
Detrital quartz	22	56
Chert and quartzite	13	11
Plagioclase	9	Tr
K-feldspar	Tr	—
Carbonate	Tr	17
Fine-grained rock fragments	36	14
Matrix (devitrifyed volcanic glass)	18	—
Heavy accessory minerals	Tr	1

[1] Sample taken from small outcrop about 100 feet east of sharp bend in dirt road to Wapiti Creek Ranger Station.

[2] Measured section of Muddy Sandstone, SE1/4NW1/4, sec. 7, T. 9 S., R. 4 E.

Since no fauna or flora is present in the Muddy Sandstone in the area of study, assignment of an Albian (latest Early Cretaceous) age to the formation is based on its stratigraphic position and lithologic similarity to dated sections in other parts of Montana and Wyoming.

Source and Depositional Environment

The depositional environment of the Muddy Sandstone in the thesis area apparently is terrestial. The abundance of current cross-bedding, scour-and-fill structures, and sandstone lenses indicates a nonmarine alluvial plain deposit, such as that suggested by Baker (4). The absence of marine fossils and presence of sedimentary structures commonly associated with fluvial deposition makes it difficult to accept the generally held opinion that the Muddy Sandstone was deposited in a paralic environment. Paull (59) presents excellent evidence for a deltaic to nearshore marine environment for the Muddy Sandstone in the Big Horn Basin of Wyoming, but this environment does not necessarily apply in the Snowflake Ridge area of southwestern Montana.

The primary provenance for most of the Muddy Sandstone was probably a sedimentary one. Rock fragments of siltstone and shale definitely came from a sedimentary source area, and it is likely that most of the quartz grains, which have overgrowths, came from a preexisting quartzose sandstone. The presence of chert grains indicates limestones were possibly also part of the sedimentary provenance.

The fine-grained volcanic rock fragments and tuffaceous matrix of some of the sandstone indicate a provenance of volcanic rock. Metamorphic source rocks also are indicated.

The presence of a shallow marine facies of the Muddy Sandstone to the southeast in the Big Horn Basin, and a fluvial facies to the east (45, p. 28) in southern Montana, considered with indications of the fluvial environment in the Snowflake Ridge area, indicates that the rivers which transported and deposited the Muddy sediments flowed south and southeast from a northern source.

Albino Formation

The late Early Cretaceous Albino Formation is a local unit that was named by Hall (38) for exposures of green, yellow, pink, and dark gray siliceous shales, siltstones, tuffs, and bentonites along Taylor Fork Valley. The formation is probably in part a correlative of the Mowry and Aspen shales.

The disconformable contacts of the Albino Formation with the underlying Muddy Sandstone and overlying undifferentiated Upper Cretaceous rocks are exposed on the southeast corner of Lincoln Mountain (Figure 14). Sediments of the Albino Formation are absent in the eastern part of the Snowflake Ridge area, and the Muddy Sandstone is directly overlain by undifferentiated Upper Cretaceous sedimentary rocks.

Distribution and Physiographic Expression

Gentle grass-covered slopes are the most common surface expression of the Albino Formation but in the thesis area this formation is exceptionally well exposed. Outcrops are confined to the northwest corner of the area, and a complete section is exposed on the southeast corner of Lincoln Mountain, where the section was measured. Outcrops are easily recognizable by their bright, light colors and interbedded dark beds.

Thickness and Lithology

The section of the Albino Formation (Table 21) measured on the north side of Taylor Fork, in SE1/4, MW1/4, sec. 7, T. 9 S., R. 4 E., is slightly more than 250 feet thick.

The Albino Formation, as described by Hall, consists of a lower part of brown, yellow, pink and green claystones, bentonites, and shales, and an upper part of mostly siliceous shales and tuffs containing well-preserved fern and wood fragments. Although a complete section of the Albino Formation is exposed in the thesis area, the deep weathering and high content of clay and altering volcanic glass made fresh samples nearly impossible to obtain. Thus samples are quantatively biased toward the more resistant siltstone and sandstone beds. Most of these more resistant beds are in the upper part of the formation.

Table 21. Albino Formation; stratigraphic section measured on the north side of Taylor Fork Valley at the base of Lincoln Mountain in the SE1/4NW1/4, sec. 7, T. 9 S., R. 4 E.

Upper Cretaceous undifferentiated
Disconformity: contact sharp

Albino Formation

Unit	Description	Thickness (feet) Unit	Total
13.	Shale and claystone: light-pink, weathers pink; black shale at base; grades upward to siliceous siltstone; abundant coaly wood fragments.	17.5	251.5
12.	Mudstone: greenish-buff; overlain by carbonaceous sandy siltstone; tuffaceous beds of cream, brown, green, and black mudstone to siltstone; weathered surface has popcorn texture.	27.5	234.0
11.	Siltstone: contains some very fine-grained, angular quartz in a montmorillonite matrix; red and black laminations (less than 3/16"); siliceous; section partly covered in middle; top 3' greenish mudstone with weathered surface of popcorn texture.	12.0	206.5
10.	Claystone: black to brown; very crumbly; tuffaceous; abundant plant debris; top 5' light green, weathers white.	22.5	194.5
9.	Siltstone: white to red; tuffaceous; finely laminated (less than 3/16"); upper 15' pink to cream sandy siltstone; contains hematite specks.	22.8	172.0
8.	Covered section: weathers to pink mud.	60.0	149.0
7.	Siltstone: green, purple, and black; siliceous; contains hematite specks.	6.0	89.2
6.	Claystone: green to dark gray; contains hematite specks.	23.5	83.2

Table 21. (continued)

Unit	Description	Thickness (feet) Unit	Thickness (feet) Total
5.	Covered section.	13.5	59.7
4.	Wacke: dark gray; siliceous; hematite specks, biotite grains, and fine-grained volcanic(?) rock fragments.	4.0	46.2
3.	Wacke: to siltstone: purple to gray, weathers white; siliceous; contains hematite specks, biotite grains; tuffaceous.	27.5	42.2
2.	Claystone: cream; loosely consolidated; weathered surface has popcorn texture; poorly exposed.	9.5	14.7
1.	Covered section: float of siliceous claystone.	5.2	5.2
	Total thickness.....	251.5	

Disconformity: contact partly exposed.

Muddy Sandstone

Petrographic examinations of the sandstones showed them to be tuffaceous feldspathic arenites, feldspathic wackes, lithic arenites, and lithic wackes. The tuffaceous feldspathic arenites are composed of subangular, fine-sand-sized grains of quartz, plagioclase (oligoclase), and biotite in a matrix of detrital volcanic glass shards and minor very finely crystalline anthigenic calcite. These tuffaceous sandstones are laminated, and the laminae are alternately tuff-rich and mineral grain-poor and mineral grain-rich and tuff-poor.

