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**Bedrock Geologic Maps of the Griffin Creek and Bailey Mountain 7.5
minute quadrangles, Powell County, Montana**

by

Jeffrey A. Brooks

B.S., Northern Arizona University, 1999

Presented in partial fulfillment of the requirements for the degree of Master of Science

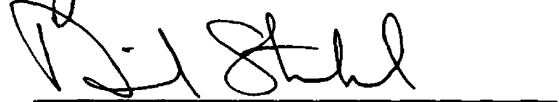
The University of Montana

2002

Approved by

A handwritten signature in black ink, appearing to read "James W. Sears", written over a horizontal line.

Chairman, Board of Examiners

A handwritten signature in black ink, appearing to read "D. J. Stahl", written over a horizontal line.

Dean, Graduate School

4-29-02

Date

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Bedrock Geologic Maps of the Bailey Mountain and Griffin Creek 7.5 minute quadrangles, Powell County, Montana

Director: Sears, James W.



A thick sequence of Cretaceous sediments is preserved in a structural sag called the Garrison Depression in the foreland basin of west-central Montana. Cretaceous Colorado Group sediments in the Garrison depression and parts of the Montana Disturbed belt are laced with K-alkalic intrusive igneous rocks. Radiometric dating has been performed on the intrusive rocks. Recent studies obtained a $^{40}\text{Ar}/^{39}\text{Ar}$ date of 75.9 ± 1.2 Ma that is considered to approximate the time of intrusion. Thus the relations between the intrusive rocks and the Colorado Group sedimentary package and structure in the area can yield information about the timing of Laramide deformation in the west-central Montana foreland. Data from this study and recent studies in adjacent quadrangles indicate that the K-alkalic rocks were emplaced after a pre-Campanian period of folding and before and during the main phase of Laramide folding. Most of the folding occurred after emplacement. Middle Eocene volcanic rocks overlie the folded Colorado Group sedimentary package with angular unconformity. The main period of Laramide deformation along this part of the Lewis and Clark line is thus bracketed between the middle Campanian and middle Eocene.

Previous workers have offered conflicting structural-stratigraphic interpretations of the study area. Marker beds and thorough coverage of structural measurements were used to clarify the structural relations. In addition, published maps are of small scale or on poor quality bases. Because of this they offer little utility for purposes such as exploration and planning. This study produced maps on modern 1:24,000 topographic bases with accompanying full-scale cross-sections. Additionally, field locations were cross-checked with a modern 12-channel GPS receiver to ensure accuracy. The maps were GIS registered by the Montana Bureau of Mines and Geology.

The study area contains an extensive marine-dominated sedimentary section that has potential petroleum source and reservoir rocks. Data from this study indicates that the late Cretaceous sedimentary section is extensively intruded by Campanian K-alkalic intrusive rocks. The Colorado Group rocks are also cleaved. Recent work on the thermal profile of the Lewis-Eldorado-Hoadley plate indicates that the temperature associated with cleavage formation was in excess of 280°C at the shallowest stratigraphic levels in the Garrison depression. The potential for preservation of oil or gas in the Garrison depression is thus very low.

Acknowledgments

First and foremost, I would like to thank the Chair of my thesis committee Dr. Jim Sears. His knowledge and patience are beyond extraordinary. I would also like to thank my other committee members, Dr. Marc Hendrix and Dr. David Friend for their patience. This project was funded by the EDMAP program of the United States Geological Survey and the McDonough Foundation, both of which I would like to thank for supporting my research. Thanks to the Montana Bureau of Mines and Geology for reviewing, digitizing, and publishing the maps and cross-sections produced during this project.

The bulk of the study area was on private land, so many thanks are in order to the families of the Gold Creek area for access to their land. I would like to thank the following landowners: the Hogan Family (especially Sam Hogan for helping pull my truck out of an irrigation ditch), the Wallace family (especially for the use of the ranch ATV), the Dutton family, the Thomas family, the Wooler families, the Beck family, Harry Grenadier and Mark Yurien of the Six C Ranch, the Mannix family of Helmville, Plum Creek timber company, the Allesbury family, and the Gilman family. I hope that includes everyone. Thank you all.

Last but far from least, I would like to thank my family for their love and encouragement. Mom and Dad, you are truly great parents.

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Introduction

This project was undertaken as a continuation of work performed by Sears et al. (2000a). There are three main foci of interest. The primary focus is the structural-stratigraphic-igneous relations among late Cretaceous Colorado Group sedimentary rocks and Campanian-aged sills and dikes. The second focus is to produce an update of the geology of the Bailey Mountain and Griffin Creek 7.5 minute quadrangles, Powell County, Montana. The update followed a combination of mapping and compilation. The third focus is to clarify the likelihood of oil or gas in an area with promising source and reservoir rocks.

The Griffin Creek and Bailey Mountain quadrangles cover a combined area of approximately two hundred and fifty five square kilometers in the south-central Garnet Range and the northern flank of the Flint Creek Range. The south-central Garnet Range near the towns of Gold Creek and Garrison, Powell County, in west-central Montana contains a thick section of Cretaceous Colorado Group sediments preserved in a structural sag called the Garrison depression. Formation of the structural sag, or depression is attributed to relative uplift of the Garnet Range and the Flint Creek Range (Gwinn, 1961; Gwinn and Mutch, 1965). The Colorado Group sediments were intruded by an extensive network of Campanian K-alkalic igneous rocks that are characterized by pyroxene-biotite diorites and andesites.

The primary focus of this thesis project is to evaluate the structural-stratigraphic-igneous relations among late Cretaceous Colorado Group sedimentary rocks and Campanian-aged sills and dikes. The evaluation of these relations allows a test of the hypothesis that the emplacement of the extensive intrusive network in the Garrison

depression postdated an earlier phase of deformation (pre-Campanian), but predated a later phase (Laramide). Deformation in and near the Garrison depression is controlled by movement along the adjacent section of the Lewis and Clark line. The Lewis and Clark line is partly coincident with the Montana Lineament (Wiedman, 1965). The Lewis and Clark line is a long-lived linear zone of structural weakness with a northwest-to-southeast trend that has accommodated several periods of crustal movement.

The Montana Bureau of Mines and Geology (MBMG) and the United States Geological Survey (USGS) recognize a need to update geologic map work on modern, large-scale topographic bases, as well as to fill in gaps in previous studies. The mapping and compilation efforts of Wallace et al. (1987) generated considerable controversy, especially their interpretation of the structure of the area covered by the Butte 1x2 degree quadrangle. The interpretation of Wallace et al. (1987) included several roughly east-west thrust faults to explain the repetitive sequence of Colorado Group rocks in the area of Gold Creek and Garrison in Powell County. The Wallace et al. (1987) interpretation was significantly different from the interpretations of early workers in the area such as Gwinn (1960) and Krause (1963). The 1998 compilation and mapping effort of Lewis disposed of the numerous interpreted thrust faults in the study area, but left a gap in structural-stratigraphic interpretation in the area near Gold Creek and Garrison (Lewis, 1998).

The mapping conducted for this thesis was part of an ongoing collaboration between the University of Montana, the MBMG, and the USGS to accurately map the extent and structural-tectonic relations of the thick Cretaceous sediments west of the

Boulder batholith. Specifically, the USGS partially funds mapping projects as part of the EDMAP Program.

In addition to the EDMAP funding, this project was partially funded by the McDonough Foundation because the study area contains extensive marine sedimentary rocks that are potential petroleum source and reservoir rocks.

Geography and Access

The Griffin Creek and Bailey Mountain quadrangles represent approximately two hundred and fifty five square kilometers. The quadrangles cover part of the south-central Garnet Range and the northern flank of the Flint Creek Range near the town of Gold Creek in Powell County, Montana (Figure 1). The elevation within the quadrangles ranges from approximately 1,256 to 2,271 meters above mean sea level. The area is usually accessible from May to November. Logging and ranch roads cut much of the region and often contain some of the best exposures. Ridge tops and stream cuts also offer good outcrop exposure. The roads often become impassable after wet weather and the local ranchers frown upon damage caused by driving on wet surfaces. The bulk of the land is privately owned and access is often controlled by locked gates and high or electrified fences. Permission must be obtained from the local owner, which often necessitates significant social diplomacy. Only a few areas were inaccessible because of inability to establish ownership or landowner refusal. I recommend that investigators avoid field work or wear hunter orange during big-game hunting season.

Methods

Two 7.5-minute topographic quadrangles were completed with a combination of geologic mapping and compilation. Scaled cross-sections were constructed using bedding orientation data obtained in the field. Measurements of structural fabrics were taken with a Brunton transit. Grain size and bed thicknesses were classified according to Compton (1985). Field locations were commonly cross-checked with a Garmin 12 channel (parallel) global positioning system receiver, North American Datum of 1927, with zone 12 Universal Transverse Mercator coordinates. Transport within the field area was primarily by foot and four-wheel drive high-clearance light truck.

Structural Setting

Tectonics of the study area are dominated by proximity to a long-lived structural lineament, the Lewis and Clark line. The Lewis and Clark line is interpreted as a Late Cretaceous sinistral transpressional shear zone that is overprinted by dextral movement associated with Tertiary extension (Sears, et al., 2000b). The Lewis and Clark line has been active during several periods from the Mesoproterozoic to the Tertiary and has accommodated several types of relative movement during separate phases of deformation (Weidman, 1965; Wallace et al., 1990). The Lewis and Clark line separates the northwest-southeast trending folds of the Garnet Range from the north-south trending folds of the northern Flint Creek Range.

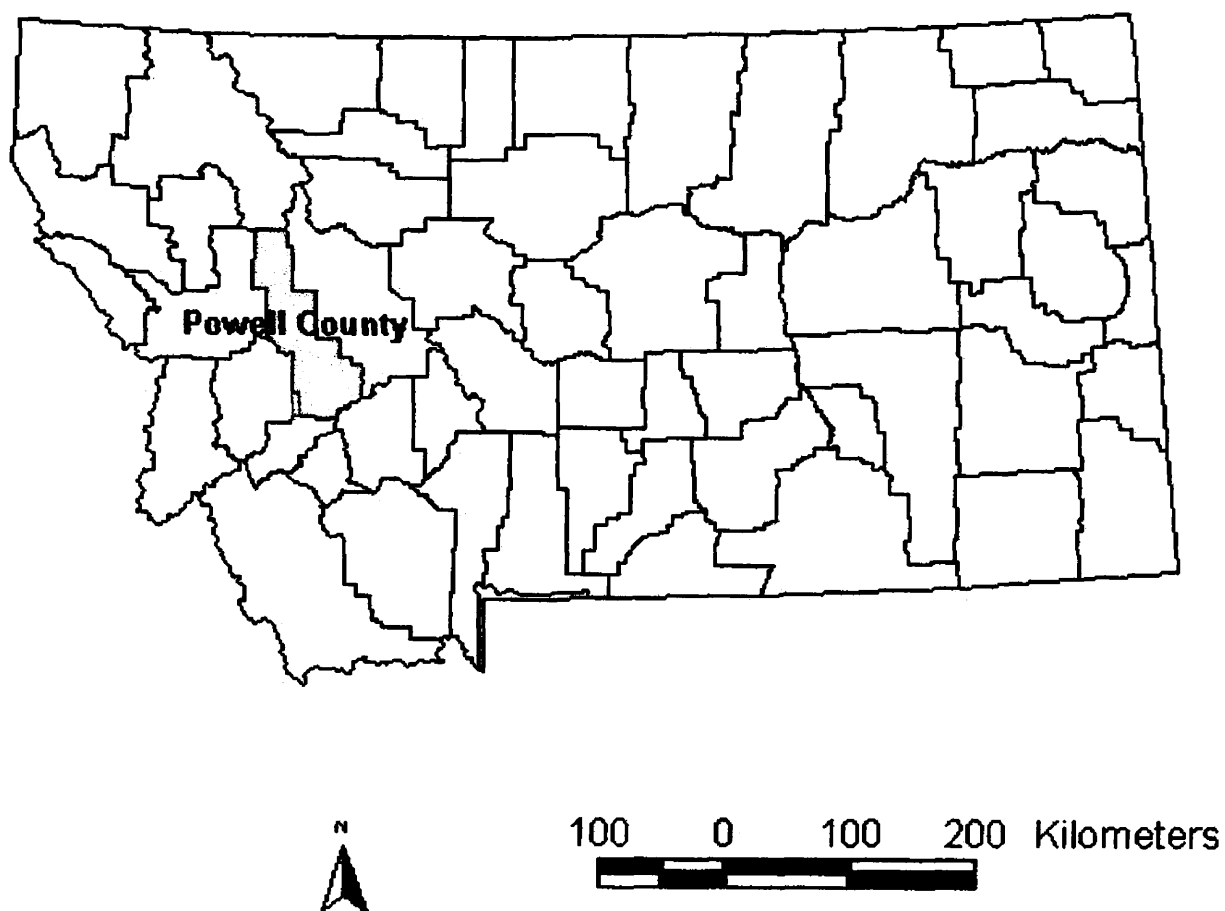


Figure 1: Study area location map. Powell County, Montana. Powell County is highlighted in gray. Study area is outlined in red.

