Geology of the Swift Reservoir area Sawtooth Range Montana

Alex T. Feucht

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Geology of the Swift Reservoir Area
Sawtooth Range, Montana

by

Alex T. Feucht
B. S., University of Wisconsin, 1965

Presented in partial fulfillment of the requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1971

Approved by: [Signature]
Chairman, Board of Examiners

Date June 28, 1971
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ABSTRACT

A 25 square mile mapped area around Swift Reservoir along the eastern front of the Sawtooth Range of northwestern Montana is underlain by a Cambrian to Upper Cretaceous sedimentary section of 5000 feet of dominantly Paleozoic carbonates and Mesozoic clastics. Quaternary deposits indicate active erosion in recent times.

The strata of the area are tightly folded and thrust-faulted in imbricate fashion with the style of deformation, dependent most upon the ductility contrast of the rocks involved. A structural analysis of the area indicates a single deformation and an inferred orientation of $\sigma_1$ at $60^\circ/0^\circ$, and $\sigma_2$ at $330^\circ/0^\circ$, fitting well into the regional picture for the northern westerly curving part of a north-south trending thrust salient, as described by Mudge (1970).
ACKNOWLEDGEMENTS

Special thanks go to Dr. G. W. Crosby, who as thesis advisor, suggested and spent considerable time advising and assisting with this project; to Dr. J. A. Peterson, who provided helpful suggestions concerning various aspects of the project; to Dr. D. L. Winston for suggestions concerning Paleozoic stratigraphy, fossil identification and correlations; to Dr. W. A. Cobban of the U. S. Geological Survey for helping to straighten out various problems related to Mesozoic stratigraphy and to the many graduate students of the Geology Department here at Missoula who provided numerous suggestions.

Many thanks go to the fine people of the Blackfeet Reservation, Dupuyer, Montana, and the Swift Reservoir vicinity for allowing access to private lands and providing an unbeatable hospitality that made the stay in the region both pleasant and memorable.

I am especially grateful to the Society of Sigma Xi for financial aid in the form of a grant and to the Montana Water Resources Board for grant No. 215 for funds which aided in making this project a reality.
CHAPTER I

INTRODUCTION

Northwestern Montana is within the eastern portion of the north-northwest trending Northern Cordillera consisting of the Main Ranges (Mission and Swan Ranges) to the west, Front Ranges (Sawtooth and Lewis and Clark Ranges) in the central part and Foothills to the east (Mudge, 1970, p. 378). The Sawtooth Range of Montana is an arcuate north to north-northwest trending imbricate thrust faulted salient composed of Precambrian to Tertiary strata in the Front Range subdivision. It extends 85 miles from the Dearborn River, southwest of Augusta, Montana, north to Marias Pass on the southern boundary of Glacier National Park. Paralleling the Sawtooth Range to the east is a 5 to 20 mile wide zone of open to tight folds and imbricate thrusts in Mesozoic strata which becomes flat and undeformed eastward. This zone, sometimes referred to as the Disturbed Belt, has been labeled the Foothills subdivision by Mudge (1970, p. 378). According to his definition, the Disturbed Belt includes the Front Ranges and the Foothills; Mudge's usage will be followed in this paper.

Mudge (1970, p. 377-379) states that the Disturbed Belt deformation occurred dominantly during Paleocene through late Eocene, during which time 45,000 feet of continuous uplift of the miogeosyncline to the west caused gravity gliding along a decollement which migrated upsection to the east. In the Canadian Rocky Mountains, Price and Mountjoy (1970, p. 23) emphasize earlier development but essentially agree with Mudge.
"The Main Ranges and perhaps the western Front Ranges structures emerged as an active zone of thrusting in the Late Jurassic and Early Cretaceous, and the Front Ranges in the Late Cretaceous."

Crystalline rocks are not involved in the gravity gliding. In the Sun River area Mudge recognized five compressional episodes which he interpreted as being successively younger from east to west.

The first significant work undertaken in the region of the Sawtooth Range was by Stebinger, between 1911 and 1918 covering stratigraphy, structure, and oil and gas geology. Deiss (1933, 1935, 1936, 1939 and 1943) mapped parts of the Sawtooth and Lewis and Clark Ranges and published several papers on Cambrian stratigraphy and trilobite faunas. Clapp (1932) published a geologic map of northwestern Montana at a scale of 1:500,000.

Cobban (1945) reported a study of the marine Jurassic of northwestern Montana wherein he measured a section of 472 feet of the Ellis Group from within the area mapped for this project. The top 134 feet was designated as the type section of the Swift Formation. Sloss and Laird (1945 and 1947) published studies of the Devonian and Mississippian rocks of northwestern Montana. Since 1959, Mudge, with others, has published seven geologic quadrangles and several papers from the Sun River area. Cobban (1945, 1950, 1951, 1955 and 1959), Weimer (1955), Imlay (1948) and Erdmann (1939 and 1959) have completed several studies singly and as coauthors of the Mesozoic strata of northwestern Montana. Several mapping projects were completed in the Blackleaf Canyon area as Washington State University unpublished Masters theses, namely Ore (1959), Hansen (1962) and Osborne (1963).

The present study covers a 25 square mile area along the eastern boundary of the Sawtooth Range, around Swift Reservoir, 17 miles west
Figure 1.

Index map

showing location of map area (shaded) in western Montana.
of Dupuyer, Montana (Fig. 1). Included within the area is 4 square miles of Foothills Mesozoic strata east of the mountain front. The study was planned as a surface geology mapping project to supplement a structural analysis.

Approximately 75 days of traversing was done in the summers of 1968 and 1969. An additional 15 to 20 days of reconnaissance study in areas ranging from Benchmark to Browning, Montana, was undertaken in an attempt to establish correlations. Mapping was on USDA aerial photos (1966) and Forest Service aerial photos (1957) both at a scale of approximately 1:20,000. A composite of four advance prints of USGS 7½ minute topographic quadrangles were enlarged to a scale of 1:12,000 and used as the base map. A large amount of the mapping was done by extending contacts and structures by photogeologic methods from field-checked stations along traverses. Photo data were transferred to the base map by inspection.

Figure 2. Swift Reservoir
Laboratory work included study of approximately 400 hand specimens collected during the traverses, including 120 specimens containing Cambrian trilobites. The trilobites were studied for correlation purposes.

Twenty-six thin sections were inspected to verify hand specimen descriptions (Appendix I). The oriented, less than 2 micron fraction of 6 Cambrian shale samples were run under CuK radiation on the X-ray diffractometer to establish clay content: 10 Å (illite) peaks dominated in all samples, 7 Å peaks (septachlorite; moderate boiling in 1 N HCl removed these peaks) were weak to strong in all but one pattern and no detectable expandable layers were recorded for any of the samples.

Data from field notes and measurements taken from the completed map were utilized in a supplementary structural analysis to infer kinematic and dynamic interpretations within the area.
CHAPTER II

STRATIGRAPHY

The severe deformation of this area complicates the recognition and correlation of the stratigraphic section. Only the Ellis Group formations have been previously studied (Cobban, 1945) in the Swift Reservoir area. Several outside areas were reconnaissanced to establish familiarity with stratigraphic units. Initially, mapping was done using unnamed lithologies, with names applied later. Out of sequence, stratigraphic units were often difficult to distinguish; for example, platy members of the Devonian and Mississippian carbonates and the brown micritic formations within the Cambrian.

About 400 hand specimens were collected for more detailed study and possible later identification. The 26 thin sections that were studied appear in Appendix I which contains detailed descriptions that supplement the descriptions in the following section.

CAMBRIAN

The oldest strata observed in the area are Cambrian. They are exposed over approximately half of the total area in disharmonically folded slices.