The feldspathic wackes, lithic wackes, and lithic arenites have a framework of detrital quartz, plagioclase, microcline, biotite, and fragments of fine-grained, basic, volcanic rock fragments. The primary matrix materials are devitrifying glass shards and clays of the montmorillonite group, which appear to be both detrital and authigenic. Montmorillonite, nontronite, and saponite(?) are present; the montmorillonite appears to be primary, but the nontronite and saponite(?) appear to be authigenic alterations of glass shards and biotite. These latter two clays are bright orangish-red to reddish-brown. According to X-ray analysis made by R. R. Rosé, (66), the zeolite clinotilolite occurs as an alteration product of the volcanic glass. Authigenic calcite and pyrite are present in small quantities.

Fossils and Age

Plant fragments are the only fossil material found in the Albino Formation. The age here assigned to the formation is based solely on its stratigraphic position between the late Albian Muddy Sandstone and the undifferentiated Upper Cretaceous rocks. The Albino Formation is, at least in part, probably a correlative of the Aspen and Mowry shales, which are of latest Albian age.

Source and Depositional Environment

The relatively small areal extent, lithology, and abundant plant debris of the Albino Formation suggests that deposition of the detrital material was in a lacustrine environment during a time of nearby active volcanism. It is possible that the lake in which the Albino sediments were deposited lay on the floodplain on which sediments of the Muddy Sandstone were being deposited.

The sources of detritus for the Albino Formation were probably close to the site of deposition and included sedimentary, volcanic, and acid igneous rocks.

Upper Cretaceous Undifferentiated

Upper Cretaceous rocks in the Snowflake Ridge area are so poorly exposed and outcrops are so widely scattered that very little meaningful stratigraphic and petrographic work could be done on them. All rocks above the Muddy Sandstone, or, locally, above the Albino Formation, have been mapped collectively as Upper Cretaceous undifferentiated. It is probable that these rocks are at least partly equivalent to rocks of the Colorado Group elsewhere in Montana (41, p. 45). However, because of poor exposures, no attempt has been made by other workers in this area to correlate the Upper Cretaceous rocks in this part of Montana with Upper Cretaceous rocks in surrounding regions.

Distribution and Physiographic Expression

Upper Cretaceous rocks crop out in the northwest corner of the area on and around Lincoln Mountain and in the northeast part of the area on the east flank of the Snowflake anticline and around Crown Butte.

Only two good exposures of this sequence occur in the area: the first is a section of siliceous siltstones and claystones, tuffaceous sandstones, and arenaceous tuffs about 100 feet thick on the south side of Lincoln Mountain; the second is a ridge of soft, friable, clean, cross-bedded, quartzose sandstone trending northwest in sec. 5 and 6, T. 9 S., R. 5 E. (Figure 15). A small outcrop of platy siltstone containing many fossil plant fragments was observed in the creek bed of Tepee Creek (Figure 16).

Thickness and Lithology

No stratigraphic section of Upper Cretaceous rocks was measured, but calculations of thickness based upon the geologic map indicate an estimate of 1000 feet thick seems conservative. Hall (38) has estimated that about 8000 feet of these rocks are present in the Upper Gallatin River Canyon area.

In the thesis area the Upper Cretaceous rocks consist of light

Figure 15. Soft, friable, clean, cross-bedded, quartzose sandstone of the Upper Cretaceous undifferentiated near Crown Butte.

Figure 16. Platy siltstone of the Upper Cretaceous undifferentiated along Tepee Creek near Crown Butte.

to dark gray, hard, siliceous, white-weathering shales; hard siliceous claystones; light-gray, soft, friable, cross-bedded, quartzose sandstones; buff, hard, dirty siltstones; and reddish-brown arenaceous tuffs and tuffaceous sandstones.

Petrographic studies of the sandstones and tuffs show them to be quartz arenites, calcareous subfeldspathic lithic arenites, lithic arenites, tuffaceous quartz arenites, and arenaceous vitric tuffs.

The sandstones of the Upper Cretaceous sandstone are composed of angular, fine- to medium-grained, detrital quartz, chert, plagioclase, biotite, and fine-grained volcanic rock fragments (basalt?). The best cemented sandstones have the framework bonded together by calcite and/or volcanic glass, but the soft, friable, very porous sandstone frameworks are held together by small patches of argillaceous material. Minor amounts of hematite, magnetite, and pyrite are present.

The vitric tuff is very thinly laminated (laminae less than 1/16 inch thick). The laminae alternate between quartz-rich and quartz-poor layers. Reddish-brown volcanic glass shards are crudely aligned parallel to the laminae and bend around the angular, fine-grained, detrital quartz and plagioclase grains, forming a poorly developed eutaxitic texture.

Fossils and Age

The only fossils found in the Upper Cretaceous were numerous plant leaves and fragments and a single specimen of the pelecypod *Cardium* (?) sp.

The age assigned to these rocks is based on their position above the Muddy Sandstone and Albino Formation and lithologic similarities to Late Cretaceous rocks elsewhere in Montana. It is possible that the dark shale overlying the Albino Formation at the site where the Albino was measured is correlative to the Mowry Shale and, thus, late Albian in age, but most of the section is undoubtedly Late Cretaceous in age.

Source and Depositional Environment

Reeside (63) thinks that most of the Upper Cretaceous of Montana was deposited in a marine environment, but little evidence was found to support either a marine or non-marine depositional environment. However, the observed current cross-bedding, numerous plant fossils, and the tuffaceous character of many of the rocks leads the author to conclude that deposition occurred on a floodplain containing lakes. This environment may possibly be a continuation in time of the fluvial plain environment on which the Muddy Sandstone and Albino Formations were deposited.

The large amount of chert and quartz probably indicates a sedimentary source, and the plagioclase and biotite seemingly indicates a source of metamorphic or intermediate to basic igneous rocks. That volcanic activity was taking place in the region at the time of deposition is attested by the considerable quantity of pyroclastic material in the beds.

Tertiary System

Dactite Porphyry Intrusion

Part of the north edge of the Gallatin River laccolith is in the Snowflake Ridge area. This intrusion has the composition and texture of a dacite porphyry.

Distribution and Physiographic Expression

The intrusion is limited in its distribution to the southeastern corner of the thesis area. Only the largest outcrops of the intrusion were mapped but many small outcrops project through the Phosphoria, Quadrant, and Madison formations east of Monument Creek. The pluton does not crop out west of Monument Creek.

Hall and McMannis (39, p. 292) and Witkind (84) have referred to the intrusion as the Gallatin River laccolith. Owing to the small size of areal exposure of the intrusion and to lack of time for extensive mapping of the dacite porphyry in the surrounding region, it was not possible to prove the laccolithic shape of the intrusion in the thesis area.

Lithology

The dacite porphyry is a light- to dark-gray, dense, aphanitic rock that contains many euhedral phenocrysts of feldspar and altered hornblende, and numerous inclusions of gneiss, schist, amphibolite, and altered carbonate rocks.