Structurally, the Garrison depression area represents a retroarc foreland basin between the Sapphire tectonic plate and the Lewis-Eldorado-Hoadley tectonic plate (Figure 2) (Dickinson, 1974). The Garrison depression is interpreted to have ridden as a piggyback foreland basin on the Lewis-Eldorado-Hoadley plate (cf. DeCelles, 1986; Sears et al., 2000b). Movement of the Sapphire and Lewis-Eldorado-Hoadley thrust

plates was accommodated by the Lewis and Clark line. The thrust plates are as much as 25 kilometers thick and have foundations of strong Mesoproterozoic Belt Supergroup siliclastic rocks (Sears, 1988). The Lewis-Eldorado-Hoadley plate is the “displaced northeastern margin of the Belt basin, inverted into the Purcell anticlinorium as it overrode the adjacent foreland” (Price, 1981; Sears, 1988, 1994). The study area is on the southwestern limb of the Purcell anticlinorium (Figure 2). On the large scale the Lewis-Eldorado-Hoadley thrust sheet (that makes up the southwest limb of the Purcell anticlinorium) is interpreted to be a homocline draping the footwall ramp along which the thrust plate propagated (Sears et al., 2000b).

The present Garnet and Flint Creek Ranges reflect uplift on Tertiary normal faults associated with Basin-and-Range extension. Ongoing seismicity in the Intermountain Seismic Zone indicates that extension is continuing in Montana (Stickney et al., 2000).

Previous Workers

Previous work in the area is generally of good quality. However, the maps available to early workers were not of great quality. In addition, published work on the study area is of small scale. The work is therefore difficult to use for exploration, planning, or other activities. The base topographic maps available today are of better quality, and accurate map location is made easier by modern 12-channel global positioning system receivers.

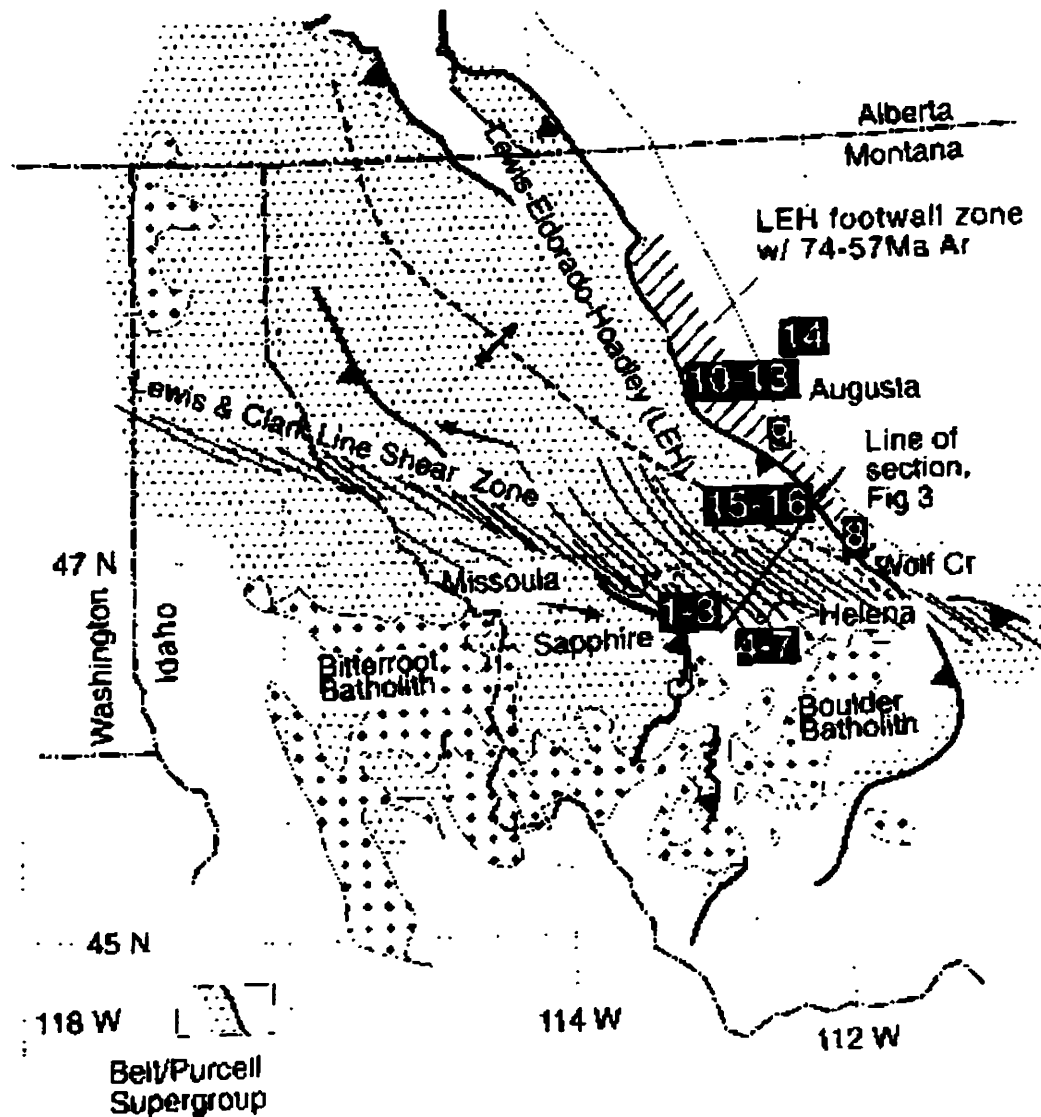


Figure 2: Generalized tectonic map of part of western Montana. Used with permission from Sears et al. (2000b). Numbered blocks are field trip stops from Sears et al., (2000b). Area of this study is in vicinity of field trip stops 4-7.

Emmons and Calkins, 1913:

Emmons and Calkins were some of the first investigators to speculate on the thickness of the Colorado Group within the Garrison depression. Emmons and Calkins

mapped the nearby Philipsburg quadrangle.

J.T. Pardee, 1913, 1916, and 1951:

J.T. Pardee was the first to document observations about Tertiary sediments in the Gold Creek area (Pardee, 1913). Pardee referred to the Tertiary sediments as the “Lake Beds”. He was also the first to document the geology he observed in the area of the Garnet Range north of Gold Creek and Garrison as part of an economic geology project to explore for phosphate deposits (Pardee, 1916). Pardee also worked in the benchlands south of the Clark Fork River to investigate the nature and origin of placer gold deposits between the northern flank of the Flint Creek Range and the Clark Fork River (Pardee, 1951). The report was titled “The gold placers of the Pioneer District, Montana”.

Extensive placer mining was conducted in the Pioneer District in the latter part of the 19th and well into the 20th century, but is currently inactive.

V.E. Gwinn, 1960:

Vinton E. Gwinn, a doctoral student from Princeton University, conducted field work for his dissertation in the summers of 1958 and 1959. Gwinn mapped approximately 335 square kilometers of the northern Flint Creek Range and the Garnet Range, during which he completed extensive work on the structure and stratigraphy of the area. The landmark Gwinn (1965) paper “Cretaceous Rocks of the Clark Fork Valley” followed the doctoral work and defined the stratigraphy of the sandstone-and-shale dominated Cretaceous Colorado Group west of the Boulder batholith. Gwinn originally mapped on large-scale black-and-white aerial photos, but then transferred his map data to a county base map that is of limited usefulness.

T. Mutch, 1960:

Thomas Mutch, another graduate student from Princeton University mapped approximately 310 square kilometers during the summers of 1958 and 1959. Mutch covered the northern flank of the Flint Creek highland and the Clark Fork benchlands. Mutch paid little attention to the Tertiary sediments of the Flint Creek flank. The base maps included with Mutch's thesis and in his 1961 MBMG publication are difficult to use. Mutch originally mapped on large-scale black-and-white aerial photographs, but then transferred to smaller scale county base maps. The county base maps are of limited usefulness.

H.H. Krause, 1963:

Hans Krause, a Master's student from the University of Kansas mapped part of the Garnet Range from Saddle Mountain to Bailey Mountain as part of his Master's thesis. Krause built upon the work of Pardee (1913) to further define the structure in the area. Krause used the stratigraphic divisions and nomenclature created by Gwinn (1960, 1965). Krause originally mapped on aerial photos at 1:24,000 and then transferred his map data to a topographic base map. Krause's base map is of poor quality and not GIS-useable.

L.V. Bell and H.D. Moore, Jr., 1965:

Bell and Moore worked as geologists for the Montana Phosphate Products Company of Garrison, Montana. Bell and Moore (1965) provide data about the Pennsylvanian Quadrant Formation and Permian strata from underground workings near

Garrison and Philipsburg (Maxville). Bell and Moore cite that the phosphatic horizon of the Permian Phosphoria Formation is almost never exposed in natural outcrop.

B. Carter, 1982:

Bruce Carter, a Master's student from the University of Montana completed a thesis on the "Geology of the Eocene Volcanic Sequence" of the central Garnet Range in 1982. The focus of Carter's work was the Eocene volcanic rocks that cover much of the Garnet Range. Carter (1982) provides a summary of radiometric dates for the Eocene rocks to the east and west of the quadrangles mapped.

T.J. Callemeyer, 1984:

Thomas J. Callemeyer, a graduate student from Montana State University completed map work in the adjacent Warm Springs Creek area in 1984. The focus of Callemeyer's work was structural, volcanic, and hydrothermal geology. The map work had some minor overlap into the Bailey Mountain quadrangle. Callemeyer performed whole rock and plagioclase K-Ar dating on Eocene igneous rocks in his study area. Callemeyer's base map is of poor quality, because it was enlarged from smaller scale maps. Part of the Warm Springs Creek area was remapped by Sears et al. (2000a).

J.S. Loen, 1986:

Jeffrey S. Loen, a Master's student from Colorado State University worked in the area south of the Clark Fork River, which is often called the Pioneer District. Loen's work focused on the origin and nature of placer gold deposits in the Pioneer District. Extensive placer mining has been conducted in the Pioneer District. Loen's work was supervised and supported by M.R. Waters and C.A. Wallace of the USGS. Loen largely refuted the findings of J.T. Pardee's 1951 report on the Pioneer District. Loen expended

considerable effort dividing and mapping the Tertiary and Pleistocene sedimentary deposits in the Pioneer District. Field-checking of Loen's work revealed that there was some confusion between Lower Renova Formation iron-stained micaceous sandstone and pebble conglomerate and the salt-and-pepper sandstone of the upper Colorado Group. Loen originally mapped on enlarged aerial photos. Data from the photos was then transferred to a topographic base map. Loen's base map was enlarged from 1:62,500 to 1:12,000, and is therefore of dubious quality.

Wallace et al., 1987:

Wallace et al. (1987) produced an interpretation of the Butte 1x2 degree sheet titled "Preliminary geologic map of the Butte 1x2 degree quadrangle". The map showed that the area of Colorado Group sediments north of the Clark Fork River was cut by several thrust faults. This work was likely based on the collaborative work of Wallace and a graduate student from the University of Arizona named Arthur French. French's Master's thesis was titled "Younger-over-older-thrust faults in the central Garnet Range" (French, 1979). Structural data to support French's interpretation is sparse. An interpretation of a series of younger-over-older-thrusts was published on the 1987 geologic map of the Butte quadrangle. The interpretation generated significant controversy. Wallace et al. (1987) have some areas of the Campanian intrusive rocks designated as Tertiary volcanics.

Wallace et al., 1990:

Wallace et al. (1990) completed a paper called "Faults of the central part of the Lewis and Clark line". W.A. Cobban is cited heavily in this article for his work on the paleontology and biostratigraphy of the Cretaceous Colorado Group. The work

summarizes the difficulties inherent in relating structures to large-scale crustal movements along the Lewis and Clark line. The structures on the Lewis and Clark line are overprinted by several successive periods of tectonism. Wallace et al. (1990) infer that right-lateral movement on the Lewis and Clark line is associated with Laramide deformation.

R.S. Lewis, 1998:

Reed Lewis of the USGS compiled and mapped the Butte 1x2 degree quadrangle (Lewis 1998), with significant revisions over the work performed by Wallace et al. (1987) on the Preliminary Geologic Map of the Butte 1x2 degree sheet. Lewis' interpretation removed many of the controversial thrust faults from the Butte sheet. However, Lewis paid little attention to the pyroxene-biotite intrusive bodies or the structure present in the Colorado Group sediments. Lewis has some areas of the Campanian intrusive bodies listed as Tertiary volcanics, which was probably taken from Wallace (1987).

M.W. O'Brien, 2000:

Matthew W. O'Brien, a Master's student from the University of Montana completed a thesis on the "Stratigraphic analysis of the Albian through Campanian Colorado Group within the Garrison depression, west-central Montana." O'Brien worked within the Luke Mountain and Garrison quadrangles, which were mapped by Sears et al, (2000a). O'Brien's work contains stratigraphic information that may be of potential use for mapping projects.

RESULTS

K-alkalic intrusive rocks

The Late Cretaceous Colorado Group of the Garrison depression is laced with an extensive network of pyroxene-biotite diorite and andesite sills and dikes (Figure 3). The pyroxene crystals are commonly euhedral, which greatly facilitates identification. The intrusive rocks are characterized by a uniform composition from area to area within the Garrison depression. On the east side of the Griffin Creek quadrangle (Plate 1) there is a sill that is cut by the Clark Fork River and Interstate 90. The sill was dated by Sears et al. (1997), who used the $^{40}\text{Ar}/^{39}\text{Ar}$ method to obtain a biotite age of 75.9 +/- 1.2 Ma. The age is interpreted as the time of crystallization. The sample location is designated GC-1 on the Griffin Creek Quadrangle (Plate 1).