A partially successful attempt was made to correlate the Cambrian strata of this area with Deiss' (1939) sections to the south. The largest continuous section of Cambrian found in the Swift Reservoir area includes 131 feet of Devils Glen Dolomite and 52 feet of Switchback Shale. A 134-foot section of limy shale below the Steamboat
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Limestone on Hungry Man Creek was measured in detail for possible trilobite correlations with Deiss' sections. This shale unit is herein referred to as Pentagon Shale. Extrapolation of a thickening northward (Deiss, 1939, p. 42-43) from Cliff Mountain to Pentagon Mountain of shale at the expense of limestone in the lower part of the Steamboat Limestone and the upper part of the Pagoda Limestone is one of the bases for this identification. Other lines of evidence suggesting that this shale is Pentagon Shale include an inferred Steamboat Limestone thickness of about 100 feet compared to 216 feet measured by Deiss (1939, p. 45) at Pentagon Mountain and affinities of the trilobites found in the Swift Reservoir area.

Strata older than Pentagon Shale are possibly present in the Swift Reservoir area, but due to the lack of fossils, probable facies changes from nearest previously described sections and lack of sequential sections prevent positive identification. Because of similarity of the Gordon Shale to the lower half of the Switchback Shale, and similarity of the brown micritic limestones of the Damnation, Dearborn and Pagoda limestones to the Steamboat Limestone, these units, if present are mapped as Cambrian undifferentiated.

Pentagon Shale

The Pentagon Shale, where measured, rests upon 10 feet of thinly bedded brown micritic limestone which could be interpreted as the top of the Pagoda Limestone or as part of the Pentagon Shale. This unit is thrust upon Steamboat Limestone. Above this basal limestone, are inter-bedded layers ranging in thickness from several inches to as much as 20 feet of the following lithologies: (1) fissile and
sometimes limonite stained, olive drab to green and occasionally violet
weathering waxy shales, (2) olive drab, fissile waxy shales with from
20% to 50%, ½ inch to 1 inch thick grayish-green limestone lentils
with abundance of trilobite fragments and occasional inarticulate
brachiopod shells, and (3) thin to medium bedded, yellow to orange
weathering silty limestone often containing layers of intra-formational
conglomerate.

Trilobites from the upper half of this unit resemble species of
Deiss' Steamboat Limestone faunas (Kochaspis aff. Walcott and Deiss)
whereas those from the lower half have affinities to those in the
The total thickness of this unit is estimated at several hundred feet
although the writer has not seen sections thicker than the 134 feet
referred to above. The basis for a greater thickness estimate is the
northward extrapolation from Deiss' sections and the probable fact that
much of this shaly unit is missing along Birch Creek because of its
forming the most prominent decollement surface within the Cambrian
strata. Where differentiated, all of the interbedded trilobite-bearing
limestone and green fissile shale below the Steamboat Limestone is here
called Pentagon Shale.

Steamboat Limestone

The most common Cambrian rocks found in outcrop are dark brown
and grayish brown, fine-grained and micritic flaggy and chunky, grayish
weathering limestones containing irregular tan and buff silt lenses.
Lithologies of this type are typically called Meagher to the east;
however, in the Sawtooth Range Deiss' Damnation, Dearborn, Pagoda and
Steamboat Limestones have this lithology. After observing all four of these formations in an unbroken sequence at Pentagon Mountain it was concluded that without fossils and continuous sections individual formations could not be satisfactorily identified. The Steamboat Limestone can be identified with some assurance, and a distinct marker bed used for this correlation was found near the top of the unit in Deiss' Ford-Straight Creek section forty miles to the south. This marker was used only for positive correlation; where not found, the rocks are mapped as C, whether Damnation, Dearborn, Pagoda or Steamboat.

By far the most frequently identified Cambrian unit is the Steamboat Limestone which does not crop out in its entirety but is estimated from photo and field calculations to be approximately 100 feet thick in this area.

Switchback Shale

Above the Steamboat Limestone is the Switchback Shale which has deformed to fill up the irregular space between the Steamboat Limestone and Devils Glen Dolomite in disharmonic folds. The Switchback Shale is usually expressed as covered areas between anticlines in which Steamboat Limestone occupies the core. The shale imparts a yellow color to the soil. The 52 feet of measured Switchback consists of interbedded, finely-laminated yellow weathering four to twelve inch layers of light green silty dolomite, and waxy shale with three to six inch long lentils of limestone. Pencil structures are commonly developed in the calcareous shales. Except for the conspicuous lack
of trilobite fragments, the lithology is exactly like the major lithology found in the Pentagon Shale.

The bottom part of the Switchback is covered by flood plain gravels below the measured section. Interpolating from the top of the Steamboat to the bottom of the measured section, with one outcrop in the middle of the stream, gives 180 feet of waxy, predominantly maroon, finely fissile shales. A total thickness of 235 feet seems too large for the Switchback Shale, since this type of lithology is invariably deformed by continuous isoclinal folds and shearing where observed in large outcrops. Estimates based on amount of thinning and thickening at various exposures suggest approximately 100 feet for the thickness of this formation.

Devils Glen Dolomite

A basal conglomerate, 6 to 40 inches thick, of either glauconitic dolomite or pyritic, subrounded, Middle Cambrian pebbles marks the base of the Devils Glen Dolomite. Except for trilobite and inarticulate brachiopod fragments within pebbles of the basal conglomerate, the Devils Glen Dolomite is devoid of fossils. A measured thickness of 130 feet of thin- to thick-bedded, fine and medium grained, white to light gray dolomite make up the dominant lithology of this unit. Although seemingly competent, this formation seldom forms prominent cliffs; it tends to lay below talus at the base of large slopes of Devonian limestones and dolomites. While not substantiated by measured sections, field estimates indicate that the Devils Glen varies considerably in thickness. It is probably less than 100 feet thick near the mouth of Hungry Man Creek.
DEVONIAN

Wilson (1955, p. 76-77), in a study of Devonian rocks of northwestern Montana, published a section from Featherwoman Mountain, four miles northwest of this mapped area. Wilson's 800 feet of Devonian is assumed for this report. Detailed stratigraphic studies would have been required to confidently subdivide the Devonian into formations, and the repetitive lithologies and intra-system thrusts further hinder subdivision of Devonian strata. Consequently, the Devonian rocks were mapped as a single undifferentiated unit.

The Devonian strata lie disconformably on the Devils Glen Dolomite with (1) a 6 inch weathered layer of olive brown shale and (2) a 1\(\frac{1}{2}\) foot layer of \(\frac{1}{4}\) inch thick lentils of brown limestone within olive gray shale partings marking the base at the two localities where the contact was observed. Above the basal layer is up to 20 feet of brown limestone with occasional olive gray shale partings and thin intraformational breccia and brachiopod and crinoid fragmental layers. Conspicuous ovoid cavities up to 4 feet long and 1 foot high typically weather out of this unit.

Solution breccias, massive vuggy sucrosic dolomites, and thinner bedded, platy yellowish gray weathering, light gray to brownish silty limestone with occasional brachiopod fragments and crinoid stems are typically found in the Devonian of this area. A thick layer of solution breccia, below the limestones of the Allan Mountain Formation in NW\(\frac{1}{4}\), SE\(\frac{1}{4}\), Sec. 4, T2N, R10W is probably equivalent to the Potlach Evaporite or Stettler Formation as referred to by Wilson (1955, p. 75).
MISSISSIPPIAN

Mudge and others (1962) measured several sections of Mississippian Madison Group limestones and dolomites in the Sun River area, 30 miles south of Swift Reservoir. These workers divided the Madison Group into the lower Allan Mountain Limestone and the upper Castle Reef Dolomite, based on lithologic differences and modal analyses. Mudge's sequences are recognizable in the Birch Creek area and therefore are used in this report. Although a complete section of neither of these formations is exposed, a rough estimate of 1300 feet of Madison Group is assumed from composites in thrust slices and sections measured by others (Mudge and others, 1962, p. 2008; Hansen, 1960, p. 31; Northern Nat. Gas, No. 1 Blackleaf-Federal "A" in Sec. 13, T26N, R10W).

