STRUCTURAL GEOLOGY OF THE NORTH-HALF OF THE SWIFT RESERVOIR

CULMINATION, SAWTOOTH RANGE, MONTANA

By

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ABSTRACT

The Sawtooth Range forms a broad salient at the eastern edge of the Sevier fold-and-thrust belt along the Rocky Mountain front of northwest Montana. The Swift Reservoir Culmination is a structural high located along the range-front of the Sawtooth Range, just south of Glacier National Park. The range is dominated by steeply-dipping imbricate thrust sheets. The culmination exposes an anomalous suite of Cambrian rocks that are not found elsewhere along the Sawtooth front. The structural complexity of the range is underscored by the high degree of imbrication that has taken place as well as the tight folding. Moreover, units in the SRC are characterized by strike-parallel cutoffs that create a surface expression of a compound eyelid window. The chief objectives of this research were to determine if the structural geometry of the culmination was compatible with an interpretation of a hinterland-dipping duplex in the footwall of the Major Steele Backbone thrust; what factors are responsible for the strike-parallel cutoffs seen in the culmination; and whether the SRC is a viable structural analog to subsurface duplex systems targeted for exploration along the Rocky Mountain front. An in-depth structural investigation of the culmination was conducted through field-based mapping, followed by lab investigations of the data collected in the field. This included geologic mapping followed by the construction of cross-sections, as well as the synthesis of this data with published magnetic and gravity data in order generate an accurate structural model of the culmination from basement to surface. Deformation within the SRC is controlled primarily through the mechanical properties of the units within the culmination, resulting in compartmentalization of the culmination into four distinct lithostratigraphic/structural domains. Moreover, this facilitated the development of duplex fault zones within the culmination. The Heart Butte thrust is the linking fault between three of these domains, and is a reflection of pre-orogenic basement lineaments that controlled the structural development of not only the Sawtooth Range, but the SRC as well.
INTRODUCTION

The Sawtooth Range of northwest Montana lies within the “Disturbed Belt” (Mudge, 1970) and forms a salient at the eastern edge of the Sevier fold-and-thrust belt along the Rocky Mountain Front (RMF). It is comprised of tightly-spaced, west-dipping thrust faults, exposing Cenozoic through Proterozoic rocks. These thrust sheets are stacked and imbricated and, due to the highly resistant nature of the Devonian and Mississippian units involved, create the appearance of “saw teeth” in profile. The Sawtooth Range has been described as, “…one of the best exposed examples of imbricate thrust faulting in the foreland fold-and-thrust belt of the western United States” (Lageson, 1987). Swift Reservoir is located in the Northern Sawtooth Range, roughly 24 km south-southeast of Glacier National Park and 29 km west of Dupuyer, MT. Birch Creek drains into Swift Reservoir at right angles to the strike of the culmination and, with its tributaries, provides deep exposures into the core of the culmination. The SRC is comprised of a stratigraphic section of Mesozoic through Paleozoic rocks, upwards of 2,000 m thick. These rocks are highly deformed, involving tight folding and intense imbrication. This extreme folding and faulting is a distinct feature of the SRC, where different units have distinct deformational characteristics with respect to composition and mechanical stratigraphy.

What sets the SRC apart stratigraphically is its anomalous exposure of Cambrian strata along the Sawtooth range front. While the presence of Cambrian rocks is not entirely uncharacteristic of the Sawtooth Range, they are typically found several thrust
sheets west of the range front where the regional décollement has cut deep into Phanerozoic rocks.

**Purpose and Significance**

The overall goal of this study is to characterize the structural architecture of the Swift Reservoir Culmination. This is achieved by addressing the following research questions:

1. Is the structural geometry of the north-half of the SRC compatible with the geometry of a hinterland-dipping duplex fault zone in the footwall of the Major Steele Backbone thrust?

2. The north end of the SRC is characterized by strike-parallel fault cut-offs that suggest the presence of a compound eyelid window, one to the south and one to the north of Feather Woman Mountain. If this interpretation is correct, then two lateral ramps comprise the north end of the culmination, where the frontal thrust climbs up-section in a stair-step fashion. Is this interpretation supported by transverse and longitudinal cross-sections?

3. If the interpretation of multiple lateral ramps is correct, then the basal décollement climbs up-section to the north parallel to the mountain front, before plunging northward towards Glacier National Park where Proterozoic strata of the Belt Supergroup comprise the mountain front in the hanging-wall of the Lewis thrust fault. What then are controls on the strike-parallel
depth variations of the décollement? Do pre-existing basement lineaments control the position of the décollement, or are other factors at play?

4. To what extent is the SRC a structural analog to the Waterton gas field in Alberta? What can be learned about reservoir-scale structures and fabrics that could facilitate enhanced oil and gas recovery in other foreland fold-and-thrust belt settings?

The significance of this research lies not only in a greater understanding of the Swift Reservoir Culmination, but also the Rocky Mountain Front as a whole. The RMF is an area of increasing exploration interest. The “inner foothills” (Dahlstrom, 1970) is a region where Paleozoic rocks have been thrust into antiformal stacks and duplex fault zones, structures that have been highly productive for oil and gas development. This research project therefore contributes to an increased understanding of the structural geometry involved in this play-trend.