At the outset of this project I proposed that the Campanian dikes and sills of the area post-date early deformation (pre-Campanian) on the adjacent section of the Lewis and Clark Line, but predate the main phase of Laramide deformation. Work from this study indicates that the sills were emplaced before and during the main phase of Laramide deformation. Most folding of the sills post-dated emplacement. The early phase of deformation referred to herein is apparent from the folded angular unconformity between the Carten Creek Formation and the Golden Spike Formation. This folded unconformity is evident on the Luke Mountain quadrangle (Sears et al., 2000a). The pre-Golden Spike unconformity cut low angle folds but then was folded by the same folds. This indicates that some pre or syn-Campanian shear occurred on the adjacent section of the Lewis and Clark line before the main phase of Laramide deformation. Thus the Campanian sills likely intruded partially folded Colorado Group rocks. The pre or syn

Campanian shear on the Lewis and Clark line is associated with emplacement of the Sapphire and Lombard plates. The end of movement of the Sapphire plate is constrained by the presence of several relatively undeformed Late Cretaceous granitic plutons (Hyndman, 1980). A renewed episode of shear on the Lewis and Clark line during and after Campanian time completed the folds presently evident in the Garrison depression. Cross-section A-A' (Plate 3) shows a large volume of magma preserved in the form of the Hoover Creek sill on the west limb of the Carten Creek syncline. Cross-section A-A' also shows that little material intruded the east limb of the Carten Creek syncline. Only two small sills were noted on the east limb of the Carten Creek syncline during this study. It appears that magma was restricted during intrusion and thus pooled on the west limb of the syncline. The magma pooled because it was restricted by partially formed folds. A similar situation is evident on the Luke Mountain Quadrangle (Sears et al., 2000). A large sill, similar in size to the Hoover Creek sill, represents a large volume of pooled magma on the northeast limb of a southeast plunging syncline.

Priest (2000) conducted a structural and paleomagnetic study of thrust rotation of a Late Cretaceous sill in the LEH plate near the east bank of the North Fork of the Sun River in the western Sawtooth Ranges. The Late Cretaceous sill that Priest studied is petrologically and geochemically similar to Campanian intrusive bodies in the Garrison depression. Additionally, the sill that Priest (2000) studied has a very similar structural-stratigraphic setting and is thought to be related to the sills in the Garrison Depression (Sears et al., 2000b). The sill Priest (2000) studied crosses stratigraphic levels over its map trace. The sills in the Garrison depression also cross stratigraphic levels. Priest (2000) infers that "either the sill did not intrude as a horizontal sheet, the sedimentary

units were not horizontal at the time of intrusion, or the sill intruded as a discordant sheet into folded or non-folded strata”.

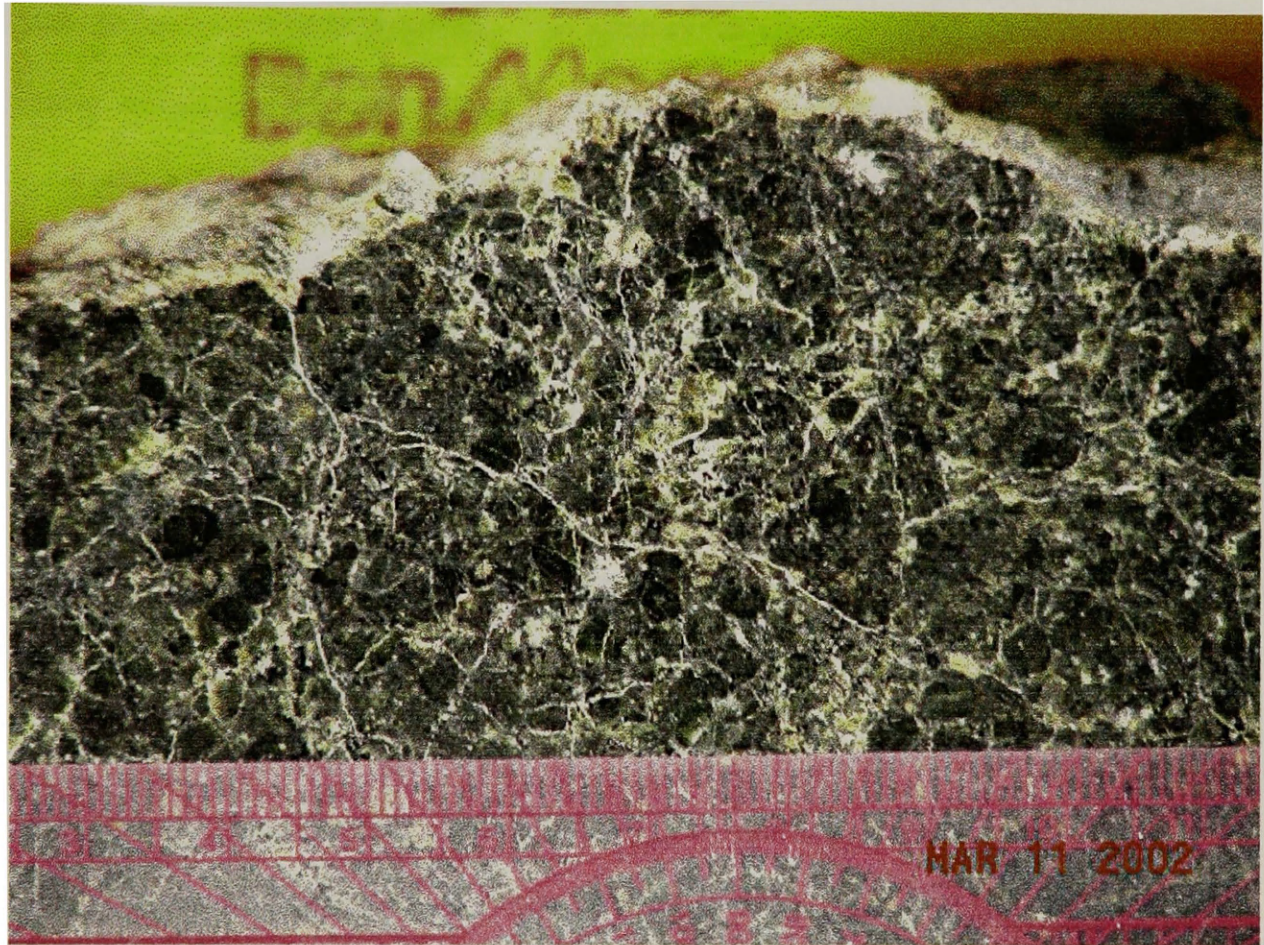


Figure 3: A polished piece of pyroxene biotite diorite taken from near the bottom of the Hoover Creek sill. Many of the augite crystals in this sample are zoned.
Location southeast $\frac{1}{4}$ Section 3, T10N, R11W. Scale in centimeters.

STRATIGRAPHY:

Mesoproterozoic

A generalized stratigraphic correlation chart is provided in Figure 4. The oldest rocks encountered during this study are part of the Missoula Group of the Mesoproterozoic Belt Supergroup. The work of Callemeyer (1984) partly overlaps the Bailey Mountain quadrangle (Plate 2). Callemeyer was primarily interested in volcanic and hydrothermal deposits and structure, so a general classification of “Middle Proterozoic Belt rocks” was cited in Callemeyer’s work to classify the Belt quartzites and argillites that he encountered. The term quartzite is used herein to describe the well-indurated feldspathic arenites that are common to the Belt series. The term argillite is used to describe well-indurated mudstones common to the Belt Supergroup. Lewis (1998) assigned the Belt rocks he encountered in the northeastern portion of the Bailey Mountain Quadrangle to the Bonner and McNamara Formations. A visit to the regional Bureau of Land Management (BLM) office in Missoula, MT (BLM Geologist Melinda Mason) revealed that BLM conducted its own mapping project in the northeastern portion of the Bailey Mountain quadrangle and classified the Belt Rocks found there as the Bonner and Mount Shields Formations. I investigated the map area covered by the Belt Supergroup rocks and agree with the BLM assessment.

The Mesoproterozoic Mount Shields Formation is reddish, gray, light brown or pink micaceous argillite, siltite, and quartzite (Barlow, 1983). Beds are thin to massive. Grain size is dominantly fine. Exposures of the Mount Shields Formation on the Bailey Mountain quadrangle are very poor.

The Mesoproterozoic Bonner Formation is pink and light brown massive quartzite. Beds are thick to massive and often ripple-marked. Grain size is fine to medium (Kaufman, 1963; Farooqui, 1994). Exposures within the northeast corner of the Bailey Mountain Quadrangle are very poor.

Paleozoic, undifferentiated

This unit includes Cambrian, Devonian, and Mississippian, mainly carbonate rocks. The Red Lion Formation was observed on the surface in the northern part of Section 1 and Section 16, T11N, R11W and also in Sections 35 and 36, T12N, R11W; undivided from Madison Group. The Red Lion Formation contains diagnostic red carbonaceous stringers, which facilitate identification. Devonian sedimentary rocks are shown in cross-sections only. Probable Hasmark dolomite is present on the surface in the northern part of Section 1 and section 16, T11N, R11W and also in Sections 35 and 36, T12N, R11W; undivided from Madison Group.

Lower Paleozoic rocks in the northern part of Section 1 and section 16, T11N, R11W and also in Sections 35 and 36, T12N, R11W were included with the Madison Group due to poor exposure, difficulty with access, and lack of time. Lower Paleozoic formations that were encountered included the Hasmark and Red Lion Formations.

Stratigraphic Correlation of Units:

Qal		Quaternary
Qo	Qt	
Unconformity		
Ts		Eocene-Pliocene
Tv		Eocene
Unconformity		
Ki		Cretaceous
Kgs	Kgsv	
	Kgsl	
	Kgss	
Unconformity		
Kcc		
Kj		
Kc		
Kbl	Kbld	
	Kblt	
	Kblf	
Kk	Kkd	
	Kkc	
	Kkb	
	Kka	
Jm	Js	Jurassic
Je		
Unconformity		Permian
Pp		
Unconformity		Pennsylvanian Pennsylvanian/Mississippian Mississippian
Pq		
Pma		
Mm		
Unconformity		Proterozoic
Ybo		
Yms		

Figure 4: Generalized stratigraphic correlation chart for the Bailey Mountain and Griffin Creek quadrangles. See Appendices A and B for legend.

The Mississippian Madison Group consists largely of greenish-gray, reddish-gray, light-gray, or white biosparite with nodular chert. Two formations comprise the group, they are the Lodgepole and the Mission Canyon formations. The formations were not differentiated for this study. Bedding planes are best expressed in the lower Madison Group, which is represented by the Lodgepole Formation. The Madison Group contains abundant marine fossils- crinoid stems, horn corals (Figure 5), and brachiopods. Fossil content in the Bearmouth area, 32 kilometers west, is detailed by Kauffman (1963). The Madison Group formations are often cliff-forming and include some of the most widespread sedimentary units in the western United States (Kaufmann, 1963).

Mississippian-Pennsylvanian

The late Mississippian to Pennsylvanian Amsden Formation is composed of yellow and red dolomitic siltstone and shale (Figure 6). This unit is often very poorly exposed in the field and usually forms subdued topographic features between the underlying Madison Group and the overlying Quadrant Formation. However, its location can often be accurately obtained by looking for obvious red and yellow iron-oxide-stained ground. The Amsden Formation is about 50 meters thick.

The Pennsylvanian Quadrant Formation is dark reddish gray, pinkish gray, light brownish gray, and light gray silicified quartzite (Figure 7). Bedding is often very difficult to discern because of uniform composition, which is dominated by fine-medium grained clean quartzose sand. Secondary grain enlargement is common in the quartzite of the upper Quadrant Formation (Kauffman, 1963). Bell and Moore (1965) divided the

Quadrant Formation into informal upper and lower members. Bell and Moore (1965) described the lower member as well-bedded light gray to tan dolomitic siltstone and silty sandstone with some beds of relatively pure dolomite. The quartzite is very-well indurated and usually forms resistant ridges above the much less resistant Amsden and Phosphoria Formations. The unit is about 100 meters thick.



Figure 5: Horn coral in Madison Group biosparite float near northeast $\frac{1}{4}$ section 12, T11N, R11W. Top of scale is in centimeters.



Figure 6: A rare exposure of the Amsden Formation in a logging road cut near the mouth of Limestone Canyon, Section 7, T11N, R10W. The outcrop has a bedding orientation of $136^{\circ}, 38^{\circ}$ (Right Hand Rule).



Figure 7: Uniform, well-indurated quartzite of the upper Quadrant Formation.

Permian

The Permian Phosphoria Formation is very poorly exposed, dark gray and brown sandstone, shale, bedded chert, and oolitic phosphate rock. The Phosphoria formation is shown east of Hoover Creek in exaggerated form only because of its proximity to the phosphate mine on Brock Creek. The formation was not seen west of Hoover Creek and previous workers have lumped what may be thin-to-nonexistent Phosphoria rocks in with the Quadrant Formation in that vicinity. For example, Pardee (1917) and Krause (1960) note that no phosphate of economic importance was found west of Hoover Creek. Unit thickness is estimated at 125 meters from work by Sears et al. (2000a) on the adjacent

Garrison Quadrangle. The phosphatic horizon is about 1.2 meters thick at Brock Creek (Bell and Moore, 1965; Pardee, 1916). There are several mines in the Phosphoria Formation to the east of the project area. Most of the mines are inactive at the time of this report.