Allan Mountain Limestone

The lower part of the Allan Mountain Limestone consists of thin platy, buff, light gray and light brown weathering, dark brown argillaceous limestone. This lithology grades upward to thicker bedded brown and gray brown limestones with increasing amounts of olive drab weathering 4 to 10 inch blackish chert nodules.

The base of the Allan Mountain is not exposed in the area, but a covered area between carbonate breccia and its lowest exposure could represent the base of the Allan Mountain. If this is the case, the thickness of the exposure is approximately 200 feet. Because of a questionable formation boundary between the Allan Mountain and the overlying Castle Reef Dolomite and thrusting of Cambrian strata upon this unit, the writer does not believe that this is the complete
section of Allan Mountain. A thickness of about 400 feet would better fit the regional picture.

Castle Reef Dolomite

The Castle Reef Dolomite consists of white to light gray limestone and dolomite with varying amounts of irregular lenses of buff weathering, dark gray to black chert and crinoidal hash. The upper part of the Castle Reef has locally abundant silicified Syringopora-like corals, spirifers, fenestrate bryozoans and horn corals and often contains both calcite and quartz geoids of approximately one inch diameter.

JURASSIC
Ellis Group

The marine Jurassic of northwestern Montana was designated the Ellis Group by Cobban (1945, p. 1262) and divided into the Sawtooth, Reirdon and Swift formations. A 472 foot, composite Ellis Group section along the east and north shores of Swift Reservoir was reported by Cobban (1945, p. 1293-1295) and the top 134 feet was designated as the type section of the Swift Formation.

Sawtooth Formation

The Sawtooth Formation lies disconformably on the Castle Reef Dolomite with the contact not exposed. It consists of thin and medium bedded olive drab, buff, tan and gray, fine grained sandstones, siltstones and shales. Waterworn belemmites and phosphatic pebbles and
pellets are common in the sandy and shaly lower members and *Gryphaea* fragments are common in the upper calcareous gray siltstone member. Cobban measured 198 feet of Sawtooth Formation.

**Reirdon Formation**

Cobban measured 140 feet of Reirdon Formation in SW 1/4, Sec. 26, T28N, R10W east of Swift Reservoir. The interbedded light, olive buff, 4 to 10 inch layered calcareous shales and olive drab fissile shales contain abundant *Gryphaea* fragments and occasional *Inoceramus* casts and impressions.

**Swift Formation**

The base of the type section of the Swift Formation consists of a six-inch layer of fine-grained, glauconitic sandstone. Fifty-four feet of greenish gray, finely micaceous, well consolidated shales and siltstones containing rusty, calcareous concretions occur above the basal unit and make up the lower shale member. Gray sandstone in thin to thick flaggy beds, containing micaceous shale partings, stained with rust, form the upper member of the Swift Formation.

In this report, the Ellis Group is mapped as undifferentiated except where formational contacts are easily traced.

**UPPER JURASSIC-LOWER CRETACEOUS**

**Morrison Formation**

Tight folding, thrust faulting and generally poor exposure of the Morrison Formation preclude good stratigraphic control for
differentiating the Morrison and Kootenai Formations. East of the reservoir, in SW ¹, Sec. 23, T28N, R10W the Morrison occurs as a partially covered area containing approximately 40 feet of section above the gray limonitic sandstone member of the Swift Formation. The top of the formation is not exposed at this locality but is found beneath a thrust slice of the Sunburst Member of the Kootenai Formation to the east. A composite of the two exposures is thought to represent the total thickness of Morrison at Swift Reservoir. A 10 foot thick layer of massive greenish tan siltstone (Manganese oxide stained), is found about 15 feet above the base of this unit. The top 30 feet of Morrison consists of variegated shales which are dominantly black and carbonaceous but contain several yellow layers and some green, violet and maroon shales.

W. A. Cobban (personal communication) reports about 40 feet of Morrison light olive green mudstones, siltstones and sandstones below the basal conglomerate of the Kootenai Formation in the Marias Pass area. Along Blacktail Creek in NW ², T29N, R8W, a well core examined by Cobban revealed no Morrison. To the south, in the Blackleaf Canyon area Osborne (1963, p. 40) reports 37 feet of Morrison. In the Sun River area, Mudge (1959, p. 20) has measured 195 feet of Morrison.

Kootenai Formation

Between the two segments of the composite section of the Morrison is 65 feet of outcropping, fairly clean, buff weathering, 5 to 15 foot thick lenses of crossbedded, fine- to coarse-grained sandstone with rounded red, green, gray and black chert pebbles scattered throughout. The basal lenticular sandstone has a coarse-grained sandstone frequently
containing rounded chert particles of granule to cobble size at its contact with the top of the Morrison. Interbedded with the sandstone lenses are equally thick greenish olive drab shale and siltstone layers with red and black, rounded chert granules and small pebbles. About 20 feet from the top of this unit, thought to be equivalent to the Sunburst Member of the Kootenai, is a gradational lens of ripple cross-bedded, green and tan fine-grained sandstone. The sandstone lenses have impressions of "worm" trails at the base and erosional surfaces at the top.

At an indeterminate distance above this sequence are found cream-weathering, dark brown micrites in layers from 1 to 10 inches thick. These beds are probably equivalent to a 40 foot limestone sequence found by Childers (1963, p. 154) in the Marias Pass area. No fossils were recognized by this writer in this unit, which probably has a total thickness of about 30 feet.

The thickness of the rest of the Kootenai was not determinable because of structural complications. It consists of several hundred feet of interbedded, polymictic (Appendix I, No. 091605), maroon and olive to bright green shale, siltstone and fine to coarse grained, sandstone with occasional layers of chocolate brown weathering limestone beds and layers of limestone nodules. The top of the Kootenai is marked by about 10 feet of unusually clean, two to six inch flaggy beds of quartz sandstone.

Blackleaf Formation

In NE₁, Sec. 23, T28N, R10W and NE₁, Sec. 16, T28N, R10W a small sequence of Blackleaf lithologies is recognized. The Flood
Member is represented by about 120 feet of partially covered, interbedded, brownish gray sandstones and gray shales. A gray flaggy siltstone with abundant "worm" trails marks the base of the Flood Member. Approximately 150 feet of Taft Hill Member occurs as thin, platy, crossbedded, calcareous, grayish tan sandstone with abundant fragments of Ostrea anomoides Meek. The Vaughan Bentonitic and Bootlegger members were not found in the area.

UPPER CRETACEOUS

Marias River Shale

An extensive covered area (most of NE 1/4 of Sec. 23 and E 1/2 of Sec. 14, of T28N, R10W) has a single outcrop of limonite-stained, fissile, calcareous black shale with a few 6 inch contorted beds of yellow weathering limestone as lenses and nodules. Sandy beds crop out toward the top of this exposure. Lag material indicates that this whole area is probably repeated thrust slices and tight folds of the Kevin Member of the Marias River Shale. A similar situation occurs for five miles of nearly continuous exposure along Two Medicine Creek east of East Glacier, Montana.

Faulting has eliminated a large portion of the Upper Cretaceous section from surface exposure in this area. The Telegraph Creek, Virgelle, Two Medicine and St. Mary River formations are found to the east but not in the Foothills mapped for this report.

Horsethief Sandstone

In the northeast corner of the mapped area a fault exposes about 100 feet of ridge-forming, lenticular sandstone identified as the
Horsethief Sandstone. The unit contains large brown limestone concreations and abundant carbonized wood fragments and "worm" trails.

QUATERNARY

Pleistocene

Fairly thin glacial moraines of probable piedmont glacial origin extend from within a mile east of the mountain front and continue for several miles to the east. Lateral, recessional and terminal moraines were not recognized in the mapped area. However, topographic maps, aerial photos and observations from light aircraft reveal arcuate patterns tens of miles north and several miles east of the mapped area that suggest terminal and recessional moraines produced by glaciers moving eastward from the mountain front. Kettle lakes are numerous west of the terminal moraines. Within a mile east of the mountain front and in the Sawtooth Range to the west, glacial deposits have essentially been removed by erosion or covered by post-Pleistocene deposition. Hanging cirque valleys exist on the highest mountains and contain poorly sorted debris with abundant angular boulders.