Microscopically, the rock is seen to be composed of zoned and partly altered phenocrysts of plagioclase and completely altered phenocrysts of hornblende in a microcrystalline groundmass of quartz, feldspar, and magnetite. The zoned plagioclase phenocrysts have a composition of about An_{60} in the core and An_{30} to An_{35} around the rim. Sericitic alteration of the plagioclase is evident along the cleavages but is not extensive. Alteration of the hornblende phenocrysts to chlorite, probably penninite, and calcite has been complete. Chlorite is the main alteration mineral. Apatite, epidote, sphene, and secondary iron oxide are accessory minerals.

Age

Witkind, in his preliminary map of the Tepee Creek Quadrangle, Montana and Wyoming (84), dated the intrusive body as Tertiary, and considered that it was emplaced before deposition of the middle

Pliocene welded tuffs.

Because of the lack of evidence in the thesis area it seems best to treat Witkind's dating as tentative.

High-Level Gravel

Isolated outcrops of Tertiary gravel occur at several places in the thesis area. Hall (38) briefly described the gravel and suggested that it is possibly Pliocene in age because the gravel is overlain by Pliocene welded tuff.

Distribution and Physiographic Expression

The largest deposit of gravel is located in sec. 11, T. 9 S., R. 4 E. on a narrow, flat-topped prominence between Sage Creek and Taylor Fork along the south side of the Gallatin River. Smaller deposits are present near the confluence of Taylor Fork with the Gallatin River and Wapiti Creek with Taylor Fork. All of the gravels are at approximately the same elevation (6,800 to 7,000 feet) and occur along streams of the present drainage system.

The gravels lie unconformably on beds of the Mississippian Madison Group, Mississippian-Pennsylvanian Amsden Formation, and Cretaceous Thermopolis Shale and Muddy Sandstone. The gravels are unconformably overlain by Pliocene welded tuff.

Lithology

The high-level gravel deposits are composed of unconsolidated, well-rounded pebbles, cobbles, and boulders of gneiss, schist, amphibolite, quartzite, and basalt, listed approximately in order of abundance.

Source and Depositional Environment

The dominance of metamorphic rock types in the gravel indicates that the primary source was the near by Precambrian rocks of the Madison and Gallatin ranges. The smaller amount of basalt pebbles and cobbles indicate a secondary volcanic provenance. Boyd (10) describes Pliocene basalt flows in Yellowstone Park that are older than the Pliocene welded tuff, and it is possible the source area of the basalt clasts was Yellowstone Park, Wyoming.

The constancy of composition of the gravel between outcrops, the well-rounded character and large size of the particles, the similar elevations at which the gravel deposits occur, and the close proximity of the gravel outcrops to the present drainage system indicate the gravels were probably deposited by a drainage system very much like the present one, but at a topographically higher level.

Welded Tuff

Tertiary welded tuff unconformably overlies every outcropping formation in the Snowflake Ridge area except the Albino Formation and the dacite porphyry intrusion. This welded tuff is believed to be equivalent to the Yellowstone tuff described and mapped by Boyd in the Rhyolite Plateau of Yellowstone Park (10) where it is about 1,000 feet thick (10, p. 393). According to Boyd (10, p. 394), welded tuff of texture and mineralogy similar to the Yellowstone tuff outcrops over large parts of Montana and Idaho west of the park.

Distribution and Physiographic Expression

Exposures of welded tuff are numerous throughout the area but are generally small and low-lying. The three largest exposures of tuff are on Crown Butte (Figure 17), the Taylor Fork - Sage Creek divide (Figure 1), and the Sage Creek - Big Spring Creek divide. Except in the southeastern corner of the thesis area every ridge has a deposit of welded tuff (Plate 2), which commonly has columnar jointing (Figure 19), crude bedding (Figure 18), and pronounced fluidal structure (Figure 20).

The patchy outcrops and marked difference in altitude and thickness between deposits suggests that the tuff was deposited on a very irregular topography, probably in the early mature stage of

Figure 17. Crown Butte, composed of layered welded tuff.

Figure 18. Sidewall of Taylor Fork rockslide on the Taylor Fork - Sage Creek divide. Nine individual flow layers are visible.

Figure 19. Columnar jointing cutting across layers of welded tuff. Taylor Fork rockslide sidewall.

Figure 20. Pronounced fluidal structure of fractured welded tuff.

development.

Thickness and Lithology

The largest single section of welded tuff in the thesis area is exposed on Crown Butte and is about 300 feet thick.

The welded tuff is light-gray to black or brown, dense, ryolite that contains numerous phenocrysts of quartz, sanidine, and plagioclase, and many inclusions of pumice, chert, sandstone, siltstone, shale, and altered limestone.

Petrographic examination of the welded tuff showed it to be composed dominantly of devitrified glass shards. In most thin sections eutaxitic texture is developed by deformation of the shards around and between the phenocrysts, but in several of the thin sections the primary eutaxitic texture has been partly destroyed by recrystallization of the tuff. Numerous flattened and elongate vesicles are present. The smaller vesicles are commonly completely filled by tridymite, but the larger vesicles have a lining of coarse, often twinned tridymite with a core of quartz in low relief. Crystallization of the groundmass immediately around the tridymite-filled and -lined vesicles and less commonly around the edges of phenocrysts has destroyed the glass shards.

The phenocrysts in the welded tuff are quartz, sanidine, plagioclase, and diopsidic-augite. The composition of the subhedral phenocrysts of plagioclase was determined to be An_{10}, intermediate between albite and oligoclase. Most of the euhedral phenocrysts of diopsidic-augite show alteration to iron oxide, and red staining of the groundmass is common around these phenocrysts. Magnetite is the only common accessory mineral.

Identification of inclusions is easiest in hand specimens. Inclusions range in size from microscopic to three inches, and inclusions of one inch or larger are common.

Numerous large vugs within the welded tuff contain masses of euhedral, needle-shaped, brown and green crystals that were identified as a zeolite (mineral name unknown) by X-ray diffraction patterns.

Age

The marked similarity and proximity of the Yellowstone tuff to the welded tuff of the Snowflake Ridge area suggests that the two are equivalent. Boyd (10, p. 410) has tentatively assigned a middle Pliocene age to the Yellowstone tuff, and it is assumed in this report that the welded tuff of the studied area most probably is the same as the tuff dated by Boyd.

Source and Mechanism of Eruption and Implacement

The large area covered by the Yellowstone tuff and the absence of structures resembling volcanos indicates that the tuff probably was erupted from scattered fissures. Also, there is evidence to indicate the tuff was deposited very rapidly in just one eruptive cycle. All of the tuff of the area has essentially the same composition and textural features, and where more than one bed of the tuff is exposed, there is no soil or erosion surface between them. Nine individual beds of alternating light and dark welded tuff are exposed on the sidewall of the Taylor Fork rockslide (Figure 18). All of the beds are equally welded from bottom to top, and there are no chill margins at their bases. This evidence strongly suggests that the individual beds, or flows, were laid down before the underlying one had time to cool.