Jurassic

The sedimentary sequence from the middle Jurassic Ellis Group marine and marginal-marine sandstones to the uppermost Cretaceous Golden Spike Formation of the Montana Group have been interpreted as foreland basin sediments (Decelles, 1986). The Jurassic Ellis Group is characterized by red, reddish gray, light gray, and dark yellowish brown fossiliferous salt-and-pepper sandstone, shale, limestone and, siltstone. Salt-and-pepper sandstone often contains well-preserved petrified wood (Kaufman, 1963). Figure 8 shows a typical occurrence of petrified wood in the Ellis Group sandstones. Outcrops of the Ellis Group are generally subdued in surface expression.

The Rierdan member of the Ellis Group consists of alternating gray limestone and limey shale. The Rierdan member is poorly exposed. Fossil content of the member is detailed by Kaufman (1963). A single, poorly preserved, unidentifiable brachiopod, approximately 3 centimeters across, was observed in the field just to the east of Bailey Mountain.

The Morrison Formation is dominated by light green and greenish-gray limestone and sandstone. The Morrison Formation is non-marine (Suttner, 1966). The formation is poorly exposed in the study area. Suttner (1966) notes that the basal conglomerate and sandstone of the overlying Kootenai Formation rests in channels in the Morrison

Formation. This relation was not observed during this study, which may be due to lack of good exposure. Thickness is about 65 meters (Kaufman, 1963).



Figure 8: Petrified wood fragments on a bedding plane in Ellis Group sandstone near southernmost central Section 22, T11N, R11W. Field book for scale.

Cretaceous

The late Early Cretaceous Kootenai Formation is dominated by redbeds and carbonates. The formation consists of four members defined by Gwinn (1960). The formation is undivided on the west half of the Bailey Mountain quadrangle (Plate 2). As a whole, the formation is dominated by light gray, pale red, red, and dark gray well-cemented salt and pepper (chert litharenitic) sandstone, shale, and micrite. The grain composition reflects the “Recycled Orogen” tectonic petrofacies of Dickinson and Suczek (1979) (Sears et al., 2000b). Chert litharenite in the Kootenai Formation near

Bradman Spur (just west of Drummond) is different than chert litharenite in the Jurassic Swift Formation because the Kootenai Formation contains both red and black chert (Suttner, 1966). The red chert is probably derived from Belt Supergroup rocks (Sears, et al., 2000b). Fossil content defines the Kootenai Formation as non-marine (Cobban, 1959; Gwinn, 1961 and 1965; McGuire, 1957; Suttner, 1966). Fossils include non-marine molluscs, ostracodes, and charophytes. From oldest to youngest, the four members of the Kootenai Formation are referred to as the Kka to Kkd on the maps and cross-sections (Plates 2, 3, and 4).

The oldest member of the Kootenai Formation is the lower clastic member. This unit is referred to as Kka in the maps and cross-sections. It is reddish gray and light gray sandstone, interbedded locally with reddish and gray shale and siltstone (Gwinn, 1965). Gwinn (1965) and Kauffman (1963) note a prominent basal conglomerate that is present in much of the lower clastic member. The conglomerate was not observed during this study.

The lower calcareous member is dark gray micritic limestone, siltstone, shale, mudstone, and minor sandstone of various colors (Gwinn, 1965). Ostracodes and charophytes were collected from the lower calcareous member approximately one mile to the west of Drummond, in Granite County (Peck 1956 and 1957; Gwinn, 1965), approximately 20 kilometers west of the town of Gold Creek (Figure 1). No fossils were observed (in hand samples) in the lower calcareous member present on the Bailey Mountain quadrangle.

The upper clastic member is green, gray, and reddish shale, mudstone, and siltstone. The member also includes minor salt and pepper sandstone (Gwinn, 1965).

Gwinn (1965) reported local occurrences of shaly limestone and limestone conglomerate near the top of the member. Unit thickness is approximately 125 meters.

The upper calcareous member is gray, light grayish brown, grayish brown, and light yellowish brown, biomicritic limestone. Most fossils in the Kootenai Formation are found in the upper calcareous member. The top of the upper calcareous member is informally termed the “gastropod limestone”. The gastropod limestone is an important marker bed for mapping, it contains *Reesideela montanensis* and *Circamelania* (Gwinn, 1965) (Figure 9).

Vertebrate fossil fragments were found in this unit just east of Bailey Mountain (Figure 10). The fragments may be remnants of turtle shell (inference and personal communication from Eric Katvala U of M graduate student. 2002). In addition, a shark tooth was found about 1.5 kilometers to the southeast in the upper calcareous member (Figure 11). The upper calcareous member is Aptian (Yen, 1949 and 1951; McGookey, 1972).

COLORADO GROUP

The Colorado Group is the sedimentary package of greatest importance for the purposes of this thesis because of its relation to pyroxene-biotite diorite-andesite sills that intrude it. The Colorado Group rocks therefore were the primary focus for this project. The late Cretaceous Colorado Group is dominated by salt-and-pepper sandstone and gray shale. The thickest Colorado Group sediments in Montana occupy the

Garrison depression (Gwinn, 1960). The sedimentary package thins from west to east. The geometry of the sedimentary prism indicates sediment source areas were more dominant in the west (Gwinn, 1961).



Figure 9: “Gastropod limestone”-upper calcareous member, Kootenai Formation, location-Section 29, T10N, R11W. Scale in centimeters.



Figure 10: Vertebrate bone fragments recovered from the lower-upper calcareous member of the Cretaceous Kootenai Formation. Location north-central Section 19, T11N, R10W. Field book is ~ 12 cm wide.



Figure 11: A chert (replaced) shark tooth in the upper calcareous member of the Kootenai Formation. Top of scale is in centimeters.

Diagnostic aids or marker beds are needed to help identify stratigraphic position within the Colorado Group section. These marker beds are discussed in the section titled “Marker Beds”. Virtually all biostratigraphy and other paleontological studies in the Colorado Group owe much to various published and unpublished efforts by W.A. Cobban.

O’Brien (2000) interpreted the Colorado Group with a sequence stratigraphic approach as defined by Van Wagoner (1985). O’Brien (2000) infers two stratigraphic sequences that are represented by two transgressive/regressive cycles within the Cretaceous Colorado Group sediments (Gwinn, 1965). The first sequence includes the

Blackleaf Formation from the basal Flood member to the middle facies of the Dunkleberg member; the second sequence begins with the middle facies of the Dunkleberg member and ends with the Carten Creek Formation (O'Brien, 2000).

Blackleaf Formation

The Blackleaf Formation (Cobban et al., 1959) represents the base of the Colorado Group in the Garrison depression. Three members comprise the Blackleaf Formation within the Garrison depression. These members, from oldest to youngest, are the Flood member, the Taft Hill member, and the Dunkleberg member.

The Flood member is dominated by dark organic shale, with brown sandstone beds, and thin gray shelly limestone, fine-to-medium grained sandstone, and siltstone and shale at the base. The lower unit is generally comprised of quartzite and carbonates. The upper unit is dominated by dark organic shale and sandstone. The sandstone observed in the shales appears to be in the form of lenses. The lenses likely represent turbidites or storm deposits (see Figure 12). No fossils have been observed in the upper Flood member, although numerous burrows and trails were observed. Surficial iron-oxide-staining was observed at several localities in the upper Flood member (Gwinn, 1960).

The thickness of the Flood member is approximately 250 meters. A large, recent landslide initiated in the Flood member to the east of the junction of Elk Swamp Creek and Hoover Creek in the southern part of Section 27, T11N, R11W. The landslide blocked Elk Swamp Creek and Hoover Creek at their junction, thereby forming Miller Lake. The landslide scar is visible from Hoover Creek Road at Miller Lake (Figure 13).

Krause (1963) talked with locals who describe



Figure 12: A sand lense (turbidite or storm deposit) in the upper Flood member black shale -Blackleaf Formation.



Figure 13: Landslide that formed Miller Lake (foreground). The slide initiated in the Flood Member of the Blackleaf Formation.

evergreen trees with intact needles under water at the lake in the 1950's. Part of the overlying Taft Hill member was involved in the landslide. The Flood member often forms prominent swales between the more resistant Taft Hill member and the upper calcareous member of the Kootenai Formation. The Flood member was dated as late Albian, based on the index fossil *Inoceramus Comancheanus* (Gwinn 1960; Cobban et al., 1976).

The Taft Hill member of the Blackleaf Formation is interlayered brown and gray, salt-and-pepper sandstone, dark greenish gray, dark gray, dark grayish, and gray mudstone and siltstone, gray to green shale and minor pebble conglomerate. Sedimentary structures include extensive cross-bedding, which can be used as a facing indicator. Grain size is dominantly fine-to-medium. Grain composition is predominantly quartz and

black chert. The contact with the overlying Dunkleberg Formation is most easily placed at the lowest Dunkleberg chert-quartzite conglomerate. The Taft Hill member is chronologically equivalent to the lower Vaughn member of the Blackleaf Formation east of the Boulder batholith in the disturbed belt. Member thickness is about 250 meters.

The Dunkleberg member of the Blackleaf Formation is interlayered light gray, dark gray, greenish gray, dark reddish-gray, yellow-brown and light brownish-gray laminated to thin bedded, siliceous mudstone, porcellanite, gray and green shale, white and gray cross-bedded salt-and-pepper sandstone, and black chert-quartzite pebble conglomerate. Conglomerate clasts exhibit characteristic pressure-solution pits (Figure 14). The lowest conglomerate aids in placing the base of the Dunkelberg member during mapping.

The Dunkleberg member is disharmonically folded on small scale. Gwinn (1960) noted petrified wood and tree trunks at several localities within the formation. Only minor occurrences of petrified wood were noted during the present investigation, none was in place. Sub-gravel size material within the member is characterized by the presence of volcanic detritus. Within the Garrison depression the Dunkleberg member has been K-Ar dated as Cenomanian (Cobban in Wallace, 1990). The upper contact with the overlying Coberly Formation was placed in the interval where the sands of the Coberly Formation become continuous and/or contain oyster reefs, abundant oyster detritus, or oyster molds. The Dunkleberg member is equivalent to the upper Vaughn member of the Blackleaf Formation in the disturbed belt. No bentonite exists in the Dunkleberg member, which differentiates the unit from the correlative Vaughn member in the disturbed belt. Unit thickness is approximately 450 meters.



Figure 14: Basal chert-quartzite conglomerate in Dunkleberg member-Blackleaf Formation. Note characteristic pressure solution pits. Fieldbook is 12 cm across.

The Coberly Formation consists of tan and gray sandstone, gray siltstone, mudstone, shale, and oyster beds-composed of *Ostrea soleniscus* (Gwinn, 1965), and oyster coquinas (Figure 15). Shelly fragments in the coquinas have a definite sub-horizontal alignment that is likely reflective of storm winnowing and concentration.

Sandstone in the Coberly Formation is usually of “salt-and-pepper” appearance due to sub-equal amounts of quartz and feldspar (salt) and black chert (pepper). The

oyster beds make up important marker horizons that aid in mapping the Coberly Formation in

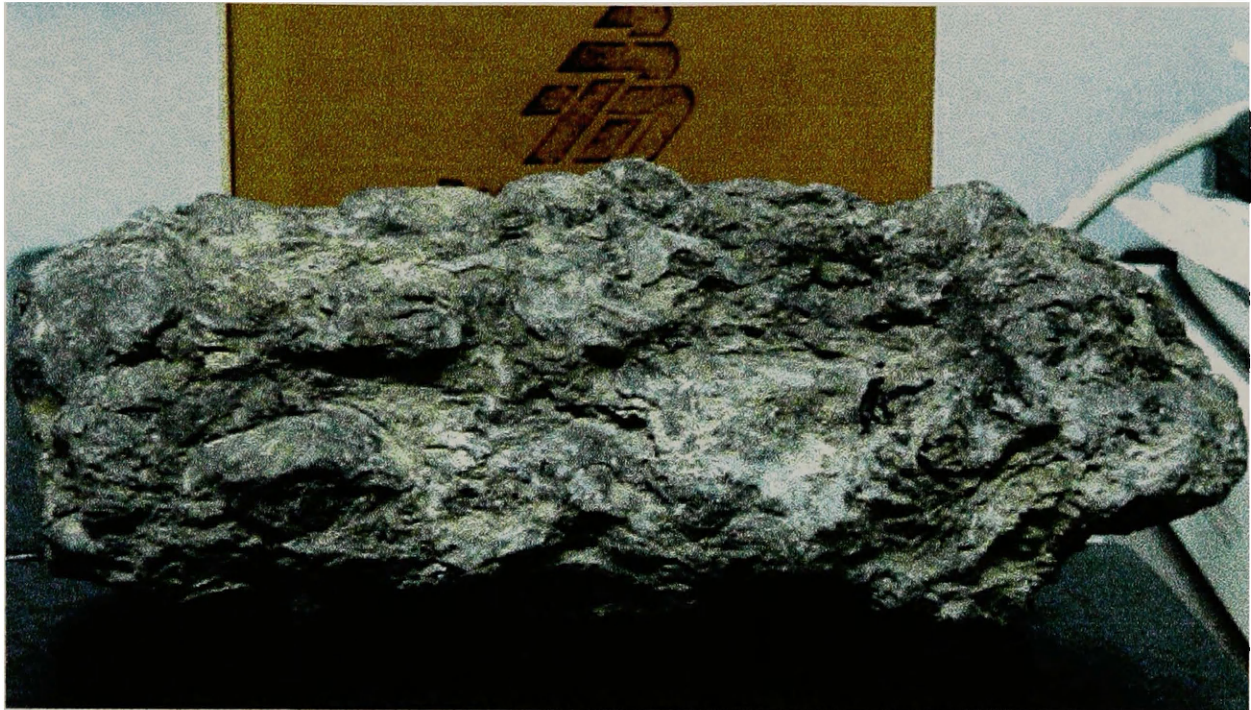


Figure 15: Oyster coquina from the Coberly Formation. Field book is 12 cm across.