**Area of Study**

The Swift Reservoir Culmination (SRC) is a structural “high” at the topographic front of the Sawtooth Range in northwest Montana (Figure 1). It falls between the north fork of Whitetail Creek to the north, Dupuyer Creek to the south, Killem Horse Creek to the west and the edge of the mountain front to the east. It encompasses an area approximately 180 km² and can be divided into a northern and southern half bisected, by Birch Creek and the Swift Reservoir. The north-half spans across three
USGS 7.5 minute quadrangle maps: Swift Reservoir, Fish Lake and Mitten Lake. Access
to this region can be gained along three creeks: Birch Creek, Whitetail Creek and Badger
Creek. These creeks cut across the structural grain of the north-half of the culmination,
allowing access perpendicular to the overall trend of the area. It is bounded to the west
by Small Creek, to the north by Badger Creek, to the east by the Mitten Lake thrust, and
to the south by Birch Creek\(^1\) and Swift Reservoir. This northern half encompasses an
area of roughly 125 km\(^2\).

The stratigraphy found in the SRC ranges from the Paleozoic to Mesozoic in age.
In the northern half, the stratigraphy is dominated by Cambrian strata comprised of
carbonates with interbedded shale. These Cambrian units have been highly deformed
into an array of close imbricate thrust faults and tight folds forming an outcrop of SW-
dipping, NW-SE-trending strata dominated by bedding-parallel thrust faults; however, in
areas these units may be isoclinally folded as well. The Cambrian units are bounded to
the west and north by Devonian and Mississippian strata, while to the east, they are
flanked by Jurassic and Cretaceous. The structural contrast between the Paleozoic rocks
is striking. While the Mississippian and Devonian rocks are thrust into imbricate stacks
like the Cambrian, they form much larger thrust sheets that can span tens of kilometers,
and on a regional scale, define the predominant structural style that characteristic of
the Sawtooth Range. Folding observed in these Devonian-Mississippian units differs as

\(^1\) As there are both a North Fork and a South Fork of Birch Creek that feed into Swift
Reservoir, from here on, when reference is made to “Birch Creek”, it is the North Fork
that is implied, unless otherwise noted.
well, in that they have larger wavelengths and inter-limb angles than the smaller isoclinally-folded Cambrian units.

Figure 1: Map of the Sawtooth Range of northwest Montana, highlighting the Swift Reservoir Culmination. Modified from (Mudge, 1972).
There have been numerous geologic studies conducted in the northern disturbed belt, and a number in the general region of Swift Reservoir. Early studies focused mainly on stratigraphy. Deiss (1933, 1939), Cobban (1945, 1955), Cobban, et al. (1959), Mudge, et al. (1962), Mudge (1972) investigated the stratigraphic units found surrounding Swift Reservoir Culmination, with further structural investigations to follow. These subsequent investigations focused primarily on 7.5 minute mapping and the structures of the disturbed belt and the overall Cordilleran fold-and-thrust belt of northwest Montana. In addition, USGS geologic maps have been produced on a regional scale along the rocky mountain front (Mudge, 1966a, 1966b, 1967, 1968; Mudge and Earhart, 1983; and Mudge et al, 1982). There have also been numerous detailed structural investigations throughout the Sawtooth Range, e.g., Stebinger (1918), Deiss (1943b), Alpha (1955), Weimer (1955), Childers (1963), McMannis (1965), Mudge and Earhart (1980) Mudge (1970, 1972b, 1977, 1982), Holl and Anastasio (1992), Ward and Sears (2007), and Fuentes, et al (2012). These provide an excellent framework for the structural interpretations of the Sawtooth Range.

Several master’s theses have also been produced on the area around Swift Reservoir. Feucht (1971) focused on the stratigraphy and deformation west of the reservoir. Singdahlsen (1986) studied the area adjacent to the reservoir to the south along the range front, focusing on the structural geology of the southern Swift Reservoir Culmination. Ihle (1988) looked at the area adjacent to the reservoir just to the north,
focusing on the internal deformation of the Backbone thrust sheet along the range front. Cannon (2008) conducted a fracture study along the Sawtooth Range, with a portion dedicated to fractures surrounding Swift Reservoir.
METHODS

To be able to achieve an accurate grasp of the structural geology of the Swift Reservoir Culmination, a detailed field-based analysis of the folds, faults and stratigraphy was required. This required detailed mapping of the region, followed by the construction of structural cross-sections. These cross-sections were used to visualize the subsurface geometries present in the SRC and attempts were made to line balance the sections. Stereonets were constructed and used to determine the overall orientation of fold axes throughout the culmination. Cross-section lines were then plotted perpendicular to these fold axes.