Boyd (10, p. 424) thinks that the Yellowstone tuff was emplaced by large pyroclastic flows, not of the nuées ardentes type, but flows that were hundreds of feet thick and extended for tens of miles. To explain the degree of fluidity that these flows must necessarily have had, Boyd (10, p. 424) states that,

> The source of the gases in the large pyroclastic flows does not seem to be a problem, inasmuch as most of them consisted of 80-90 per cent liquid magma at the time of eruption.

Quarternary System

Unconsolidated Glacial Deposits

High-level till deposits on and near Marble Point, sec. 4 and 9, T. 9 S., R. 4 E. (Figure 21), are the only unconsolidated glacial deposits in the Snowflake Ridge area. The Marble Point tills represent the oldest of four glacial episodes that occurred in the Madison and Gallatin ranges. The Marble Point stage, named by Hall (36) for the Marble Point till, possibly correlates with the Buffalo stage first described by Blackwelder (7, p. 321-333) in northwestern Wyoming. A more complete summary of regional glacial deposits and their ages is given in the section on geomorphology.

The Marble Point till lies at an altitude of about 8,000 feet on the divide between Taylor Fork and the Gallatin River (Plate 2). It has a fresh appearance and has developed only a thin soil layer (Figure 22). The usual hummocky topography of moraine is absent, and the deposit has no morainal form. Rock types in the deposit include gneiss, schist, amphibolite, quartzite, Paleozoic limestones, sandstones, and chert, Kootenai sandstone and conglomerate, and Tertiary dacite porphyry. Many of the erratics are very large; several were observed to be greater than 20 feet in length.

Figure 21. Marble Point. Boulders seen in this picture are some of the erratics in the Marble Point till. View looking west toward high Madison Range.

Figure 22. Marble Point till. Note fresh appearance of the deposit and the small amount of soil.

The Marble Point till was deposited by a glacier which flowed east into the area from the higher parts of the Madison Range. The high Madison Range, 14 miles west of the Marble Point deposit, is the nearest source area for the Precambrian metamorphic rocks, as well as for rocks of Early Paleozoic age.

Tillite

No published reference to any previous knowledge of tillite in the thesis area or in the immediately surrounding region could be found. It is the author's belief that tillite that occurs in the studied area has not previously been recognized and that it is being described for the first time in this report.

Distribution and Physiographic Expression

Unconformably overlying all the formations on which it rests, the tillite trends nearly perpendicularly across the strike of the underlying units. The tillite is limited in geographical extent to a single deposit on the west side of Sage Creek Valley, about 1.3 miles north of the south boundary of the thesis area in the unsurveyed part of the area (Plate 2). Boulders, cobbles, and pebbles of glacial debris, and small blocks of tillite are found as float on the weathered surface of the unit. However, excellent cliff exposures of the deposit are found along the edge of the landslide adjacent to the tillite on the north (Figure 23).

The tillite ranges from an elevation of about 8,550 feet near the crest of the ridge west of Sage Creek to an elevation of 7,040 feet along Sage Creek. It appears to have been part of a terminal moraine formed by a receding glacier that once flowed from the high part of the Madison Range northwestward into the thesis area.

Thickness and Lithology

Since the base was not exposed, measurement of the thickness of the unit was not possible. Exposures in excess of 60 feet were found along the landslide scarp at the north edge of the tillite.

The tillite is a massive, well-consolidated, extremely poorly sorted, totally clastic unit possessing a range in grain size from clay-sized particles to boulders in excess of 10 feet in diameter. Rock types included in the tillite are gneiss, schist, amphibolite, and quartzite of Precambrian age; chert, limestone, sandstone, and quartzite of Paleozoic age; and Cretaceous sandstone, Tertiary dacite porphyry, and Tertiary welded tuff. High porosity is evident, although the tillite is well-indurated. Rounding of boulders and some rounding of cobbles has taken place, but pebbles are usually subangular. Particles smaller than pebble size are angular to very angular.

It was visually estimated from thin sections and hand samples

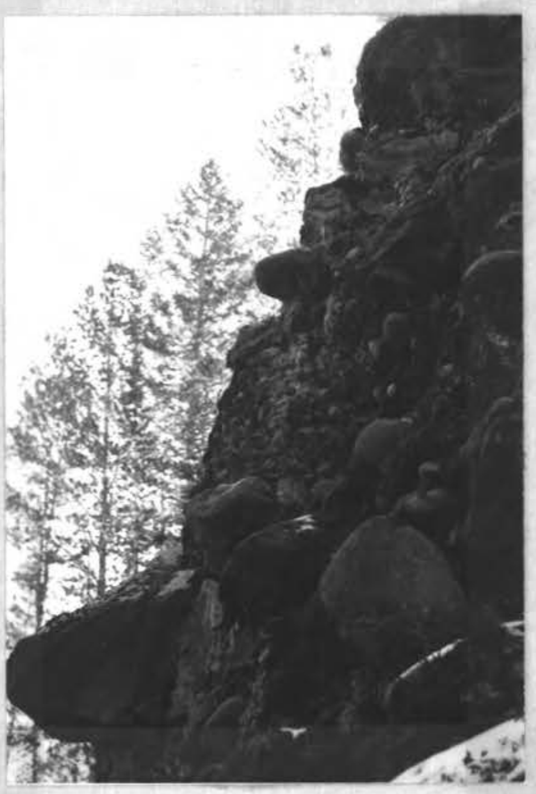

Figure 23. Tillite. A landslide produced this scarp exposure of very poorly sorted, well-consolidated, glacial debris.

that 65 percent of the tillite is made up of sand sized or larger particles. All grains observed in thin sections are angular to very angular. The matrix bonding the larger particles together is a mixture of detrital clay and silt. Sand-sized mineral grains are chiefly quartz, plagioclase, microcline, and biotite but also include a variety of metamorphic minerals including tourmaline, muscovite, epidote, hornblende, garnet, sillimanite, kyanite, and magnetite.

Age

The most nearly accurate statement of age that can be made for the tillite is that it is younger than the welded tuff. The tillite contains clasts of welded tuff, which seem to have been derived from tuffs contemporaneous with the welded tuff of the Snowflake Ridge area and the Yellowstone tuff mapped by Boyd (10) on the Rhyolite Plateau of Yellowstone Park.

The assemblage of rock types included in the tillite and the high altitude at which the tillite occurs suggest that the glacial debris for this unit was deposited at the same time as the Marble Point till. However, there is no proof that the tillite is of Marble Point age.

Source Area and Depositional Environment

Deposition of the glacial debris of the terminal moraine was probably coincident with a climatic change that caused the glacier to retreat, but the circumstances that led to lithification of the till are unknown.

The nearest source area for the material of metamorphic origin in the tillite is the high Madison Range, about six miles to the southwest and outside of the thesis area. Glacial deposits along Sage Creek south of the studied area indicate that a glacier flowed northeastward in the valley of Sage Creek.

Landslide Deposits

Approximately eight square miles of the studied area is covered by deposits that possess features of mass-gravity movement. These deposits are of two types: (1) unconsolidated and very poorly sorted debris containing large boulders and blocks of sandstones, chiefly of Cretaceous age, and (2) unconsolidated rockslide deposits consisting solely of large blocks of Tertiary welded tuff. The geomorphic features of these mass-gravity deposits are described in the section on geomorphology, and only the sediments composing the deposits are described here.