Note sub-horizontal alignment of shelly debris.

the southern Garnet Range near Gold Creek. Sears et al. (2000a) used the oyster beds as marker horizons in the adjacent Garrison Quadrangle. Two distinct oyster beds were observed on the east side of the Gold Creek syncline (Plates 1, 2 and 4). This is consistent with mapping conducted on the Garrison Quadrangle directly to the east by Sears et al. (2000a). The oyster beds became more difficult to identify on the northern section of the east limb and on the west limb of the Gold Creek syncline due to transition to a sandier facies (Figure 16). One poorly preserved, slightly strained ammonite about 1.3 centimeters across was found in a fine sand and silt horizon at the outcrop in the figure below (Figure 17).



Figure 16: Sandier facies of Coberly oyster bed on northern section of east limb-Carten Creek syncline. Note dark oyster fragments as on float piece above hammer handle. The outcrop is dipping southwest toward the viewer.



Figure 17: A slightly strained ammonite found in the outcrop from Figure 16. Coberly Formation, east limb of the Carten Creek syncline. Central Section 31, T11N, R10W. Note dark shell debris. Scale in centimeters.

It should be noted that small sections of oyster beds and coquina are locally present in the underlying Dunkelberg member. The type section used by Gwinn (1960) to define the Coberly Formation west of the Boulder batholith is located in the southwest corner of the Bailey Mountain quadrangle along Hoover Creek (Plate 2). The Coberly

Formation has been biostratigraphically dated as Cenomanian through Turonian (Cobban in Wallace et al., 1990). Unit thickness is approximately 200 meters.

The Jens Formation consists of light greenish gray, dark gray, gray, grayish brown, very pale brown, grayish brown, and reddish brown shale with thin tabular, gray sandstone beds and minor porcellanite. The Jens Formation is locally cleaved; and contains *Inoceramus* sp. (Gwinn, 1965). Both the upper and lower contacts of the Jens Formation are gradational. Concretions of unknown origin were found at several localities within roughly 2.4 kilometers lateral distance and in the same approximate stratigraphic interval within Jens Formation shale (Figure 18).



Figure 18: Concretions in Jens Formation. Hammer for scale. Northeast Griffin Creek quadrangle.

A single marginally preserved inoceramid mold (5.5 cm long axis) was observed in an outcrop of reddish brown fine-medium grained sandstone in the core of the Carten Creek syncline (Figure 19). The Jens Formation often forms prominent swales. Unit thickness is approximately 200 meters. The Jens Formation is correlative to the Telegraph Creek Formation farther east along the Rocky Mountain front.

The Carten Creek Formation of Gwinn (1965) is inter-layered dark gray, light gray, red, grayish brown, and light brownish non-resistant gray shale, yellow- brown weathering, friable, cross-bedded, “salt and pepper” chert-litharenitic sandstone (Waddell, 1997) and minor conglomerate. The formation contains *Cardium pauperculum* (Wallace et al., 1990). Other invertebrate fauna, observed and listed by Gwinn (1960) in the bluff south of the Clark Fork River (southwest ¼ section 27, T10N, R11W), include the pelecypods: *Pedalion* sp., *Ostrea* cf. *O. soleniscus*, and *Protodonax umbonianus*; also includes the gastropod *Lispodesthes mptialis* and the ammonite *scaphites* (W.A. Cobban in Wallace, 1990). Gwinn (1960) also collected the pelecypods: *Brachidontes* sp., *Corbula* sp.; and the gastropod *Melania?* sp. to the east of the mouth of Brock Creek (southeast ¼, T10N, R11W). Coquina (Figure 20) and petrified wood (Figure 21) were found near the base of the formation to the east of Gough Creek during the course of this investigation. Shelly debris in the coquina has a sub-horizontal alignment that suggests deposition during a storm event. Coquina was also observed near the contact with the lower Renova Formation in the southeast ¼ of section 8, T9N, R11W. Waddell (1997) examined paleocurrent indicators within the Carten Creek Formation just east of the study area and concluded that dominant paleoflow directions were to the south and east. Exposures of the Carten Creek Formation are often very poor. Maximum unit thickness

observed from cross-sections B-B' and C-C' is approximately 1.8 km. The base of the Carten Creek



Figure 19: Inoceramid mold found in the Jens Formation, Carten Creek syncline, Bailey Mountain quadrangle. Top of scale is in centimeters.

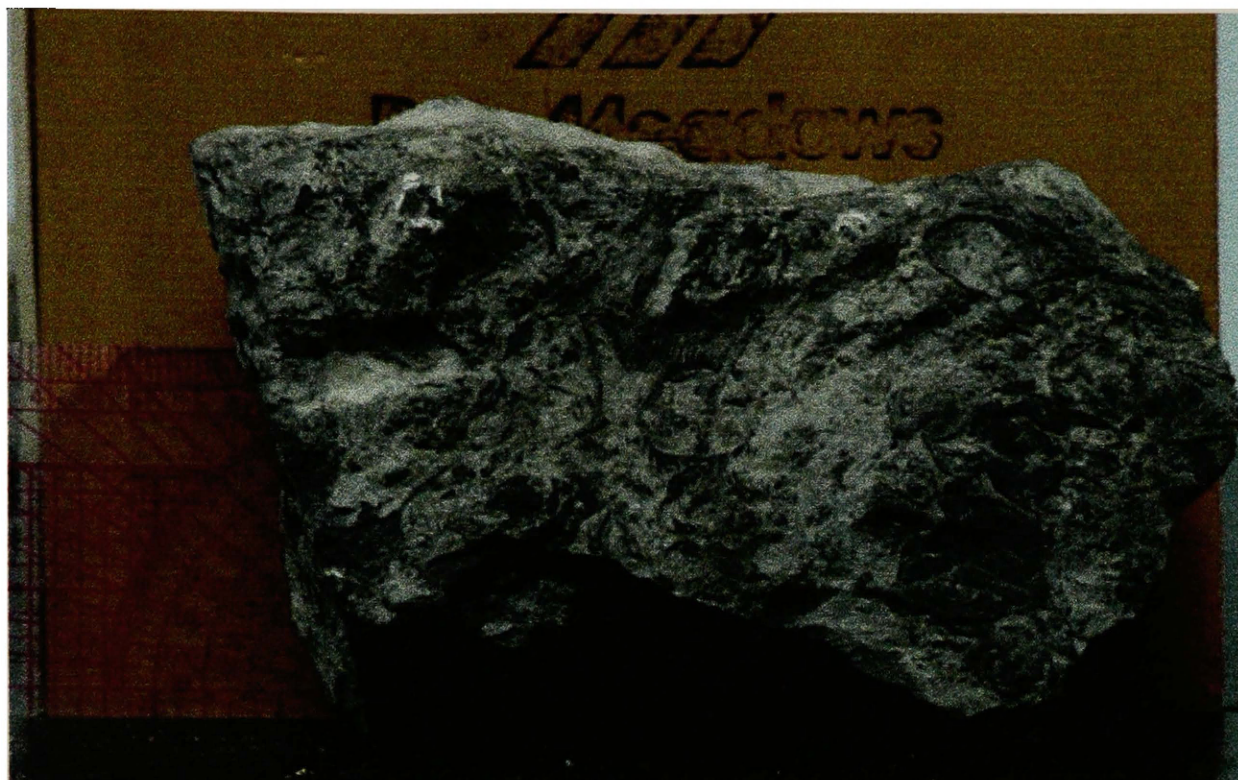


Figure 20: Coquina found near the base of the Carten Creek Formation to the east of Gough Creek. Field book is ~ 12 cm wide.



Figure 21: Petrified wood found near the base of the Carten Creek Formation to the east of Gough Creek. Top of scale is in centimeters.

Formation was dated as 88 Ma (upper Coniacian) by W.A. Cobban in Wallace et al. (1990). The unit thins considerably from west to east along an angular unconformity

beneath the Golden Spike Formation. Comparison of cross-section thicknesses from the Griffin Creek quadrangle and the Garrison quadrangle (Sears et al., 2000a) shows that the unit thins from approximately 1.8 km to less than 0.5 km. It should be noted that there has been and continues to be considerable confusion about the correct name of this unit. The namesake creek for this unit uses the spelling “Carten” Creek. Gwinn mentions in his dissertation (Gwinn 1960), that the unit and the creek were named after a local family of early settlers. The Carten Creek Formation is referred to as the Kiss Creek Formation in Gwinn’s (1960) dissertation. The Carten Creek Formation is the local equivalent to the Mesa Verde Formation (Sears, et al., 2000b).

The Golden Spike Formation

The Campanian-Maastrichtian Golden Spike Formation of the Montana Group was mapped and compiled according to the efforts of Gwinn and Mutch (1965) and Sears et al. (2000a). The Golden Spike Formation is dominated by inter-layered, laterally discontinuous, southeast-thickening, non-volcanic and volcanic rocks, 2.0 to 2.5 km thick, which were differentiated by Gwinn and Mutch (1965) into the following informal mapped units:

The Golden Spike informal non-volcanic unit of Gwinn and Mutch (1965) is composed of dark greenish gray, and light gray non-volcanic sandstone, shale, and conglomerate. The informal non-volcanic unit is referred to as Kgss on the Griffin Creek and Garrison Quadrangles (Sears et al., 2000a). The sandstones often exhibit the same salt and pepper aspect as the bulk of the Mesozoic sandstones including sandstones of the Jurassic Ellis Group and the Cretaceous Colorado Group. The salt and pepper aspect

reflects a composition dominated by dark chert (and other sedimentary rock clasts) and quartz. The sandstones generally lack micas and other igneous detritus. Modal analysis of sandstone composition indicates that non-volcanic sandstones of the Golden Spike Formation are very similar in composition to Carten Creek sandstones except that Carten Creek sandstones contain significantly more plagioclase (Table 1 in Gwinn and Mutch, 1965). Pebbles and cobbles in the conglomerates have an approximate maximum diameter of about 30 centimeters. The conglomerates are compositionally immature (Figure 22). Gwinn and Mutch (1965) present clast composition in order of decreasing abundance; the order of abundance was obtained from clast counts. The most abundant clasts are reddish-gray, and greenish-gray Beltian quartzites and very rare vitreous reddish and white quartzite from the Pennsylvanian Quadrant, Formation; limestones from the upper calcareous member of the Kootenai Formation and the Coberly Formation, Colorado Group mudstone, chert from the Madison Group and the Phosphoria Formation, and Colorado Group Formation sandstone. The softer clasts such as limestone are well rounded, while the dura-clasts such as chert and quartzite range from subrounded to subangular.

The Golden Spike lava flow units (informal unit), referred to as Kgs1 on the Griffin Creek and Garrison quadrangles (Sears et al., 2000a) are dark gray andesitic lava flows. Texture is dominantly aphanitic, but some areas display a porphyritic texture. The occurrence of clinopyroxene phenocrysts in the lava flows unit, which Gwinn and Mutch (1965) noted are apparent on sawed polished faces, may be significant because of the clinopyroxene (augite) common to the Campanian intrusive bodies. A thorough petrologic analysis of a possible relation between Golden Spike volcanic units, Elkhorn

Mountain volcanics-Boulder batholith, and the Campanian intrusive rocks might be considered for future research. Gwinn and Mutch (1965) noted zeolite filled amygdules



Figure 22: Conglomerate in the informal non-volcanic unit of the Golden Spike Formation. Location southeast $\frac{1}{4}$ Section 8, T9N, R10W.

near the tops of several flow sub-units within the informal lava flow unit. It is unknown if these deposits occur in economic quantities.

The Golden Spike volcanoclastic sedimentary unit (informal unit), referred to as Kgsv on the Griffin Creek and Garrison quadrangles (Sears et al., 2000a), consists mainly of light gray and dark greenish-gray volcanoclastic sandstone and conglomerate. The volcanoclastic sandstones are poorly sorted, with dominantly fine-to-medium grains. Gwinn and Mutch (1965) and Waddell (1997) interpreted sedimentologic data from the Golden Spike Formation informal volcanoclastic sedimentary unit to show that the

volcaniclastic debris that comprises the unit was transported by mudflows and landslides and is not derived from pyroclastic airfall.

The architecture of the Golden Spike units reflects the origins of the materials that comprise the formation. Gwinn and Mutch (1965) postulated that the inter-tongued architecture reflects predominant source areas of sedimentary material in the northwest and igneous material from the Elkhorn Mountains Volcanic area to the southeast. The base of the Golden Spike Formation has been dated by Cobban in Wallace (1990) as 83-80 Ma. The presence of the ostracod *Staringia* indicates that deposition of the Golden Spike Formation extended into the Maastrichtian (Mackie, 1986). The Golden Spike Formation has been correlated with the Two Medicine Formation (Gwinn and Mutch, 1965; Viele and Harris, 1965). Sears, et al. (2000b) “infer the Golden Spike Formation to be the oldest stratigraphic unit unequivocally deposited in the wedge-top portion of the foreland basin”. Much of the Golden Spike Formation is intruded by the Campanian calc-alkalic rocks, as evidenced on the geologic map of the adjacent Garrison quadrangle (Sears, et al., 2000a).