Holocene

Forest and fresh talus lie below most of the prominent ridges. Occasional areas of huge unoriented blocks suggest rockslide rather than rockfall deposition for some of these debris piles. Arcuate and lobate fronts extending from talus slopes and ridges (SW^1/4, Sec. 15, and NW^1/4, Sec. 22 of T28N, R10W) as fresh and forested, hummocky surfaced areas, suggest avalanching as described by Mudge (1965) for the Sawtooth Ridge area.
Extensive areas of tilted aligned conifers in areas of thick soil indicate active slumping in recent times. Evidence of soil creep can be found on most steep slopes with a soil cover.

Tufa deposits are forming where springs issue from solution channels in the Paleozoic carbonates.

Loess deposits are presently forming just east of the mountain front. Evidence is particularly noticeable in Spring, northeast of the dam, where the last melting snow is covered by a quarter inch or more of brown mud and silt. Accumulative drifts of dust or silt up to 20 feet thick underlie some of the quaking aspen groves directly in front of the reservoir. Blowouts above the reservoir support this hypothesis.

Kettle lakes and beaver ponds are presently receiving deposits of mud and silt. When white men first arrived in this area, beaver dams impounded large areas east of the mountain front (local traditional history). The silts trapped by these ponds, which make some of the most fertile soils in the region, cover some of the eastern part of the mapped area.

Recent fluvial deposits cover the bottoms of stream valleys with rounded, stratified and unstratified, silt to boulder sized debris. Below Swift Reservoir, Birch Creek alluvium, 3/4 mile wide and tens of feet thick, was freshly deposited on June 8, 1964, when the dam burst. The North, Middle and South Forks of Birch Creek, Haywood, Hungry Man, Killem Horse, Blind, Phillips, Tubby and several intermittent drainages contain spectacular examples of rapid deposition related to this flood. Stratified terraces up to 30 feet thick, some partially dissected, certainly must have formed in a matter of hours--days at the most. The reshaping effect of the flood was great enough to warrant using post-flood aerial photos even though the pre-flood set showed better contrast.
CHAPTER III
STRUCTURAL ANALYSIS

STRUCTURAL STYLE

To avoid confusion in terminology the folded structures developed in the Swift Reservoir area will be discussed within the framework of the Donath and Parker fold classification (1964, p. 45-62).

The severity of deformation, anisotropy of the involved strata, and less than desired stratigraphic control have complicated the mapping of this area. The deformation has, nevertheless, produced a distinct structural geometry that expresses the tectonic events.

A two mile wide strip of tightly folded and thrust faulted Cambrian strata underlies the central part of the mapped area. Identified strata include the Pentagon Shale through Devils Glen Dolomite representing possibly the entire Cambrian section in the area. Thrust surfaces invariably occur near the top of the Pentagon Shale and erosion exposes the Steamboat Limestone in at least 70% of the Cambrian outcrops.

The variable competence between the 100 foot thick interlayered shales and limestones produce unmistakable quasi-flexural folding at the interformational scale (Plate 2, Fig. 2). The Pentagon and Switchback shales in the main, passively adjusted to the changing configuration of the Steamboat Limestone during the folding process (Plate 2, Figs. 2 & 3). Locally, in a restricted thickness of the section, passive flow was observed in shales. Medium-bedded limestone layers within these shale sequences were especially adapted to quasi-flexural
deformation (Plate 2, Fig. 4). The Steamboat Limestone was observed most often as overturned anticlines with amplitude to wavelength ratios of 1:1 to 5:1 (Plate 3, Fig. 1; Plate 4, Figs. 1 & 7) and wavelengths varied from 100 to 1000 feet where folding was at the interformational scale. Fold intensity varied from opened to isoclinal with about equal occurrence of flexural slip and flexural flow (Plate 3, Figs. 1, 2 & 3). The massive Devils Glen Dolomite, although seldom exposed, deformed differently depending on whether it was involved in the intense deformation with the Steamboat Limestone (Plate 2, Fig. 2) or rode along with the above Devonian limestones (southeast of Mount Sentinel).

The platy limestones and dolomites in the lower two thirds of the Devonian section deformed ductile within repeated thrust slices. The plasticity is expressed as isoclinal folds with amplitudes generally about ten times as great as the wavelengths (Plate 4, Fig. 1). The more massive carbonates toward the top of the Devonian overrode the platy units.

The platy Allan Mountain Limestone deformed plastically wherever the massive Castle Reef Dolomite broke away and overrode it. As in the Devonian platy limestones and dolomites, tight folds are common. Where part of the Allan Mountain rode with the main thrust sheet, it folded recumbently and the lower limb acted as the upper glide surface. Several hundred feet of this argillaceous limestone can be seen on the north cliff of Mount Richmond, extending for a mile or more at the base of a thrust plate consisting mostly of Castle Reef Dolomite.

The massive Castle Reef Dolomite is in a fold style that is generally more open, and on a larger scale. Thrust zones occasionally
exhibit drag folds ranging from mild undulations to overturned closed folds, but the most impressive folds are overturned anticlines at the leading edge of the largest of the thrusts in the area (Plate 4, Fig. 2). Surprisingly, thrusts within this massive unit are seldom associated with extensive deformed zones. A prominent thrust revealed in a fresh cut is expressed as a four inch gouge layer with no pervasive deformation in the overlying or underlying beds. Although subparallel to bedding, this particular fault seemed little controlled by bedding. Such faults, quite easily missed in the field (and many undoubtedly were), are best detected by noting truncation of beds revealed on aerial photos. Caution in applying this criterion must be exercised, however, inasmuch as biostrome structures tend to produce a similar impression on the photos. As elsewhere in the Sawtooth Range, this formation is the most prominent ridge former by virtue of its massiveness and relative homogeneity.

The soft sediments of the Ellis Group rode on top of the underlying Castle Reef Dolomite during thrust movements, and conform passively to the structures of that unit (Plate 4, Fig. 3). Bedding surfaces and axial surface cleavage combine to form pencil structures where the underlying Castle Reef has been folded. The overall effect is passive flow with thinning and thickening of the Ellis taking up space as created by the more competent layers. The sandy member of the Swift Formation, in places, deforms in a more brittle manner exhibiting low angle thrust faults and even high angle shear parallel to axial planes and conjugate fractures. When subjected to stresses imposed by an overriding thrust plate this member deformed in a manner similar to that developed in the Morrison, Kootenai and Blackleaf formations.
The variable competence of the shales, siltstones, sandstones, and occasional limestones of the Morrison, Kootenai, and Blackleaf formations lend well to tight quasi-flexural folding when under the stress of overriding thrust plates. Near the base of large thrusts tightly spaced axial plane shears parallel the main thrust fault. Farther from the thrust quasi-flexural deformation is typified by open asymmetrical to isoclinal overturned and recumbent folds, as in NW 1/4, Sec. 15, T28N, R10W. Still farther from the mountain front, one mile to the east, flexural slip becomes the dominant deformational mechanism with shale layers acting as slip surfaces for low angle, bedding plane thrusts which seldom cut across the stratification.

The soft black shales of the Marias River Formation are highly contorted in two small outcrops. Because of the excessive width of the area underlain by these shales, it is presumed that closely spaced imbricate thrusts and isoclinal folds characterize this unit, as is the case in a five mile wide area along Two Medicine Creek to the north.

Isoclinal folds with wavelengths of about 500 feet and amplitudes about twice as great is the structural style in the small exposures of Horsethief Sandstone in the northeast corner of the mapped area.