Most, by far, of the landslide debris is comprised of Kootenai, Muddy, and Upper Cretaceous sandstones. The weaker, softer, and highly porous shales and mudstones of the Thermopolis, Albino, and Upper Cretaceous beds have acted as lubricants for the more competent sandstones to slide on. Except for the Taylor Fork rockslide and the few rockslide deposits along Sage and Monument creeks, all major landslide deposits in the thesis area occur on Cretaceous terrain.

The Taylor Fork rockslide (Figure 24), in sec. 10 and 11, T. 9 S., R. 4 E., and the large rockslides along Sage Creek are composed of Tertiary welded tuff blocks. There are also two rockslides along Monument Creek. The smaller slide on the east side of Monument Creek is made up of dacite porphyry debris. The larger rockslide further upstream and on the west side of the creek is made up of Quadrant sandstone boulders and blocks.

Alluvium and Terrace Deposits

Unconsolidated silt, sand, and gravel occur along the streams of the thesis area. The thickness of these deposits is unknown.

The stream gravels are composed predominantly of Precambrian gneiss, schist, amphibolite, and quartzite. Lesser amounts of chert, limestone, and sandstones are present. Several angular cobbles of petrified wood were found along Tepee Creek near the north edge of the studied area. The gravels of the Gallatin River contain a larger variety of rock types, principally volcanic rocks, than do gravels of other streams of the area. No study was made of the fine-grained alluvium.

Figure 24. Taylor Fork rockslide. View looking southeast up to the headwall of the slide.

Terrace deposits are made up of sediments similar to those of present stream deposits. No examination of the fine-grained sediments was made.

STRUCTURAL GEOLOGY

The frontal edge of the great Disturbed Belt of a thick sequence of deformed and overthrust, geosynclinal sedimentary rocks extends roughly north-south through westernmost Montana. East of the Disturbed Belt are less-deformed, shelf rocks of lesser thickness of the Central Rocky Mountains. According to Foose, Wise, and Garbarini (30, p. 1148),

> This shelf region existed as a broad and stable structural platform with relatively shallow marine inundation throughout Paleozoic and Mesozoic time until late Jurassic or early Cretaceous time when more rapid subsidence of the shelf and extensive marine flooding occurred.

The Snowflake Ridge area lies at the extreme western edge of the Central Rocky Mountains on what was the Wyoming shelf.

Regional Tectonic Setting

The Disturbed Belt is characterized by numerous eastward-yielding thrust faults, reverse faults, and overturned folds. In contrast, the Central Rocky Mountains are characterized by juxtaposed uplifts and basins composed of broad, asymmetrical folds, high-angle reverse faults, and normal faults. Structural features of the shelf were probably created by folding and faulting of the Precambrian basement rocks. The faults and associated folds of the shelf usually have a northwest trend and the folds are predominantly asymmetric to the southwest. Structural trends and the age of deformation in the region indicate that the major compressive force during the Laramide orogeny was from the west-southwest.

The Snowcrest, Tobacco Root, Ruby, Gravelly, Madison, and Gallatin mountain ranges all lie on the western margin of what was the Wyoming shelf. All have similar structural trends and cores of Precambrian basement rocks.

Thom (75, and in 28) recognized seven phases in the deformational history of the region: two during the Precambrian, one during the period between late Precambrian and Permian, another during the Triassic to Early Tertiary Nevadian-Laramide orogeny, and three during the Late Tertiary. Of the seven phases, the Laramide revolution, or fourth phase, produced most of the folding, thrust-faulting, and reverse faulting seen in the region. Deformed Precambrian rocks are exposed in most of the mountain ranges of western Montana, but Precambrian deformational chronology is not nearly as well known as that of later time. Lesser structural significance is attributed to the post-Laramide faulting that represents the seventh and latest episode of deformation.

Snowflake Ridge Area Structure

Overturned and asymmetric folds and a high-angle reverse fault, all parallel to the regional north-northwest structural trend, are prominent structural features of the Snowflake Ridge area. Folding and faulting within Precambrian basement rocks during the Laramide orogeny probably formed these folds and faults. Several minor late Cenozoic normal faults cut across the general structural trend.

Folds

Three anticlines and four synclines occur within the thesis area (Plate 2) of which the largest and most pronounced of these folds is the Snowflake anticline of this report. None of the other folds in the thesis area are named, but two have been given names outside of the area, where they become prominent structures. All of the folding in the studied area is considered to have occurred in a single episode during the Laramide revolution.

Snowflake Anticline

The name Snowflake anticline has been given by the author to the largest fold in the Snowflake Ridge area. Snowflake Ridge (Figures 25 and 26), the topographic expression of the anticline, and

Figure 25. Snowflake Ridge. View to northwest.

Figure 26. Snowflake Ridge. View south from Sunshine Point.

Snowflake Springs, at the north end of Snowflake Ridge on the south side of the Gallatin River, are the geographic features from which the name was derived.

The Snowflake anticline is a large, overturned, north-plunging anticline more than nine miles in length that extends completely across the central part of the thesis area. Two small synclines flank the Snowflake anticline; one lies east of the anticline in the south-central part of the area, and another lies west of the anticline in the north-central part of the area. The fairly straight axis of the anticline strikes almost due north except near the south edge of the area where the strike is N. 07° W. to N. 25° W. However, south of the area of study the axis swings back to the west to continue the overall north trend. One mile north of the Snowflake Ridge area the anticline is destroyed in the structural complex caused by the intersection of the north striking Snowflake anticline and the N. 20° W. striking Buck Creek anticline.

The east flank of the Snowflake anticline is strongly overturned to the west and has overturned dips as high as 41° W. A high-angle reverse fault, which has little displacement, extends the entire length of the anticline on the overturned east flank.

The axis of the anticline closely parallels the outcrop pattern of the formations, and the axial trace stays within the Madison Group. A stratigraphic section that includes beds from Madison limestone to Upper Cretaceous rocks crops out on the east flank along the northern part of the overturned anticline. Flank thinning, especially of the Triassic, Jurassic, and Lower Cretaceous formations is pronounced. Figure 27 shows the markedly thinned formations of the east flank of Snowflake anticline exposed on the north side of U. S. Highway 191 where the Gallatin River has cut through the anticline. Formations of the Pennsylvanian, Triassic, Jurassic, and Cretaceous are all exposed in this figure, but at this point the Permian Phosphoria Formation has been faulted out.