The angular unconformity between the Golden Spike Formation and the underlying Carten Creek Formation is folded on the adjacent Garrison quadrangle (Sears et al., 2000a). The unconformity cut low angle folds and was in turn folded by the same folds.

Eocene-Miocene

The Tertiary deposits found within the quadrangles consist of poorly consolidated to unconsolidated sediments. The sediments were left undivided in some areas due to

poor exposure, lack of access due to such factors as inability to obtain landowner permission, or lack of time. The undivided Tertiary sediments include the Sixmile Creek and Renova Formations.

The Lower Renova Formation consists of pinkish gray, and very pale brown, poorly consolidated, iron-stained micaceous sandstone and pebble conglomerate. The nature of the topographic expression of the Lower Renova Formation is noticeably subdued in comparison to the topographic expression of the Cretaceous Carten Creek Formation on the west side of the Griffin Creek quadrangle (Plate 1). The change in topographic expression helped to place the contact between the Lower Renova Formation and the Carten Creek Formation. Lower Renova-type sands are noted in other Tertiary basins, elsewhere in Montana (Thomas et al., 1995). Outcrops are typically poor.

The Upper Renova Formation is pale yellow, poorly consolidated to unconsolidated volcanoclastic and nonvolcanoclastic sandstone, tuffaceous mudstone, siltstone, limestone, clay, and minor lignite (Figure 23). Freshwater snails were observed in place during this survey (southwest ¼, Section 19, T9N, R10W), but previous workers in the area have noted abundant fossils including mammal bones and teeth (Konizeski and Donahoe, 1958; Gwinn, 1960; Loen, 1986; Rasmussen, 1977). Rasmussen (1977) compiled extensive lists of the flora and fauna observed in the Upper Renova Formation in the Pioneer District.

Miocene-Pliocene

The Miocene to Pliocene Sixmile Creek Formation consists of poorly consolidated to unconsolidated gravel and cobble conglomerate. The maximum clast size

observed in the upper Sixmile Creek Formation was approximately 0.5 meters. Typical clasts were pebble to cobble size. Boulder conglomerate at the base of the Sixmile Creek Formation was used as a local mapping aid. The basal conglomerate contains subrounded boulders up to 2.0 meters in diameter. Clast composition is dominated by Quadrant quartzite, granitoid, black chert, and brown and gray schist. Quartzite clasts in the Sixmile Creek Formation commonly exhibit percussion marks (Loen, 1986) (Figure 24). The Sixmile Creek Formation has a mud and sand matrix (Pardee, 1951; Loen, 1986).

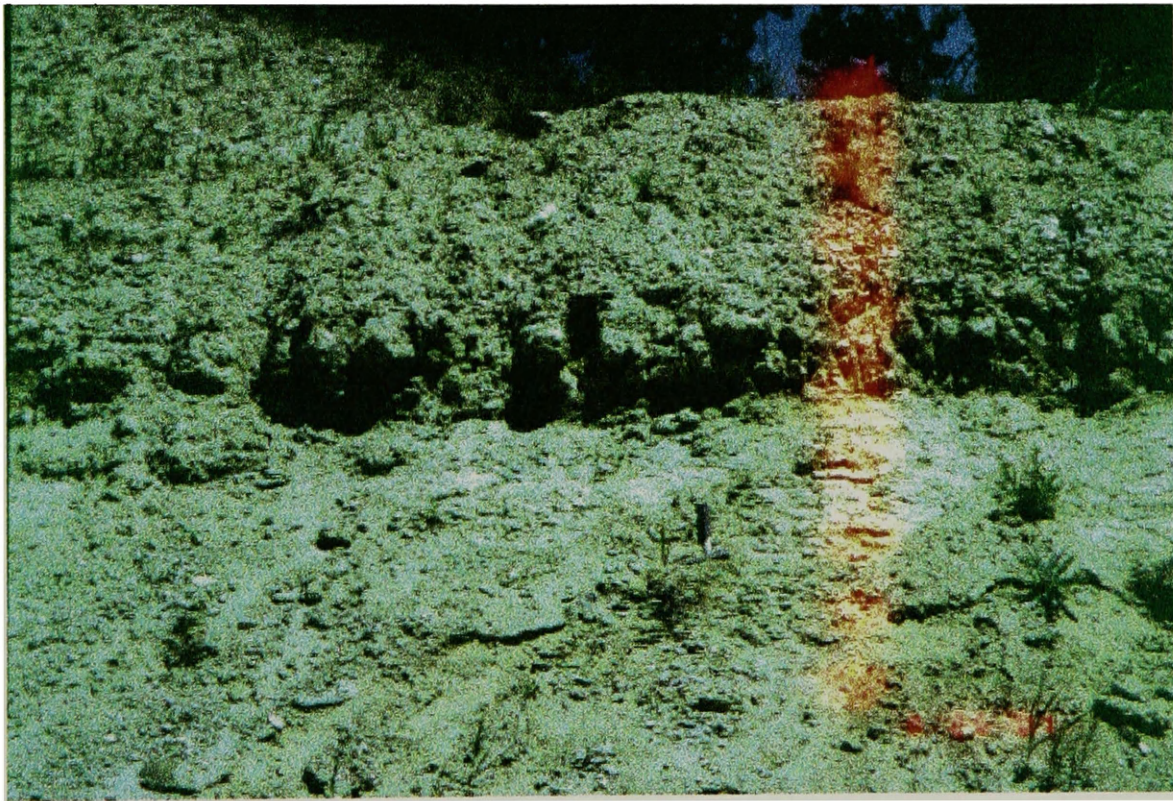


Figure 23: A good outcrop of the Upper Renova Formation observed in a roadcut southwest $\frac{1}{4}$ Section 19, T9N, R10W. Hammer for scale.



Figure 24: Percussion marks in a Quadrant Formation quartzite clast. Sixmile Creek Formation. Hammer for scale. Northwest $\frac{1}{4}$ Section 19, T9N, R11W.

Two additional, but minor occurrences of Miocene to Pliocene aged rocks are noteworthy. Neither was of sufficient lateral coverage to justify mapping. Pediment gravels were observed by Sears et al, (2000a) capping high-level erosional surfaces on the north central Garrison quadrangle. Very scattered occurrences of clasts were observed on the high-level erosional terrace between Carten and Hoover Creeks. One location is near the east limb of the Carten Creek syncline in the southwest $\frac{1}{4}$ of Section 30, T11N, R10W. Clast composition is dominated by rounded chert and quartzite. The clasts were observed to be 2 to 3 centimeters on the long axis. Another interesting lithology that was observed was possible hot-springs-related rocks in the area of north-central Section 8, T10N, R10W. The rock closely resembles Madison limestone, but is notably free of crinoids or other fossils that are often evident in Madison Group

carbonates. The location where these deposits were observed is stratigraphically distant from the Madison Group carbonates. Extensive carbonate hotspring deposits were mapped by Sears et al, (2000a) on the high terrace between Brock and Warm Springs Creeks. The mapped deposits of Sears et al, (2000a) are approximately 5 kilometers to the southeast of the unexplained Madison-like rocks observed during this study.

QUATERNARY

Pleistocene

Jeff Silkwood of the U.S. Forest Service produced a digital map that shows the extent of Glacial Lake Missoula as inferred from glacial landforms, sediments, and land surface elevation (Silkwood, 1997). The map shows the lake extending as far east as Garrison, Montana. The Clark Fork River plain cuts roughly east-west across the northern portion of the Griffin Creek Quadrangle. The lake may have covered the Clark Fork plain across the map area, but no obvious glacial lake sediments or other features that appear to be related to the lake were observed during this study.

The Pleistocene geology in the southwest corner of the Griffin Creek Quadrangle was compiled, field-checked, and modified from the works of Alden (1953), Pardee (1951), Mutch (1961) and Loen (1986). These previous workers mentioned above identified up to four periods of glaciation in the Flint Creek Range. The Garnet Range was never affected by glaciation (Alden, 1953).

Two units were used to map Pleistocene deposits within the Griffin Creek quadrangle. Glacial till deposits, referred to as Qt on the Griffin Creek quadrangle (Plate 1) (Loen, 1986; Mutch, 1961; Pardee, 1951) consist of unconsolidated silt, sand, and

boulders. The till displays varying degrees of morainal topography. The till was divided by Loen (1986) into several units based on topography.

Glacial outwash deposits (Loen, 1986; Mutch, 1961; Pardee, 1951) consist of boulders and cobbles with a mud and sand matrix. Clast composition is dominated by granodiorite with a small percentage of quartzite.

Pleistocene-Holocene

Alluvial gravel, sand, silt, and silty clay deposits occupy all modern stream valleys. The first placer gold discovery in Montana was made in Quaternary alluvium at the confluence of Gold Creek and the Clark Fork River.

The Pioneer District, which occupies much of the southern portion of the Griffin Creek quadrangle (Plate 1) has an extensive history of placer mining. Thus, there is an abundance of historic mining waste and tailings in the Gold Creek drainage and many of its tributaries (Figure 25). Much of the mining waste was not mapped for the purposes of this study. A limiting factor for placer mining in the Pioneer District is a shortage of water.



Figure 25: Waste from placer mining operations at Gold Creek. Fence posts are approximately 1.2 meters high.

Marker Beds

Several diagnostic marker horizons facilitated mapping of the area. The marker horizons are presented from oldest to youngest. They are the “gastropod limestone” of the Kootenai Formation, the black shale of the Flood member, the “chert-pebble” conglomerate of the Dunkleberg member, the oyster beds of the Coberly Formation, and the basal bouldery conglomerate of the Sixmile Creek Formation. In addition, the Pennsylvanian Quadrant Quartzite can be very helpful to investigators in unfamiliar areas due to its tendency to form prominent ridges.

The gastropod limestone, the youngest member of the Kootenai Formation, is very useful as a marker bed. The unit contains an abundance of gastropods up to 1 cm across (*Reesedila Montanensis*) that are difficult to miss in the field (Figure 9).

The Upper Flood member of the Blackleaf Formation is dominated by dark, fissile organic shale. The easily identifiable and extensive dark shale may be used as an aid to locate stratigraphic position for investigators in unfamiliar areas (Figure 12).

The Dunkleberg member of the Blackleaf Formation contains a basal chert-pebble conglomerate within the Bailey Mountain Quadrangle. The pebbles of the basal conglomerate have characteristic pressure solution pits that are obvious to the naked eye (Figure 14). Thus, the conglomerate can be used as an aid to infer stratigraphic position within the Colorado Group.

The Coberly Formation contains distinctive yellow-brown and gray weathering oyster beds in the Gold Creek area. The oyster beds are resistant and often up to a meter thick. Two beds are noted in several localities within the Griffin Creek, Bailey Mountain and Garrison quadrangles (Plates 1 and 2; Figure 15) (Sears et al., 2000a).

Igneous Rocks

K-Alkalic Province Intrusives

The late Cretaceous Colorado Group is laced with very dark gray, dark greenish gray, olive, olive gray, and pale yellow, pyroxene-biotite andesite and diorite sills and dikes. The sills are typically in stacks of up to five. Large euhedral pyroxene crystals and clots of biotite are common (Figure 3).

A $^{40}\text{Ar}/^{39}\text{Ar}$ date was obtained from biotite and is considered to represent a crystallization age of 75.9 +/- 1.2 Ma from sample GC-1 near Mile Post 169 on the north side of Interstate 90 west just east of Gold Creek. Site GC-1 is displayed on the Griffin Creek quadrangle (Plate 1). The crystallization age is thought to roughly coincide with

the time of intrusion (Sears et al., 1997). The Campanian intrusives were a major focus of this study.

The structural-stratigraphic relationships observed during the construction of the project maps and cross-sections and from the geologic maps and cross-sections of the neighboring Garrison and Luke Mountain Quadrangles (Sears et al. 2000a) indicate that magma was intruded before and during Late Cretaceous Laramide deformation associated with movement along the adjacent portion of the Lewis and Clark line. The lowest stratigraphic level that the sills occupy is at the horizon between the upper calcareous member of the Kootenai Formation and the lower Flood member of the Blackleaf Formation (Sears et al., 2000a). Only minor sediment alteration from contact with the intruding sills was observed. Krause (1963) notes a maximum 3 meter aureole of slightly altered Dunkleberg Formation sediments on the margins of the Hoover Creek sill. Grus derived from the intrusive masses is highly micaceous and contains pyroxene crystals. The grus may aid with the location of intrusions in areas of poor exposure.

Krause (1963) postulated that some degree of gravitational differentiation caused concentration of more heavy mafic mineral constituents near the bottom of the Hoover Creek sill than near the top. Observations made during this project appear to confirm this conjecture. Material towards the top of the Hoover Creek sill appears to contain less dense mafic components than does material toward the bottom of the sill. However, it is unclear whether this is a factor of weathering or of such factors as biased sampling. A thorough sampling program and petrologic study might answer the question of whether or not gravitational differentiation occurred. The sill network is more extensive than shown

on the project quadrangles. No doubt a number of small sills were missed in the course of investigation of this project due to poor exposure.