STRUCTURAL GEOMETRY

As an aid to a structural analysis the following orientation data were plotted in equal area stereographic projection and rose diagrams:

- $S_1$ - stratification
- $S_2$ - thrust faults
- $L_1$ - fold axes
- $L_2$ - axial traces measured from the completed map
The poles of $12^44$ $S_1$ data were plotted and contoured on density per $1\%$ area (Plate 1, Fig. $S_1$). The pole to the great circle in figure $S_1$ is $326^\circ/0^\circ$. Maximum concentration in the girdle is $56^\circ/49^\circ$ indicating a statistical preference for stratification orientations at $326^\circ/49^\circ$ SW.

Attitudes of thrust fault surfaces were calculated by solving from three-point problems from map elevations along traces. Calculations were extended back from the thrust fronts in an attempt to reduce the upturning effects caused by toeing at the front edge of the imbricate thrusts. Only 15 values were determined. The stereogram (Plate 1, Fig. $S_2$) for $S_2$'s shows a point maximum at $63^\circ/18^\circ$. Elongation of the $S_2$ distribution, although weak, suggests a girdle for which the pole is $333^\circ/0^\circ$.

Thirty-five fold axes were plotted and contoured in figure $L_1$ at $3^\%$ per $1\%$ area intervals (Plate 1) indicating a point maximum at $150^\circ/12^\circ$. Azimuths of 1000 foot segments of axial traces were measured from the finished map and plotted as a rose diagram (Plate 1, Fig. $L_2$) in 10 degree petals. An $L_2$ point maximum occurs at $329^\circ$ based on 600 data.
CHAPTER IV
DISCUSSION AND INTERPRETATION

Thrusts normally place older strata upon younger, but exceptions occur where the opposite relationship is true: the latter are thought to be thrusts of minor displacement. Where truncation of thrust faults is apparent, the thrust fault to the west truncated the one to the east; for example, in SE$\frac{1}{4}$, NW$\frac{3}{4}$, Sec. 27, T28N, R10W, a thrust plate of Castle Reef Dolomite is truncated by a thrust plate of Cambrian above; and, above that in SW$\frac{3}{4}$, NE$\frac{1}{4}$, Sec. 27, T28N, R10W, an upper thrust plate of Cambrian truncates another of Cambrian below and to the east. Thus, apparent migration of thrusting was from east to west.

Where shaly beds are associated with thrust faults possibly as layers with high fluid pressure-overburden ratio associated with gravitational gliding (Judge, 1970, p. 375), they are found most often in the plate above the fault surface. This relationship is apparent in NW$\frac{1}{4}$, Sec. 31, T28N, R10W, where shaly Allan Mountain Limestone stratigraphically underlies massive Castle Reef Dolomite, overrides another plate with Castle Reef Dolomite at the top. Thrust faults without associated shaly beds have Thin zones of breccia or gouge between the upper and lower thrust plates.

From the four types of orientation data presented above, an ideal model is herein attempted in order to relate structural patterns to movements, strain and inferred stress directions. An empirical scheme, based on accuracy and reliability of measurements, was used to calculate average stress direction. Weighting factors of 5, 4, 5, and 3 were used for each data of $S_1$, $S_2$, $L_1$ and $L_2$, respectively (Crosby, 1969,
An average of $327^\circ/0^\circ$ was derived for the intermediate principal stress direction ($\sigma_2$). No attempt was made to reconcile the $12^\circ$ southeasterly plunge of the $L_1$'s since many fold axes also plunge to the northwest and a greater number of data might have balanced the distribution.

With only the intermediate principal stress direction, $\sigma_2$, established there remains the problem of determining $\sigma_1$ and $\sigma_3$. The intersection of the plane containing $\sigma_1$ and $\sigma_3$ with the horizontal will be referred to as $\sigma_{1\prime}$, and is considered coincident with the horizontal mean movement direction (Fig. 3). Therefore $\sigma_3$, is vertical.

![Figure 3](image)

Inferred stress directions
Maximum $S_1$ and $S_2$ orientations suggest possible relationships to the deforming mechanism. Several considerations must be accounted for to resolve $\sigma_1$ and $\sigma_2$ at the time of deformation. The majority of $S_1$'s were measured in Cambrian strata which deformed by quasi-flexural folding at the interformational scale. The Steamboat Limestone, which was exposed most often, deformed flexurally and formed overturned anticlines with the backlimb dipping at approximately 65°. That the 49° southwesterly dip of $S_1$ in figure 3 represents the most commonly exposed orientation is verified by observation. The main drainages in the area flow eastward, transverse to the structural trend. Secondary drainages parallel the structural trend in most cases but the overall pattern is not distinctly trellis. Backlimbs of anticlines, which often occur as dip slopes, are better exposed than forelimbs. Thus, the drainage pattern of the area strongly influences the location of the point maximum of $S_1$'s in figure $S_1$ of Plate 1.

Many of the $S_1$'s measured in the area were in massive bedded units that deformed in a brittle manner. Ideally, brittle deformation should produce thrusts at 30° to $\sigma_1$. Step-bedding-plane thrusts (Badgley, 1965, p. 189; Childers, 1963, p. 161; Mudge, 1970, p. 382), an effect of anisotropy and local reorientation of stress, reduce the statistical average of this ideal angle. Back-limb thrusting (Badgley, 1965, p. 189; Mudge, 1970, p. 382), common near the leading edge of thrust salients, would act to increase the average dip angle of the thrust surfaces. A maximum tilt of 8.5° to the east, calculated by Mudge (1970, p. 377) as the cause of gravitational gliding; and possible post-thrusting tilt in the opposite direction (Crosby, 1968, p. 2013) would further complicate determination of geometric-dynamic relationships.
Thus, it is concluded that true orientation in space of $\sigma_1$ and $\sigma_3$ at the time of deformation, even with the assumption of ideal conditions, cannot be closely determined with the available information.

The problem of $\sigma_1$ orientation can more easily be approached at the regional scale. Assuming a miogeosyncline to the west, original oceanward dip of sediments, a maximum of 8.5° of eastward tilt during thrusting and primary decollements along the basement contact and bedding planes, strongly suggest an initial regional $\sigma_1$ near horizontal. This regional $\sigma_1$ essentially fits the model proposed by Price and Mountjoy (1970, p. 18) where gravitational gliding, as such, is not alluded to as the mechanism of thrusting. Maximum regional shortening is obviously coincident with this orientation of regional maximum principal stress.

Hubbert (1951, p. 367-371) applied Newtonian laws of motion (for more rigorous derivation see Hafner, 1951, p. 373-398) to a horizontally stressed block (Fig. 4) to account for asymmetrical folds and concave upward reverse faults in thrust zones. Frictional forces cause the $\sigma_1$-trajectories to diverge downward. The conjugate shear set is likewise diverged downward to the right, as for example in figure 4. Selective faulting along the concave upward shear surfaces produces the pattern typical of thrust zones.

Figure 4. Divergence of stress trajectories and potential shear directions. Folds drawn in to correspond to local stress orientations. Adapted from Hubbert (1951, p. 370).
Field evidence, except in the case of break thrusts as described by Badgley (1965, p. 195) at the front of some thrust slices, indicates that folds had not been cut or reoriented by later thrusting. Folded thrust surfaces were not observed. Folding and faulting probably occurred simultaneously with axial surfaces of folds primarily oriented perpendicular to regional \( \sigma_1 \) (Fig. 4) but possibly locally reoriented by drag during faulting. Thus, the axial surfaces of folds are rotated more into parallelism with the fault surfaces.