To obtain an accurate age of folding for the Snowflake anticline it is necessary to consider the trend of the continuation of the axis of the northwest plunging syncline on the west flank of Snowflake anticline northward beyond the thesis area. One mile north of the area of study the syncline swings off more to the west, where it is known as the Buck Creek syncline. This syncline, which was formed simultaneously with Buck Creek and Snowflake anticlines and all other major folds in the region, can be followed northwestward about 16 miles to a point where it passes through Sphinx Mountain. On Sphinx Mountain is one of the very few known exposures of Sphinx Conglomerate in the Madison Range. This conglomerate unconformably overlies the Late Cretaceous - Early Tertiary Livingston Formation and has been dated by Beck (5, p. 133) as late Paleocene or early Eocene. The so-called Early

Figure 27. View north from Snowflake Ridge showing overturned beds on the east flank of Snowflake anticline. PP q - Quadrant Fm., Tru - Triassic undifferentiated, Jr - Rierdon Fm., Js - Swift Fm., Jm - Morrison Fm., Kk - Kootenai Fm. Top of knob has blocks of residual welded tuff overlying Tertiary gravels.

Basic Breccia, or Specimen Creek Formation, of middle Eocene age, exposed north and east of the thesis area, unconformably overlies the Livingston Formation and is younger than the folding. Thus, if an early Eocene age is accepted as correct for the Sphinx Conglomerate, folding occurred in the early middle Eocene.

Minor Folds

Four synclines and two anticlines, none of major proportions in the thesis area, occur in the eastern half of the Snowflake Ridge area (Plate 2). Two of these synclines are flank structures of the Snowflake anticline. The other two minor synclines, and one of the anticlines, make up the structural complex on the west side of Monument Creek Valley (Plate 3). The other anticline separates the southern part of the Snowflake anticlinal structure from the Monument Creek complex.

The small, slightly asymmetric, northwest-plunging syncline to the west of the Snowflake anticline, near the northern boundary of the thesis area, is the southern segment of the Buck Creek syncline, whose axis swings to the west just north of the thesis area and continues northwest for nearly 20 miles. In the area of study the axis of the syncline strikes N. 22° W. Dips of about 30° occur on the northeast flank, and dips of 12° to 15° on the southwest flank.

The second of the synclines associated with the Snowflake anticline lies east of the major anticline in the southern part of the area and was formed simultaneously with the Snowflake anticline. The northern part of the fold is recumbant off the overturned east flank of the large anticline but the southern part of the structure is nearly symmetrical owing to the displacement along the high-angle reverse fault. The axis of the syncline parallels the axis of the Snowflake anticline and plunges northward into the steeply dipping beds on the east flank of Snowflake anticline and converges with the northward plunging anticline that separates the Monument Creek complex from the Snowflake anticline. This syncline is probably a continuation of the Monument Mountain syncline mapped by Witkind in the Tepee Creek Quadrangle (84).

The northward plunging, asymmetric anticline separating Snowflake anticline from the Monument Creek structural complex ranges in strike from N. 00° W. to N. 38° W. The anticline is asymmetric to the southwest and has dips up to 52° on the northeast flank and up to 19° on the southwest flank.

The Monument Creek structural complex, on the west side of Monument Creek Valley (Plate 3), is comprised of three folds: a symmetrical, northwest-plunging syncline, an overturned, northeast-plunging anticline, and an asymmetrical, northeast-plunging syncline. The symmetrical syncline, which lies furthest to the west of the three folds, has an arcuate axis that ranges in strike from N. 27° W. at the south end to N. 10° W. at the north end. The small anticline separating the two synclines strikes approximately N. 25° E. The east flank of the anticline is partly overturned and has dips ranging from vertical to 80° overturned; dips on the west flank of the anticline are about 30° to 40°. The third fold of the complex, a syncline, also has an average strike of N. 25° E. This syncline is a recumbant fold just east of the east flank of the overturned anticline and has been faulted into three segments. The compressive force which formed this complex was evidently so great that faulting as well as folding was necessary to dissipate the energy. As a result a large part of the surface expression of the anticline has been faulted out.

The compressive force that formed all of the folds in the area was from the west-southwest. The proximity of all the folds to each other and their similar structural trends indicate they were all formed in a single diastrophic episode.

Faults

Thirteen faults of sufficient extent to be mapped were found during the field investigation of the thesis area. Strikes of two of the largest faults parallel the trends of associated folds. The smaller faults do not appear to be genetically associated with the folded structures, and the strikes of most are oblique to the trend of the regional structure. Exposures along the faults are poor and prevent accurate measurements of displacements. Dense forest cover undoubtedly obscures some faults in parts of the thesis area.

The largest fault in the area, both in terms of displacement and extent, is the high-angle reverse fault along the east flank of the Snowflake anticline. The strike of this fault parallels the axis of the anticline. The fault trace can be traced completely across the Snowflake Ridge area, a distance of six miles. Formation of the fault took place during folding of the Snowflake anticline. The west side of the fault has moved up relative to the east side, but the displacement is small, probably not exceeding 100 feet at the south edge of the area (Figure 28).

Another fault has an arcuate trace that parallels the trend of the Monument Creek structural complex and runs along the west flank of the eastern-most syncline. Faulting was contemporaneous with the folding of the complex. Movement along this normal fault has caused the surface expression of the north part of the overturned anticline to be faulted out. Several small normal faults, which have affected the same formations, are associated with the large fault and probably were formed simultaneously with it.

Several minor normal faults are present north of the Gallatin River along the east flank of the Snowflake anticline. These faults strike N. 50° W. and cut diagonally across the north trend of the

Figure 28. View north from south edge of the thesis area showing high-angle reverse fault along Snowflake anticline. Beds west of fault are overturned and steeply dipping to the west.

anticline. They have displaced the large high-angle reverse fault and, thus, must be post-early middle Eocene.

One and a half miles up Sage Creek a set of four normal faults have strikes that are nearly perpendicular to the general trend of the main structures of the thesis area. The faulting has involved beds of the Madison, Amsden, Quadrant, and Phosphoria Formations, and welded tuffs of middle Pliocene age, but exposures are extremely poor, owing to dense forest cover. Since one of the faults appears to cut the welded tuff, faulting is probably post-middle Pliocene.

Several minor normal faults that strike north-northeast occur along Taylor Fork and the Gallatin River valleys. These faults are considered of late Cenozoic age because of their disassociation with the major structural features of the area; however, no evidence for definite age determination was found. Many small faults and joints are present throughout the area, but these were not mapped or studied in detail.

GEOMORPHOLOGY

Stream Erosion

This mountainous region is thoroughly dissected by stream erosion and has a well-developed drainage system. Most of the interstream divides are rounded and narrow and relief is considerable. The major canyons are bounded by steep cliffs; the valley floors are narrow and flat. Near the confluence of Tepee Creek with the Gallatin River meanders completely crisscross the valley floor (Figure 29) which attains a maximum width of about a quarter of a mile. The smaller tributary streams have very narrow valleys and have high gradients. The area is in an early mature stage of stream erosion.

Many of the streams in the thesis area flow northward and are subsequent to the north-northwest trend. Differential erosion of the dominantly north striking beds is the major factor controlling the drainage pattern. However, in the western part of the area, south of Taylor Fork, several streams are developed on a northwest dip-slope. These dip-slope-controlled streams must also be considered as subsequent, since the dip-slope is not a newly created surface.