Eocene–volcanics and minor intrusives

The Eocene volcanic cover exposed in the area is usually very-fine grained and heavily weathered, which often makes identification in hand sample difficult. The Eocene rocks are greenish gray, light and dark gray, pink, and brown extrusive and minor intrusive rocks (Figure 26), and are undivided for the purposes of this study. The Eocene igneous rocks overlie Late Cretaceous and older rocks of the area with angular unconformity. The dominant rock types are andesite, dacite, basalt, and rhyolite (Carter, 1982; Callmeyer, 1984). Apparent flow banding and autobrecciation (Figure 27) were observed in andesite and rhyolite on Bailey Mountain. Columnar jointing was observed in basalt north of Six Shooter Peak (Figure 28). The area mapped as Tertiary volcanics includes a small area of white, welded rhyolitic tuff in northernmost central Section 7, T10N, R10W. The Eocene igneous rocks observed in this study are presumed to be equivalent to the Lowland Creek volcanics (Sears et al., 2000a). K-Ar age dates for Tertiary igneous rocks directly to the east and west of the study area for this project are clustered in the range of 43.7 +/- 1.2 to 47.4 +/- 1.6 Ma (Carter, 1982).



Figure 26: Outcrop of intermediate composition Tertiary intrusive rock, east side, mouth of Gough Creek. Camera case for scale.

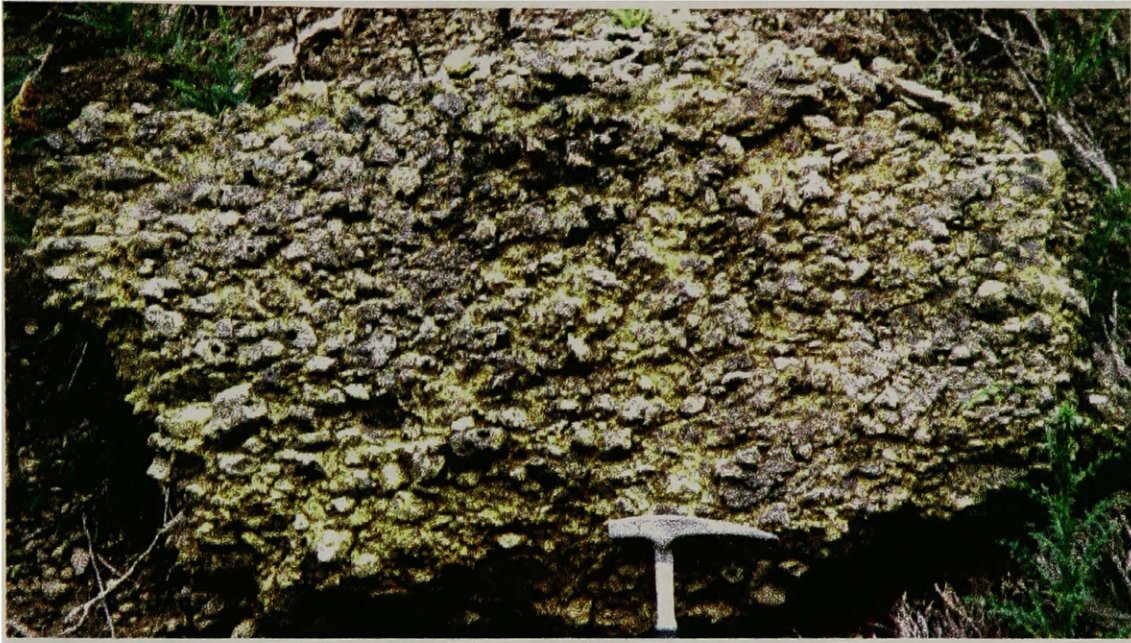


Figure 27: Felsic-intermediate composition autobreccia in Tertiary volcanics.



Figure 28: Columnar joints in basalt (Tertiary volcanics), from roadcut 0.7 km northeast of south Chimney Peak.

STRUCTURE

Folds

Two equal area nets were constructed for two major folds, the Saddle Mountain anticline, and the Carten Creek syncline. Sixteen data points from strike and dip measurements were used to construct a stereonet for the Saddle Mountain anticline (Figure 29). The Saddle Mountain anticline plunges southeast at about 20-25 degrees.

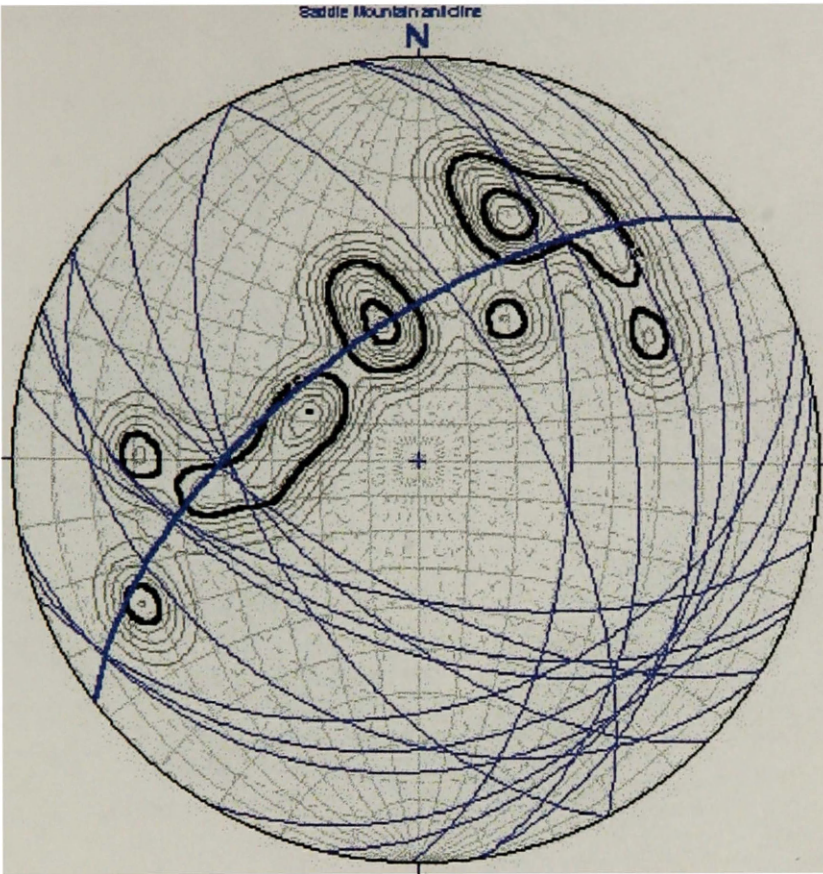


Figure 29: Equal area net poles to planes-bedding orientation, Saddle Mountain anticline.

N = 16.

Ninety one bedding orientation data points were used to construct a stereonet for the Carten Creek syncline (Figure 30). The Carten Creek syncline plunges south-southeast at about 15-20 degrees. The trend and plunge of this fold are consistent with other folds on the Lewis and Clark Line. The Carten Creek syncline is asymmetric in form; the east limb dips at a steeper angle than the west limb, as shown by field structural data and a down-plunge projection view from cross-section A-A' to cross-section B-B'.

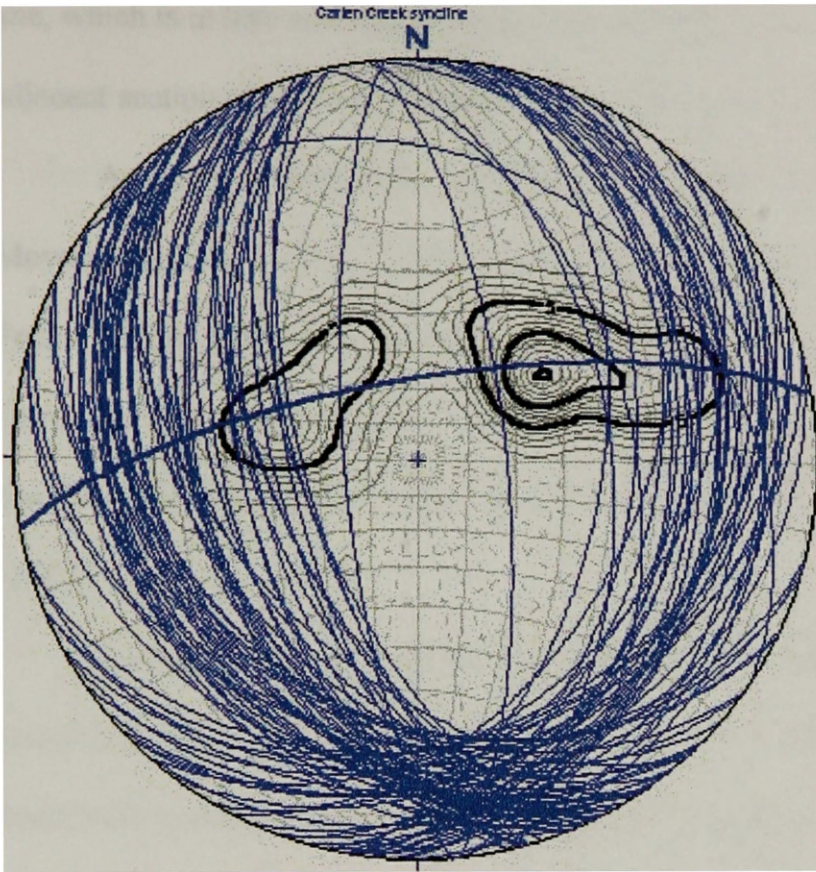


Figure 30: Equal area net poles to planes-bedding orientation, Carten Creek syncline.

N = 91.

Faults

Mesoproterozoic Belt Supergroup rocks overlie Paleozoic rocks on thrust faults in the northeast portion of the Bailey Mountain quadrangle. The lateral extent of the thrust faults is obscured by Eocene volcanic cover. This spatial relationship of the thrust faults to the Eocene volcanic cover indicates that the thrust faults are older than the cover. The thrust faults verge to the west, which is consistent with the steeply dipping east limb of the Carten Creek syncline. West vergent structures are common on the Lewis and Clark

line, which is in line with the interpretation of Sears et al. (2000a) who interpret the adjacent section of the Lewis and Clark line as a positive flower structure.

A small northeast-trending normal fault is present in section 2, T11N, R11W. Movement on the fault has dropped Mississippian-Pennsylvanian Amsden and Pennsylvanian Quadrant Formations on the east side of a small drainage. The Quadrant Formation quartzites exposed on the relatively upthrown side of the fault are highly brecciated. This apparent normal fault was inferred to be a strike-slip fault by Krause (1963).

A small northwest-trending normal fault has dropped the Cretaceous Coberly and Jens Formations fossiliferous sandstone and dark shale into contact with Cretaceous Blackleaf Formation-Dunkleberg member siliceous mudstone in the area to the west of Gough Creek. The fault was originally inferred by Gwinn (1961). Gwinn extended the fault trace to cut the southeast margin of the Hoover Creek sill. Gwinn's inference was field checked and a distinct change in lithology, as mentioned above does occur across the apparent fault zone. An additional northwest-trending normal fault appears to have uplifted Cretaceous Jens Formation dark shale to the level of the Cretaceous Carten Creek Formation in the vicinity of section 18, T10N, and the boundary between Range 10 and 11 west. This fault was originally inferred by Gwinn (1960). Evidence for the existence of this fault is not as strong as for the fault at the mouth of Gough Creek. Analysis of aerial photographs, sparse structural data, and lithologic change indicates that the map trace of this fault may actually represent a collection of parallel closely spaced faults oriented in a narrow zone.

The Golden Spike Formation is truncated by a northeast-trending normal fault on the northwest boundary of surface outcrop. Across this fault, the Golden Spike Formation has dropped to the level of the Carten Creek Formation. The existence of the fault was first inferred by Gwinn and Mutch (1965). The fault extends to the adjacent Garrison quadrangle (Sears, et al., 2000a).

A northeast-trending normal fault, present on the west side of the Griffin Creek quadrangle drops Eocene-Oligocene Lower Renova Formation iron-stained micaceous sandstone and pebble conglomerate to the level of the Cretaceous Carten Creek Formation. An additional apparently short, northwest-trending normal fault drops the Lower Renova Formation to the level of the pronounced spur of Carten Creek Formation rocks in section 27, T10N, R11W. Both of these faults terminate in an adjacent section of the Lewis and Clark line that approximately parallels the Clark Fork River.

The “Buckskin Gulch” normal fault drops Eocene volcanic cover to the same level as Madison Group carbonates. Additional circumstantial evidence for the existence of this fault is the linear nature of Buckskin Gulch itself. The gulch likely represents the approximate position of the fault zone. The current depression presumably eroded through fault gouge. This fault was first inferred by Callemeyer (1984).

A north-northeast trending normal fault has uplifted the Miocene-Pliocene Sixmile Creek Formation near the southeast corner of the Griffin Creek quadrangle (Plate 1). The existence of the fault was first inferred by Loen (1986). Loen (1986) mapped the Sixmile Creek Formation as a unit he referred to as the Pioneer Beds. The work of Stickney et al. (2000) indicates ongoing seismicity in the “Intermountain Seismic Belt” of western Montana. This recent seismicity, coupled with the significant vertical offset of

beds deposited as recently as the Pliocene indicate some unknown degree of seismic hazard.

There are an undetermined number of small normal faults that were not mapped due to exposure, time, or because displacement was too small to show at the map scale.

Cleavage

The term cleavage as used herein is defined as a secondary fabric element formed under low temperature non-metamorphic conditions that imparts a tendency to split along planes to the rock (van der Plume and Marshak, 1997). The limbs of the Carten Creek syncline display axial plane cleavage. The cleavage typically exhibits steep angles to horizontal. Shale horizons in the Colorado Group often exhibit pencil cleavage. Weiss (1987) inferred that the temperature associated with cleavage formation in Mesozoic rocks at the shallowest stratigraphic levels in the Garrison depression was at least 280° C.