A graphic example of the frictional effects on the orientation of axial surfaces is shown in figure 5. Figure 5 shows purposed directions of \( \sigma_1 \) related to axial traces of folds reoriented by drag from a major thrust fault. Extrapolation of the fault plane and axial plane orientations outside the area of the photo indicate that the frictional effects were more widespread in the Kootenai sandstone, siltstone and shale below the fault than in the Cambrian limestone and shale above. Possibly frictional stresses dissipated within a shorter distance in the thick soft waxy Cambrian shale than in the thinner, gritty Cretaceous shale.
Variation of deformatonal style in lithologically similar strata of the Morrison, Kootenai and Blackleaf formations as a function of distance from a major thrust fault has been noted above (p. 24). Immediately below the thrust fault (Fig. 5) shear fractures parallel to the fault surface and parallel to axial planes of small folds contain thin accumulations of sheared anthracite—indicating mobility.
and metamorphism of carbonaceous material. Lignitic material migrated out of the core of a closed fold between limbs of Kootenai sandstone. Farther from the thrust fault, in a zone approximately ½ mile wide, tight and disharmonic folds are dominant. Beyond this zone deformation is by flexural slip and small scale thrusting. Like with ductile faulting (Plate 2, Fig. 1, Donath and Parker, 1965, p. 48) strain is concentrated in a zone. However, the field example indicates gradual strain outward from the major thrust fault, whereas Donath and Parker's experimental cylinder does not. Conceivably, increased effective confining pressure near the fault increases the uniform flow field as suggested by Donath and Faill (1963, p. 103-104) and subsequently increases the apparent ductility toward the fault. An increase of effective confining pressure could be achieved by decreasing pore pressure (Handin, 1967, p. 287) which for figure 5 would be in direct disagreement with the requirement of high pore pressure for gravitational gliding.

Other considerations inherent with respect to the ductility problem would be: (1) heat dissipation outward from the fault zone, (2) change in porosity or permeability as a function of effective confining pressure, deformation, or distance from the fault, and (3) the effects on ductility change as a function of variation of temperature and pore pressure on percent of expandable clays in the Kootenai below the fault. From clay analyses done on several Cambrian shales it is assumed that no expandable clays exist above the fault. Possibly the existence of expandable montmorillonite in the Kootenai could explain the asymmetry of the σ1 distribution in figure 5; although, porosity, permeability, and composition could also be effective causes of the broader field of
divergence of $\sigma_1$ in the Kootenai than in the Cambrian. At any rate, a detailed and systematic analysis of the clays in the Kootenai below the fault could shed light on the ductility problem by revealing a temperature gradient, variation of water and pore pressure effects or deformational effects other than the apparent ductility variation.

In the Swift Reservoir area, ductility contrast within and between rock types is the dominant controlling factor of deformational style (Table II). The summary of styles in Table II seems to agree well with the mean ductility-ductility contrast scheme derived empirically by Donath and Parker (1964, p. 50).

![Diagram of ductility contrast](Image)

**Figure 6.** Types of folding related to mean ductility and ductility contrast. From Donath and Parker (1964).
Table II. Summary of types of folding and stratigraphic units within which each is found.

<table>
<thead>
<tr>
<th>Type of folding</th>
<th>Unit symbol</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural Slip</td>
<td>C</td>
<td>medium to thick bedded limestone, massive 100 ft. unit</td>
</tr>
<tr>
<td></td>
<td>Mc</td>
<td>medium to thick bedded limestone and dolomite, several hundred ft. thick and massive</td>
</tr>
<tr>
<td></td>
<td>Kk Kb</td>
<td>massive sandstone layers with shale and siltstone layers as slip surfaces, crossbedded and flaggy weathering</td>
</tr>
<tr>
<td>Flexural Flow</td>
<td>C</td>
<td>medium to thick bedded limestone, massive 100 ft. unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>medium and thick bedded limestone layers within shale units, rare</td>
</tr>
<tr>
<td>Passive Flow with possibly some Passive Slip</td>
<td>C</td>
<td>within waxy shales</td>
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<td></td>
<td>Du Ka</td>
<td>platy argillaceous limestone sequences several hundred ft. thick</td>
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<td></td>
<td>Je</td>
<td>thin to medium bedded, interbedded shale, siltstone and sandstone</td>
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<td></td>
<td>Kmr</td>
<td>within fissile shale</td>
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<td>Quasi-flexural</td>
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<td></td>
<td></td>
<td>within shale formations, thin and medium interbedded limestone and shale</td>
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<tr>
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<td>Kk</td>
<td>interbedded thick bedded sandstone and thin to medium bedded siltstone and shale; occurs in zone at given distance in front of major thrust fault</td>
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<tr>
<td></td>
<td>Kmr</td>
<td>1 ft. thick, rigid limestone layers in thicker sequences of shale</td>
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CHAPTER V
SUMMARY OF CONCLUSIONS

A statistical analysis of structural orientations indicates a nearly horizontal, regional maximum principal stress from the southwest (237°), probably in response to major uplift of the miogeosynclinal basin in western-most Montana (Mudge, 1970, p. 397).

The deformational style of the folded strata fit well into the mean ductility-ductility contrast scheme proposed by Donath and Parker (1964; Fig. 8 and Table II of this report).

Except in the case of break and stretch thrusts, field evidence, in the form of tilted axial surfaces associated with thrusts (Fig. 6) indicate to this writer that folding and faulting occurred contemporaneously as a fairly continuous creep process. If layers with abnormally high pore pressures were influential the effect was that of reducing normal stress and subsequently the shear stress needed for faulting. Had the normal stress been reduced to a great enough extent to produce a buoyancy as envisioned for a thin decollement layer then the re-orientation of stress directions indicated in figure 6 would not have been in as thick a zone. Thus, evidence of thin layers needed for gravitational gliding were not supported by field observation within this project area but might exist along major decollements at depth.

The meager evidence available from this project indicates east to west migration of thrusting as was also documented by Mudge (1970, p. 379) to the south; but this writer envisions these as minor back-limb imbrications as suggested by Jones in Badgley (1965, p. 237) and believes that migration of major regional thrusting was probably from
Plate 1

$S_1$
$D = 1244$

$S_2$
$D = 15$

$L_1$
$D = 35$

$L_2$
$D = 600$

$R = 100$
Plate 2

Figure 1. Ductile fault in limestone deformed to 20 per cent strain under 800 bars confining pressure. The specimen has not lost cohesion. From Donath and Parker; 1964, Plate 1, Figure 1.

Figure 2. Quasi-flexural folding at the interformational scale in Cambrian limestone and shale (NE1/4, Sec. 4, T28N, R10W). Both folds are overturned to the left.

Figure 3. Passive deformation in Switchback Shale. Thin limestone beds reveal strain-slip cleavage.

Figure 4. Quasi-flexural folding at two scales in Pentagon Shale.
Plate 3

Figure 1. Overturned folds in Cambrian limestone. The shales adjusted passively while the limestones deformed mainly by flexural-slip but also exhibit flow within layers.

Figure 2. Slip between flexed layers of Cambrian limestone.

Figure 3. Flexural flow and slip in Cambrian limestone.
Plate 4

Figure 1. Overturned high amplitude folds in Cambrian and Devonian beds.
Right Circle: Cambrian folds.
Left Circle: Devonian isoclinal folds.

Figure 2. Flexural slip in Mississippian Castle Reef Dolomite.

Figure 3. Four inch limestone layers reveal passive nature of deformation in marine Jurassic shale.
APPENDIX I

HAND SPECIMEN AND THIN SECTION DESCRIPTIONS

Abbreviations used in the descriptions are mainly from Mitchell and Maher, 1957. However, additional abbreviations were borrowed or devised and were found to be convenient. These are given below.

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Hydrochloric acid (0.1 N) treatment on carbonates.