The Gallatin River, flowing northeastward along the eastern margin of the area, and Taylor Fork, flowing eastward into the

Figure 29. View south up Gallatin River Valley showing meandering Gallatin River.

Gallatin River, are the two major drainages for the region. Both are probably superposed drainages that cut across the regional structural trend. These courses of older major superposed streams, along with numerous other courses of major drainages in the Rocky Mountains, are thought to be inherited from streams that flowed over a Late Tertiary surface of relatively low relief which masked the underlying structure (3).

Terraces

Alluvial terraces are poorly developed and difficult to distinguish. Only two terrace levels are known to occur in the area.

The oldest alluvial terrace level is now 80 to 100 feet above stream level. It is present near the confluence of Sage Creek with the Gallatin River in sec. 11 and 12, T. 9 S., R. 4 E., (Plate 2), where there are two small level areas, one on each side of the Gallatin River. On the north side of the river, in sec. 12, the terrace has been cut on Madison limestone, and no alluvial gravels remain on the terrace. Directly across the river to the southwest, in sec. 11, old stream gravels rest on a narrow, flat-topped prominence between Sage Creek and the Gallatin River. High-level gravel deposits are also present near the confluence of Taylor Fork with the Gallatin River and Wapiti Creek with Taylor Fork. The terrace is probably of Late Tertiary age, since it is overlain by deposits of Pliocene welded tuff. Owing to the fairly large areal extent that this terrace probably once covered it seems most likely that this feature can be attributed to a former different climatic regime.

The second terrace level occurs along the floodplain of the Gallatin River southeast of Tepee Creek. It is not present downstream from this point. This terrace, which is only about ten feet above the river and seemingly much younger than the previously discussed terrace, is best developed on the north side of the river in sec. 7, T. 9 S., R. 5 E., near Tepee Creek, and on the south side of the river in sec. 28, T. 9 S., R. 5 E., where Monument Creek joins the Gallatin River. This terrace was probably formed during late Pleistocene time when the meltwater from glacial ice was transporting and depositing large amounts of detritus. These deposits have since been partially removed by later stream erosion.

Landslides

Mass-gravity movements have been responsible for characteristic and striking geomorphic features in the Madison and Gallatin ranges. Hall (37, p. 200) states that about one-fifth of the region has undergone landsliding extensive enough to completely mask the bedrock geology.

Within the thesis area mass-gravity movements are largest and most abundant in the western part, along Little Wapiti, Wapiti, and Meadow Creek valleys. However, landslides are not restricted to these valleys but are numerous throughout the area. Fifty-three individual landslides, covering a total of approximately 7.8 square miles, are identified within the Snowflake Ridge area.

In classifying the types of mass-wasting in the area the classification developed by C. F. S. Sharpe (69) is used. From this classification four types of creep (rock, talus, soil, and rock-glacier), one type of flow (earthflow), and three types of slip (slump, rockslide, and rockfall) are recognized.

The features created by the various types of creep are small and only rarely obscure an appreciable amount of the bedrock geology. Because of this, these features were not mapped. However, the high frequency with which creep features occur makes them an important part of total mass-wasting in the area.

Figure 30 shows a good example of rock creep along the north side of Taylor Fork Valley. Large numbers of boulders of Cretaceous Kootenai sandstone and conglomerate are slowly progressing down the slope. Talus creep is especially significant in the large talus deposits at the bases of the cliffs of Mississippian Madison limestone. Soil creep occurs throughout the area on steep grass-covered slopes. Rock-glacier creep (?) occurs only in the large slide area mapped along Little Wapiti Creek in the southwest corner

Figure 30. Rock creep along the north side of Taylor Fork Valley. Large boulders of Kootenai sandstone and conglomerate are slowly progressing down the slope.

of the thesis area. This large slide appears to have had a multiple origin. Slump and earth-flow features are present, but there are also some elongate mounds of what appears to be glacial debris. These mounds may have been formed by rock-glacier creep coming out of Sunlight Basin, a cirque at the southeast edge of Pika Point, just one mile south of the southwest corner of the thesis area.

Most of the landslide areas mapped can be classified as earthflows, which exhibit the characteristic hummocky topography and have many swamps, ponds, and small lakes in the closed depressions on their surfaces. Commonly these flows are one to two miles long and up to half a mile wide. However, there are several other features that are characteristic of some or all of the earthflows in the region. These are: (1) a semicircular headwall region in which slump, not earthflow, is the dominant type of mass-movement (see Figure 31, showing tree covered slump blocks above the earthflow), (2) a somewhat narrower bottleneck zone approximately midway between the head and toe of a slide, (3) ridges resembling lateral moraines, some of them 10 to 20 feet high, composed of what was the slower moving debris at the edges of the earthflow (these ridges are easily recognizable on low-altitude aerial photographs), and (4) a toe area that rests on the valley floor (Figure 2), generally semicircular, well-formed, and wider than the rest of the earthflow.

The importance of slump and rockslide features was first

Figure 31. View looking northwest at tree covered slump blocks above a large earthflow.

noticed by Hall (37, p. 202), who placed these features second to earthflows in terms of area affected. As has already been mentioned, slump features occur most commonly at the heads of earthflows. Large slump blocks of Cretaceous Muddy Sandstone can be seen in Figure 31, which shows the source area for the large slide in sec. 4, 5, and 8, T. 9 S., R. 4 E. This earthflow does not have the usual semicircular headwall, but slumping is nevertheless the originating movement for this flow. Not until the slump material is a considerable distance from the headwall does it assume earthflow features.

Rockslides are not as large or as extensive as earthflows but they do have certain distinguishing features. In the thesis area rockslides are more common on steep slopes. They generally have high, near-vertical headwall and sidewall scars, are somewhat variable in shape, and have no bottleneck zone at midslide. All rockslides in the region appear to have descended very rapidly in a single large movement. The largest and most spectacular single rockslide in the area is the Taylor Fork rockslide, located in sec. 10 and 11, T. 9 S., R. 4 E. This rockslide descended the south side of Taylor Fork Valley and stopped abruptly against the cliffs of Mission Canyon Limestone that form the north side of the valley at this point. Taylor Fork probably was dammed for a time, but there is now no evidence of a lake having been formed behind the slide. If a lake was indeed so produced, it would have been small and short lived.

Rockfall activity is constantly taking place in the Snowflake Ridge area but is of only minor importance when one considers the total area affected. The numerous vertical cliffs, in conjunction with the severe weather conditions, are the primary factors in producing rockfalls.

In the thesis area the wide extent and variability of mass-gravity movement offers some evidence of the conditions that must have existed to produce these features. Factors condusive to mass-wasting in the area include: (1) high relief with steep slopes, (2) high precipitation producing a high moisture content in the ground, (3) formations made up of poorly consolidated or highly porous material, (4) the deposition of relatively weak Tertiary welded tuffs on a mature topography of considerable relief, (5) numerous faults, fractures, and steeply dipping beds related to the complex regional structure, and (6) the high frequency of earthquakes to which this area is known to be subject. Some of the above factors, along with other factors which are not applicalbe to the Snowflake Ridge area, have been discussed by Hall (37).