A few areas have cleavage that trends at high angles to fold axial planes. One area of unexplained cleavage to note is in the southeast ¼ of Section 12, T10N, R11W. This unexplained cleavage likely reflects small-scale or obscure structure that was not observed in the field.

Joints

Joints are defined herein as fractures with no observable offset or displacement. Three sets of joints occur in the area of the Hoover Creek sill (Plate 2). The Hoover Creek sill exhibits low-angle unloading joints. A second joint set trends approximately east to west, while another set trends roughly north to south. The east to west and north

to south oriented joint sets are steeply dipping. The Dunkleberg Formation surrounding the Hoover Creek sill also has steeply dipping north to south and east to west oriented joints.

General Structural Style

The Sevier foreland basin, which includes the foreland basin of western Montana spanned from Jurassic to Tertiary time. Under the classification of Dickinson (1974), the basin is a retroarc-type foreland basin. The structural geology of the project quadrangles is dominated by two periods of deformation. The first period of deformation was associated with the Laramide Orogeny. The en echelon, southwest-trending folds in the study area and along the adjacent section of the Lewis and Clark line were formed during the emplacement of the Lewis-Eldorado-Hoadley tectonic plate. Sears et al.(2000b) interpret the southwest-facing en echelon folds in and adjacent to the study area to indicate that sinistral movement occurred on the central part of the Lewis and Clark line during the late Cretaceous to Paleocene. It should be noted that the structures of the Lewis and Clark line are overprinted from several periods of tectonism (Wallace et al., 1990).

The second major period of deformation to affect the current structural style of the study area is on-going Basin and Range extension. Extension associated with ongoing Basin and Range extension is responsible for the current topography of the Flint Creek Range and the Garnet Range. Sears et al. (2000b) interpret that Tertiary extension along the central portion of the Lewis and Clark line was accommodated by dextral movement on the line.

Several pieces of evidence that are indicative of the Tertiary tectonic history of the study area and a large portion of central-western Montana are worth noting. but first, some fundamental principles must be considered. Tectonism creates uplifted source areas for sediment. Uplifted source areas in turn receive more precipitation than lower elevation areas. The evidence for Tertiary tectonism includes the following: the iron-stained micaceous sandstone and pebble conglomerate of the Lower Renova Formation, the middle Miocene angular unconformity between the Renova Formation and the Sixmile Creek Formation, the coarse composition of the Sixmile Creek Formation. Post Pliocene tectonism is indicated by fault offset Sixmile Creek sediments observed on the Griffin Creek quadrangle (Plate 1). Stickney et al. (2000) show recent seismicity in close proximity of the faults responsible for uplift of the Sixmile Creek Formation.

Mesozoic-Early Cenozoic Tectonic History

The Mesozoic geologic history of the Gold Creek area is characterized by two periods of deformation. The first period, referred to as the Sevier Orogeny is represented by sediments of the Late Jurassic Ellis Group through the Blackleaf Formation (DeCelles, 1986). The second period of Mesozoic deformation took place from the Late Cretaceous through the Paleocene. This second period of tectonism is commonly referred to as the Laramide Orogeny. The spatial-structural relationship of the K-alkalic Campanian intrusive bodies to the Colorado Group sedimentary package indicates that development of southwest trending folds, in the study area and along the adjacent section of the Lewis and Clark line, did not occur until about 76 Ma (Campanian).

Discussion

Laramide tectonism is well bracketed on the lower end by GC-1 (74.9 \pm 1.2 Ma from Sears et al. (1997)). The upper end is bracketed by the Sun-2 date of 59 Ma in a denuded portion of the Lewis-Eldorado-Hoadley footwall (Sears et al., 2000b). Tertiary volcanics (dated from 47-44 Ma in Carter, (1982)) overlie folded Colorado Group sediments with prominent angular unconformity.

I infer that the pyroxene-biotite Campanian sills were intruded before and during ongoing Laramide deformation in the Garrison depression. This inference is based upon the spatial relation of the intrusive bodies to the folds present in the area. The large sill on the west side of the Carten Creek syncline is referred to as the Hoover Creek sill (Gwinn, 1960; Krause, 1963). The map trace of the sill is approximately ten kilometers before its trace is lost under Eocene volcanic cover to the northwest of Bailey Mountain. The Hoover Creek sill (or laccolith) represents a large volume of material on the west limb of the Carten Creek syncline while little sill material is found on the east side of the syncline. The large amount of sill material on the west side of the Carten Creek syncline indicates that folding may have already been in progress during intrusion or that folding associated with the Laramide Orogeny may have begun shortly after intrusion started. Mapping conducted for this study indicates that most folding of the Hoover Creek sill post-dated emplacement. The sill shares the folds of the enclosing strata. These results agree with Priest (2000) who concluded that the K-alkalic Campanian sill in his study intruded into partially deformed Colorado Group sedimentary rocks. Sears et al (2000) inferred that the sills in the Garrison depression are related to the sills in and near the

study area of Priest (2000) based on petrology, geochemistry, and structural-stratigraphic setting. Priest (2000) suggested that the sill in his study intruded into Colorado Group rocks that had already been folded 20 to 30%. This is consistent with the folded and intruded angular unconformity between the Carten Creek and Golden Spike Formations that is evident on the geologic map of the Luke Mountain quadrangle (Sears et al., 2000a). The intruding magma was probably constricted in the hinge area of the Carten Creek syncline during folding. This interpretation is contrary to prior interpretations such as that of Gwinn (1961) and Sears, et al., (2000b) who interpret that the sills were emplaced before late Cretaceous-Paleocene movement of the Lewis-Eldorado-Hoadley plate. An alternate explanation for the igneous-sedimentary relations observed is that the magma may have been emplaced in pulses, during which magma was pushed through some areas, leaving little behind, but stuck in others areas.

Conclusions

The benefits derived from this project are closely linked to the purposes for which the work was conducted. First, the interpretations of the relationship between the Campanian intrusive bodies, the Colorado group sediments, and the structure of the area yield important information regarding the timing of folding in the study area and thus the timing of movement on the adjacent portion of the Lewis and Clark Line.

Second, the extensive mapping, field-checking, and compilation work conducted allowed a fresh look at the problem of differing structural interpretations. Refinement of previous work and the use of a GIS friendly base makes the geologic maps generated during this study very useful.

The Garrison depression contains an impressive section of Cretaceous marine sedimentary rocks. The sedimentary section contains seemingly excellent source and reservoir rocks. However, the stacks of Campanian sills present in the Garrison depression intrude a significant portion of the Colorado Group sedimentary section. In addition the temperatures associated with the formation of the cleavage likely were an additional factor in perturbing the geothermal gradient. I interpret that a combination of the temperatures involved with cleavage formation, the study area proximity (border zone) to the Boulder batholith, and the intrusion of the sills raised the geothermal gradient in the Garrison depression such that conditions were not conducive to the preservation of oil and gas.

Recommendations for additional work

The Campanian age K-alkalic intrusive bodies present in the map area should be further studied. Studies could further define the petrology of the pyroxene-biotite diorites/andesites. In addition, the modes of compositional differentiation are poorly understood. Further research is necessary to establish the relationships between widespread Late Cretaceous igneous rocks across west-central Montana. For instance, the pyroxene-biotite sills and dikes that occupy the Colorado Group within the Garrison depression are close to the Boulder batholith and have similar chemistry to the batholith.

A thorough petrologic analysis of a possible relation between Golden Spike volcanic units, the Elkhorn Mountains volcanics, and the Campanian intrusive rocks might be considered for future research.

In addition, quadrangles that border the Griffin Creek, Bailey Mountain, Garrison, and Luke Mountain Quadrangles have yet to be mapped on recent, GIS useable, 7.5 minute topographic maps. Further structural-mapping studies could help cement the work on the relationship between the intrusive bodies and the Colorado Group that was performed as part of this thesis and as part of the work of Sears et al. (2000a).

Paleomagnetic work may be considered to fill in the gaps between previous investigations of the emplacement of the Lewis-Eldorado-Hoadley plate. Previous investigators include Symonds and Timmins (1992), Jolly and Sheriff (1992), Brunt, (1997), and Priest (2000). Paleomagnetism studies in the widespread Campanian sills or from fine-grained red-bed strata could serve the purpose of confirming or refuting the interpretations of previous workers with regard to the tectonic transport of the Lewis-Eldorado-Hoadley plate.

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Appendix A: Map units and symbols-Griffin Creek Quadrangle

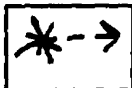
md	Tailings (Holocene)
Qal	Alluvium of modern channels and floodplains (Pleistocene and Holocene)
Qo	Glacial outwash, unconsolidated gravels (Pleistocene)
Qt	Glacial till , moraine forms, unconsolidated silt, sand, gravel, and boulders (Pleistocene)
Tsm	Sixmile creek Formation (Miocene and Pliocene)
Tru	Upper Renova Formation (Oligocene-Miocene)
Trl	Lower Renova Formation (Oligocene)
Ts	Sediment or sedimentary rocks, includes undivided Sixmile Creek and Renova Formation (Oligocene-Pliocene)
Tv	Volcanic and intrusive rocks, undivided (Eocene)
Ki	Intrusive rocks, andesitic and dioritic sills (Cretaceous-Campanian)
Kgsv	Volcaniclastic sedimentary rocks, informal unit of Golden Spike Formation (Cretaceous)
KgsI	Lava Flows, informal unit of Golden Spike Formation (Cretaceous)
Kgss	Nonvolcanic sandstone, shale, and conglomerate, informal unit of Golden Spike Formation (Cretaceous)
Kgs	Undivided Golden Spike Formation, shown only on Cross-Section C-C'

- Kcc Carten Creek Formation (Cretaceous)
- Kj Jens Formation (Cretaceous)
- Kc Coberly Formation (Cretaceous)
- Kbld Dunkelberg Member of the Blackleaf Formation (Cretaceous)
- Kblt Taft Hill Member of the Blackleaf Formation (Cretaceous)

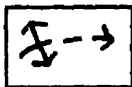
Geologic Map Symbols



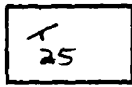
Contact; dashed where approximately located



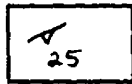
Synclinal fold; dashed where approximately located, dotted where concealed, arrow indicates plunge direction



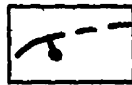
Anticlinal fold; dashed where approximately located, dotted where concealed, arrow indicates plunge direction



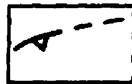
Strike and dip of bedding; degree of dip indicated



Strike and dip of cleavage



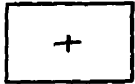
Fault, dashed where approximately located, ball and bar on downthrown side



Thrust fault; dashed where approximately located, teeth on overthrust side



Oyster marker bed in Coberly Formation (Kc)



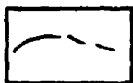
Mile Post (MP) 169, GC 1 sample location for radiometric dating, in
Cretaceous sill (Ki)

Appendix B: Map units and symbols-Bailey Mountain Quadrangle

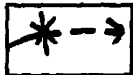
Qal	Alluvium of modern channels and floodplains (Pleistocene and Holocene)
Tv	Volcanic and intrusive rocks, undivided (Eocene)
Ki	Intrusive rocks (Cretaceous-Campanian)
Kcc	Carten Creek Formation (Cretaceous)
Kj	Jens Formation (Cretaceous)
Kc	Coberly Formation (Cretaceous)
Kbld	Dunkelberg Member of the Blackleaf Formation (Cretaceous)
Kblt	Taft Hill Member of the Blackleaf Formation (Cretaceous)
Kblf	Flood Member of the Blackleaf Formation (Cretaceous)
Kkd	Upper calcareous member- "Gastropod Limestone", Kootenai Formation (Cretaceous)
Kkc	Upper clastic member, Kootenai Formation (Cretaceous)
Kkb	Lower calcareous member, Kootenai Formation (Cretaceous)
Kka	Lower clastic member, Kootenai Formation (Cretaceous)
Kk	Kootenai Formation, undivided (Cretaceous)

Jm	Morrison Formation (Jurassic)
Jer	Rierdan Member, Ellis Group (Jurassic)
Je	Ellis Group, undivided (Jurassic)
Js	Sedimentary rocks, undivided (Jurassic)
Pp	Phosphoria Formation (Permian)
IPq	Quadrant Formation (Pennsylvanian)
IPMa	Amsden Formation (Late Mississippian and Pennsylvanian)
Mm	Madison Group, undivided (Mississippian)
Pzu	Paleozoic rocks, undifferentiated
Ybo	Bonner Formation (Middle Proterozoic)
Yms	Mount Shields Formation (Middle Proterozoic)

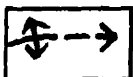
Geologic Map Symbols



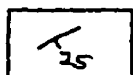
Contact; dashed where approximately located



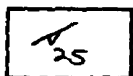
Synclinal fold, dashed where approximately located, dotted where concealed, arrow indicates plunge direction



Anticlinal fold, dashed where approximately located, dotted where concealed, arrow indicates plunge direction



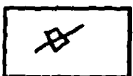
Strike and dip of bedding; degree of dip indicated



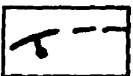
Strike and dip of cleavage



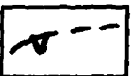
Strike and dip of joints



Vertical joints



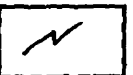
Fault; dashed where approximately located, ball and bar on downthrown side



Thrust fault; dashed where approximately located, teeth on overriding plate



Oyster Bed in Coberly Formation (Kc)



Schematic Folds in Jens Formation, on cross-section A-A' only