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<tr>
<td>moderate</td>
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<tr>
<td>fast</td>
<td>fa</td>
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**Micrite**

- Micrite
- Micritic
- Millimeter
- Occasional
- Orientation
- Oriented
- Parallel
- Parallel to
- Pattern
- Perpendicular
- Perpendicular to
- Phosphatic
- Phosphorous
- Phosphorus
- Pink
- Pleochoric
- Presence of
- Present
- Random
- Recrystallization
- Recrystallized
- Rust, Rusty
Hand specimen descriptions are given in the left-hand column. Descriptions of thin sections cut from the hand specimen are in the right-hand column.
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<th>Thin section number</th>
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<td>SR - 30</td>
<td>Kh</td>
<td>?</td>
<td>Thin sect.</td>
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<td>Lt tn gy wthrd, m gr, m xbd, calc ss / elg sbrd to rd gr and mnr pnk gr. .30 cem wh and gey gy qtz: .05 = .10 blk skly gr. HCl: fa. Av gr sz: .15 mm.</td>
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<td>Taft Hill Kem.</td>
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<td>Kb</td>
<td>calc layer</td>
<td>.40 qtz, .15 calc, .20- .30 cht and mnr P mat and glau. Oyster shell frags / lam struc. .15 biocl calc. Mnr glau, hem / surr lam strn, sericitized chunks, strained biot, intstl magnetite and chlorite.</td>
</tr>
<tr>
<td>Lt brn gy wthrg, f gr calc ss / abnt p to fr srtd wh qtz gr. Oyster frags and calc cmt abnt. Av gr sz = .2 mm.</td>
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<tr>
<td>Specimen number</td>
<td>Thin section number</td>
<td>Map unit</td>
<td>Position in unit</td>
<td>Thin sect</td>
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<tr>
<td>091006</td>
<td>SR - 45</td>
<td>Kk</td>
<td>top</td>
<td></td>
</tr>
<tr>
<td></td>
<td>091605</td>
<td>Kk</td>
<td>up pt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>091605</td>
<td>Kk</td>
<td>up pt</td>
<td></td>
</tr>
</tbody>
</table>

**Hand speci**

*It olv brn, fr to mod srd, low por, f lam, ang ss / av gr sz = .3 mm. Lam as str of blk particles.*

**091605 SR - 28**

*Dk gn gy wthrd, dk bl gn gy, f to m gr, s & p ss. Gr col: .10 blk, .60 gy and .30 wh. HCl: sl. Av gr sz: .1 mm. Fr srtg. Pyr prsn.*

**091605 SR - 27**

*M gr, s & p ss / yel gn-gy hue. HCl: n Gr sz: .1 - .3 mm. Gr col: .05 - .10 blk, .03 bl gy, .10 dk gy, the rest is wh crm and clir. Fr srtd, sbang to sbrd ss / some pmk fld gr.*

**Position in unit**

*.80 qtz, .10 cht and mnr P rat. Sbang to sbrd, mod srted qtz and cht. .02 wthrd fld. Mnr pyr, plag, hem, lmn stn, P mat, magnetite and corundum xlz.*

**Map unit**

*Kk up pt*

*.60 cht (pos vol gl), .01 hem and .005 pyr. .115 chloraphite / mnr chlorite. .01 alt to scericite .01 musc. .015 plag (biax -). .005 auth clinzoizite. .10 strained qtz (biax / undulatory ext).*

**Map unit**

*Kk up pt*

*.50 qtz, .20 cht. Qtz: mod to w srd, ang but / hi spher. Av gr sz = .3 mm. Hax gr sz = .5 mm. Chl: sbnd .10 vol gl / Il aln plag laths. .05 chlorite or chloraphite (pleoc Il yel, Il gn); kinking both intstl and gran. .15 fld: .05 - .10 / albite twin, Carlsbad and tartan twins com. .01 biot: pleoc Il brn, I yel. Mnr pl fos, scericite, zircon, corundum, kao and lmn.*
<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Thin section number</th>
<th>Map unit</th>
<th>Position in unit</th>
<th>Hand speci</th>
</tr>
</thead>
<tbody>
<tr>
<td>072302</td>
<td>SR - 44</td>
<td>Kk</td>
<td>thrust zone</td>
<td>Chunks of dk gn gy to olv b/ wthrg v f to f gr ss. Aln elg gr / .06 mm lgh as grd b/rg. Col: .30 wh, .60 gy, .10 blk.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thin sect</th>
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<tbody>
<tr>
<td>.25 qtz, .40 cht, .01 P. .25 p srtd, f ang aln qtz grs / av dia = .07 mm. .15 fld; mostly plag and microcline. .40 cht and volc gl. .05 chlorite: pleoc gn I lgh. .03 op: magnetite and f pyr. .01 P mat (wood frags?) and mmr bit. .01 strained biot. .01 cly. Mr h/ relief grs.</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>082101c</th>
<th>SR - 25</th>
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</thead>
<tbody>
<tr>
<td>Gm olv to olv brn b/ wthrd, s &amp; p, f lam, calc, f gr ss. Pry prsn. HCl: mod Gr sz: .1 - .25 mm.</td>
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<thead>
<tr>
<th>Jm</th>
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<tbody>
<tr>
<td>.15 calc, .50 qtz / .35 cht in mtx. .40 sbrd, fr srtd qtz; av sz = .2 mm. .35 cht. .15 intstl, prob bicocl calc less than .3 mm dia. .01 intstl chlorite Mr biot, plag, masc, hem cly, rx frags and op. Wthrd edge consists of f gr (.02 mm dia) frags.</td>
</tr>
</tbody>
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<thead>
<tr>
<th>091602</th>
<th>SR - 26</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rus gy wthrd, m gr ss. Frs surf: Tn and gy intlam xbd, s &amp; p ss, .60 wh milky qtz or cht. HCl: n.</td>
<td></td>
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<tr>
<th>Js</th>
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<tbody>
<tr>
<td>.50 qtz, .20 cht and .01 P. Ang qtz, av sz = .2 mm. .01 - .02 plag / albite twin. .02 - .05 op: magnetite, pyr, hem and zircon com. .05 pl fos. .05 cly. Mr olivine.</td>
</tr>
</tbody>
</table>
Specimen number | Thin section number | Map unit | Position in unit | Hand speci
---|---|---|---|---
091601 | SR - 24 | Js | Low arg mem | Nod form. Lm stn surf cov / f cly. Some as irreg len /in spci.
Av gr sz: .2 mm to .35 mm.

Th. yel, olv brn and lt py chky and f slty tex f ss / num fos frags of Gryphaea and cast of Inoceramus.
P srttd and p rd / low por.
Av gr sz = .2 rm.
HCl: fa.

070204D | SR - 42 | Jr | ? | .60 qtz, .05 cht, .05 - .10 fld / mnr magnetite, chlorite, rx frag, biot and glau.
F to m gr, ang to sbang, strained qtz. Thn vnl of magnetite. Albite twin in plag. Thn cly len Il nod surf.

070203B | SR - 41 | Jr | basal | .70 calc, .15 qtz, .10 pyr and hem and mnr P.
.05 - .10 f dism pyr / hem rims to .5 mm dia.
.05 - .10 ang qtz / av dia = .02 mm.
.10 - .20 cly / 1mm stn.
Less than .01 P mat.
.02 .4 m biocl calc / fos pat.
.70 calc spar / av xl sz = .05 mm.
.02 fls.
Mnr pl fos.

Wthrd rim of chky olv bf layer and stryvio surr slty calc gy to rm py cnyr. Conch frac con in cnyr pt. Surf has fos frags of belemnite and Gryphaea.
Specimen number | Thin section number | Map unit | Position in unit | Thin sect
---|---|---|---|---
070201 | SR - 43 | Jsa | basal | .65 calc, .05-.10 qtz, .15 chl, .10 P and clay.

Hand speci

Lt tn bf chky wthrg olv brn, mdst or arg ls / 1/32 in tan vnls containing .06 mm dia particles.
HCl: fa.

080608 | SR - 23 | Me | basal | .03 calc, .05 dol, .20 qtz and .70 chl.

Wh wthrd, f gr dol / 1/8 to 1/4 in wh wthrd dk gy chl and mas ireg blobs of gy chl.
HCl: sl.
Frst surf: Lt gy / some wh to crm wh chl surr ran frac.

080603 | SR - 22 | Ma | basal | .70 dol, .10 qtz and .05 hem or P stn.

Chk sm lt brn to olv brn wthrd bdg surf.
HCl: sl to mod; fa on .2 mm vnls.
Frst surf: Blk brn/thn len less than 2.5 cm lg and 1 mm wd. Some len of dk er fer mat.