Although evidence indicates that mass-wasting is occurring in significant amounts at present, most of the larger areas that have been involved in mass-gravity movements, especially areas of earthflows, appear to be at least temporarily stable. This suggests that the earthflows are of Pleistocene or sub-Recent age. Possibly they formed during the melting of glacial ice.

Glacial Features

Glacial features are very common in the Madison and Gallatin ranges. Numerous cirques, U-shaped valleys, hanging valleys, and moraines are evident throughout the region. However, in the Snowflake Ridge area the only glacial features are two associated till deposits and a tillite.

The two till deposits lie on and near Marble Point, in sec. 4 and 9, T. 9 S., R. 4 E., at an elevation of about 8,000 feet. These glacial deposits lack morainal form and the usual hummocky topography. They appear freshly formed and have developed only a very thin soil layer. Some of the erratics have a length of 10 feet or more (Figure 32).

The tillite lies on the west side of Sage Creek Valley, slightly more than one mile north from the south edge of the mapped area. It has a definite terminal moraine form but is not now extensive enough to exhibit a hummocky topography.

Hall (36) has recognized four stages of glaciation in the Madison and Gallatin ranges. Of these stages, the Marble Point stage, named for the till deposit on Marble Point, is the oldest, as indicated by the

Figure 32. Large glacial boulder of Kootenai conglomeratic sandstone on Marble Point.

high elevation, position on divides, distance from source rocks, lack of good topographic expression, and extensiveness. The other three stages distinguished by Hall, which are represented in deposits in the region surrounding the thesis area, are: Intermediate stage, Sawmill stage, and a younger episode of very small-scale glaciation.

Alden (1, p. 182-183) recognized the Sawmill and Intermediate stages along Taylor Fork west of the thesis area, but did not mention the Marble Point deposit or the tillite. The Marble Point till occurs along Taylor Fork, 1,000 feet higher in elevation than the Sawmill moraine, for which the Sawmill stage was named, and four miles downstream from the latter. The tillite lies 3.5 miles south of the Marble Point till at a similar elevation. Alden suggested either an Iowan or Illinoian age for the Intermediate stage. However, it is probable that neither of the proposed ages are correct. Richmond (65) and de la Montagne (24) have described high-level pre-Wisconsin glacial deposits in the Rocky Mountains, and both have showed that deep weathering and a well developed soil profile are characteristic of these deposits. The similar composition of the tillite and Marble Point till and the fresh appearance of the Marble Point deposit suggests that these two glacial features are early Wisconsin in age. Thus, they may be correlative in time to the Buffalo stage glacial deposits of northwestern Wyoming described by Blackwelder (7). If this interpretation is correct, the Intermediate stage could not be of Iowan or Illinoian age. Hall (36, p. 195, 197) has tentatively correlated the Sawmill and Intermediate stage with the Pinedale and Bull Lake stages of Blackwelder in northwestern Wyoming.

GEOLOGIC HISTORY

The first geologic event recorded in the Snowflake Ridge area was deposition of Early Mississippian (Lodgepole) limestones. The cyclic repetition of oolitic, lump, and bioclastic shallow water limestones alternating with deep water micritic limestones and limy mudstones probably resulted from repeated fluctuations in water depth. During late Lodgepole time the shelf became progressively more stable, as reflected by the gradational thickening of beds until, during Mission Canyon time, the shelf reached relative stability. Thick, massive deposits of micritic limestone were laid down in the Mission Canyon sea below the effect of wave activity; most of these deposits have since been dolomitized.

The fact that the Amsden Formation lies upon a karst surface developed on the top of the Mission Canyon Limestone indicates that a period of erosion followed deposition of the Mission Canyon. According to Strickler and Zeisloft (74, p. 77-78) the detrital dolomites and quartzose sandstones of the Amsden Formation suggest the formation was deposited in a continental environment, probably on a low, fairly broad floodplain. An interval of pre-Quadrant erosion is indicated by the local absence and variable thickness of the Amsden Formation in the thesis area and elsewhere in southwestern Montana.

The excellent sorting and cleanness of the quartzose limestones and quartz arenites of the Quadrant Formation suggest that the sea advanced slightly during or before deposition, and wave and/or current action must have been in effect to produce the excellent sorting of the Quadrant sediments. Thus, a shallow marine, high-energy environment is indicated for deposition of the Quadrant sediments.

The quartz arenites and oolitic-pelletal phosphate of the Phosphoria Formation suggests deposition in a high-energy, shallow marine environment, similar to that of the Quadrant Formation, and it is possible that deposition was continuous from Pennsylvanian into Permian time. However, the bedded chert units of the Phosphoria appear to have been formed mostly by the diagenetic reorganization of sponge spicules that were deposited in deeper water than were the sandstones and phosphorite.

During the Early Triassic this area over the Wyoming Shelf probably remained fairly stable and the sea shallow. The Lingula-bearing and ripple-marked rocks of the Dinwoody Formation indicate a shallow marine environment. The depositional environment of the Woodside red-beds are in question, but are probably also shallow marine. The thinness of the Woodside Formation in the Snowflake Ridge area and its absence in other parts of southwestern Montana (48, p. 233) testifies to an uplift of the area and/or a regression of the sea that was followed by an interval of erosion that was post-Woodside and pre-Rierdon in age.

Middle Jurassic time was marked by a return of the sea, but the fauna of the Rierdon Formation and the calcarenite of the Swift Formation are evidence that deposition took place in water no deeper than the upper part of the neritic zone. The lithologies of the Rierdon and overlying Swift formations indicate the sea was becoming progressively shallower. By Morrison time (Late Jurassic) the region was again above sea-level. Deposition of the Morrison Formation took place on a low fluvial plain containing ephermeral lakes.

The conditions of Late Jurassic time carried over into the Early Cretaceous, and the conglomerates, conglomeratic sandstones, fresh-water limestones, and argillaceous rocks of the Kootenai Formation were deposited on a floodplain associated with lakes, similar to that on which the Morrison Formation was deposited. The upper Kootenai quartz arenite and the Thermopolis Shale mark a return to marine conditions. These conditions were relatively short lived, and once again the region was uplifted above sea-level in Late Cretaceous time, when the Muddy Sandstone and Albino Formation were deposited on a low, fluvial plain.

The Early Tertiary part of the Laramide revolution accounted for all of the major folding and faulting of the area, and this event was followed by a period of extensive erosion and intrusion of a dacite porphyry laccolith. Pliocene welded tuffs were laid down on the Tertiary erosion surface and, locally, over high-level fluvial gravels.

Quarternary glacial deposits, especially moraines, are present in the Snowflake Ridge area and abundant in the surrounding region. Post-glacial erosion has disected the glacial deposits and at present is actively eroding the area. Minor local alluvial deposits are forming on some of the valley floors.

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