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<table>
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<tr>
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<th>Position in unit</th>
<th>Thin sect</th>
</tr>
</thead>
<tbody>
<tr>
<td>080602</td>
<td>SR - 21</td>
<td>D</td>
<td>mid</td>
<td>.35 calc, .65 dol, .01 hem. Prsn spar. Brec frags: v it o lv stn of 0 or lmm of less than .1 mm def rhmbs. Scat spec hem; av sz .01 mm. Vugs to .01 mm dia, some filled / calc. Vnl, .02 mm wd. Concen of hem abt some vnl, to .30 hem. V mn cly, f qtz, 0 stn and lm stn. Vnl: Rcxl calc to .05 mm / ran orien and scat intra xl vugs, frac and kink brds. Var sz dol frags in vnl. Some older vnl to .1 mm thk / xls walls show indst etcs whereas frs vnl have dst etcs.</td>
</tr>
<tr>
<td>080502</td>
<td>SR - 39</td>
<td>D</td>
<td>?</td>
<td>.45 calc, .50 dol. Kert (blk): .85 mort / av sz xl = .001 mm, .10 .03-.2 mm rhmbs, .01-.02 op: hem. Mn calc vnl. Spar area: .85 .05 mm rhmbs, .10 mort and .02 op: hem, lmn but mostly Mn-ox.</td>
</tr>
<tr>
<td>080106b</td>
<td>SR - 20</td>
<td>D</td>
<td>basal</td>
<td>.95 dol, .01 qtz, tr cht?, tr P7. Prsn spar, .02 Crin and .05 rxcl. .90 of brn stn dol of var sz; av sz = .05 mm; max sz = .15 mm, .01-.05 rxcl Crin stems .01-.03 hem of .02 mm spec dism in strg. .01 qtz gr of .03 mm sz, sbrd. tr of 0 stn or micgr lmn stn.</td>
</tr>
<tr>
<td>Specimen number</td>
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<tr>
<td>082503</td>
<td>SR - 38</td>
<td>Cd</td>
<td>mid</td>
<td></td>
</tr>
</tbody>
</table>

**Hand speci**

Lt bf and lt bf gy wthrg / sdy tex surf. Indst 1/3 in dia ool forms on cut surf.
Mnr por due to 1 mm vugs.
Mnr wh vnl.
HCl: sl.

| 082501a         | SR - 37             | Cd       | basal cgl        |

**Thin sect**

.85 calc, .01 qtz, mjr pyr and mnr chl and P
Rd elg cp pbl / .10 Trilo chit frags, concen of .2 mm qtz grs and var dism pyr grs: .98 calc.
Rd mort pbl 1.5 cm lg /
.01 mm gr and .02 mm thk vnl of 1mm.
Elg mort pbl / .05 mm and 2 mm wd pyr vnl.
.20 mtx: .02 mm wd biocl calc frags, .3 mm lg /
.10 ang, .01 mm qtz, int-stl 1mm and .005 mm calc and .05 to .10 pyr and het frags. Concen of pyr and qtz and chit len.

| 081709          | SR - 36             | Cs       | ?                |

Cd, yel bf, intbd / 1/8 in brn and salmon brn lam. Contains rexl calc vnl. Chk tex on oly bf wthrd surf.
Frst surf: wh calc vnl; op in bg, .60 tan, .05 blk, .30 gy and .05 uh.
Av gr sz = .05 mm.
HCl: mod.

.50 dol spar, .30 qtz.
Augen: 2.5 mm lg; .50 hem and .50 pyr.
Th area: .50 .02 mm lt brn rhubs of 1mm stn dol, sid or ankerite? .005 glau or malachite. .01 op. .01 chlorite needles. .40 .01 mm, ang qtz and mnr fdl.
Calc vnl: Av .03 mm thk / .10 twin.
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>081910</td>
<td>SR - 35</td>
<td>Cs</td>
<td>?</td>
</tr>
</tbody>
</table>

**Hand speci**

Lt gn wthr lg ls and lt pnk brn wthr irreg slty len. Rus brn, wh and gn 1/3 in fes xlam. Bdg surf wthrs lt olv bf. V f gr.
HCl: sl.

**Thin sect**

,80 dol, .05 qtz and mnr P.
Dol: .03 mm rhmbs.
.01 pyr wthr hem and lmn.
.03 fld concen in lam.
Concen of .02 mm ang qtz / undulose ext.
Mnr musc, P, chlorite, anhed malachite?, intstl cly and lmn.

<table>
<thead>
<tr>
<th>071605</th>
<th>SR - 34A</th>
<th>Cst</th>
<th>marker bd near top</th>
</tr>
</thead>
</table>

Meregue surf, bf, olv brn and gy brn wthrg, choc brn mrt / cnnc cyl tubes l bdg / outside dia = .5 to 1 cm and inside dia = approx. .3 cm; and irreg trns1 calc xl to 1 cm lg.
Wh calc vnl, .025 mm wd, orien in 2 dir.
In slty irreg vnl and len to 5 mm wd / .06 mm xl.

**Mort**

av xl sz = .01 mm / .01 op.
Wh vnl: less than .02 mm wd / ran orien .02 mm crr calc xl, some twin.
Ireg slt len: .005 mm irreg dol rhmbs, hem and lmn stn.
.05 op, pred hem / .001 dia. Len edges of hem stn, .3 mm dia, twin calc xl.
Ireg crr calc: like vnl / concen op.

<table>
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<tr>
<th>072103</th>
<th>SR - 33</th>
<th>Cp</th>
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</table>

.10 Trilo frags to 1 cm lg.
Olv bf wthrd surf / gy Trilo frags.
Frs surf: olv gy mort.
HCl: fa.

**Calc**

.90 calc, .02 qtz and .001 P.
.10 calc Trilo frags.
Calc spar: av sz = 1 mm.
P mat in concavo-convex lenses: Lingula sp.
V mnr op.
<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>070406</td>
<td>SR - 31</td>
<td>C</td>
<td>prob pre</td>
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<td>Cp sh</td>
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</tbody>
</table>

**Hand speci**

- F xl to mort dk brn ls / 1/8 in wh rexl calc vnl. 1/32 in thk wh rexl vnl and 1/8 in tubes? and blobs. Wthrd surf 1t gy brn slty tex and olv bf ta, f sdy tex where 1/8 in ireg slty len wthr on surf. HCl: fa.

**Thin sect**

- Mort area: .95 calc / av gr sz = .005 mm and max gr sz = .04 mm. .04 qtz / av gr sz of .005 mm. .005 illemnite, Hmr zircon, and f gr pyr surr 1.2 mm lg calc vug.
- Snty area: .75 frs, rexl, twin calc / av sz = .1 mm. .15 euhed dol rhmbs / av sz = .05 mm dia. .10 ireg mort frags (av sz = .001 mm) brn stn. Op: magnetite or illem- enite surr by lmn stn.

<table>
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<tbody>
<tr>
<td>070407</td>
<td>SR - 32</td>
<td>C</td>
<td>pos Gordon</td>
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<td>Sh?</td>
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</tbody>
</table>

- Sh, olv to dk brn gn wthrg, mica, wxy / cly cov bdg surf. lam 1 - 3 mm wd. Cut sect shows 1/2 to 2 mm tn gy and blk xlam. Frs surf: olv wxy, or gy to bl gy or gn gy / num wh calc vnl, 3 mm thk, I bdr. V lt Fe-ox stn in some vnl. HCl: fa.
- .01 to .02 glau sph: 1 mm dia, some elg. .01 to .02 brn P elip sph. .20 yel, gn, brn and blk pleoc strgs .15 mm dia. .01 mm wd, orien ll bdg. Pos p, alt biot or chlor­ ite. .03 .1 mm lg, hi birf strg sbll bdg; .001 to .01 mm wd: auth mica? .01 .05 mm dia, anhed qtz or fld gr ltly brn stn. .05 intstl scericite and cly.
- Calc spar: mjr const as biocl gr .10 mm dia and .5 mm rexl. Vnl: ran orien, 1 mm lg anhed calc xl / scat mnut op grs.
REFERENCES