Field Mapping

The foundation of this project was based on detailed field mapping. As the surrounding area had been previously mapped at a reconnaissance scale of 1:125,000 (Mudge, and Earhart 1983), any type of detailed structural analysis requires a larger scale of observation. Field maps were made at a scale of 1:24,000, with some areas of intense folding mapped at 1:10,000. This scale of mapping not only enhanced the overall geologic picture of the region, but allowed for a more accurate assessment of surface and subsurface structures within the culmination. This becomes increasingly important when attempting to asses reservoir-scale attributes. Field mapping was conducted over a period of three summers, with the majority of time spent within Cambrian strata in the heart of the culmination. USGS 7.5 minute quadrangle
topographic maps (Swift Reservoir, Fish Lake and Mitten Lake) were used as base maps, wherein geologic contacts were drafted from surface exposures of individual units. Field data such as strike and dip, trend and plunge, and fracture measurements were taken with a Brunton Geo Transit compass. Locations where these data were collected were recorded on paper as well as with a GPS unit. Both a Trimble GeoXH as well as a Garmin eTrex handheld GPS were used to record station locations electronically. With the Trimble unit, measurements were recorded on the unit through a customized data dictionary along with GPS coordinates, while the Garmin unit was used only to record GPS coordinates. Paper maps were then digitized using ArcGIS 10.1 digital mapping software. A regional Digital Elevation Model (DEM) was converted to a shaded relief map (or hillshade), using ArcGIS as well. The effect of the hillshade is created by adding a lighting effect to the variations of elevation contained within the DEM, mimicking the vertical angle and azimuth of the sun’s location in the sky, thereby creating a pseudo-3-D visual effect. The digitized geologic map was then overlain upon the hillshade creating a pseudo-3D geologic map.

Cross-Sections

Cross-sections were plotted out in a grid fashion across the SRC. Lines of section were chosen where data was readily available, and perpendicular to the regional fold axes. Thus allowing for the most representative depiction of fold geometries in the
subsurface. These sections were then drafted on paper and finally digitized in Adobe Illustrator for clarity and image quality.

Balancing

The importance of the construction of balanced cross-sections lies in the ability to test geometric validity. The goal of the cross-section is not only to get an accurate interpretation of the subsurface structural geometry, but to be able to restore the deformed-state cross-section to an undeformed state. If this is achieved, the section is considered “viable” (Elliott, 1983). Moreover, when cross-sections are constructed, the structures included are witnessed not only in nature, but should be seen exposed in the surface geology (i.e. folds, thrust faults, etc. in a reasonable interpretation). Following this rubric allows the section to be considered “admissible” (Elliott, 1983). A cross-section is considered balanced when it is both viable and admissible (Elliott, 1983). However, a cross-section is not entirely without validity if it is not balanced. In turn, a balanced cross-section is not a unique solution, though balancing will in effect reduce the number of geometrically feasible solutions. A goal of balancing of bed lengths was attempted in order to achieve the most accurate subsurface interpretation possible; however, in the end cross-sections were not successfully balanced.
Well Data

There are two wells in the immediate vicinity of the SRC (*Mittens 1 and Blackfeet Tribal 12-1*). *Mittens 1* is at the north end of the culmination, approximately 0.75 km south of Mitten Lake; it was drilled by Union Oil Company of California in 1955, reaching a total depth of 2,343 m. The Blackfeet Tribal 12-1 well is located just north of the mouth of Birch Creek and was drilled by Humble Oil & Refining Company in 1971-72, and achieved a total depth of 2,409 m. Each was abandoned as a dry hole, but stratigraphic data attained from them was used to help reconcile subsurface units and act as a control for unit depths where possible in the construction of cross-sections.

Equal Area Stereonets

Rockware’s Stereostat software and Richard Allmendinger’s Stereonet 9 were used for the construction of stereonets. Measurements were compiled in Microsoft Excel worksheets as strike-and-dip data (right-hand rule format) before being entered into the software packages. These data were plotted as poles, in a lower-hemisphere projection, on an equal-area net. The plots were then contoured under both the Kamb and 1% area methods. Kamb contouring leads to a contoured diagram with a smoother texture than some traditional density diagrams, and therefore allows for a more easily interpretable data set. The 1% area method was used in interpreting fold features like asymmetry where increased smoothness can hinder interpretation. Following this step, a best-fit great circle (π-girdle) was derived from the collection of poles; the pole
to the $\pi$-girdle is the $\pi$-axis, which is the fold-axis. While kinematic data measured on fault surfaces will indicate the direction of transport, determining the fold axis through stereonets is useful for plotting cross-section lines where kinematic data is sparse.
GEOLOGIC BACKGROUND

Montana Disturbed Belt

The Sawtooth Range of northwest Montana lies within the Disturbed Belt and forms a salient at the eastern edge of the Sevier fold-and-thrust belt along the Rocky Mountain Front. It crosses Pondera, Teton and Lewis and Clark Counties, and is roughly 40 km wide x 130 km long (Lageson, 1987). The range is bounded to the north and west by the Lewis thrust, to the east the foothills of the Rocky Mountain fold-and-thrust belt (Ward & Sears, 2007), and to the south approximately where the Lewis thrust and the foothills of the Rocky Mountain fold-and-thrust belt meet at the Helena Salient (Lageson, 1987).

The Rocky Mountains of Montana-Idaho and southern Canada encompass a region roughly 350 kilometers wide from the eastern edge of the Rocky Mountain Front to Idaho’s western border. This section of the Rockies can be divided into eastern and western portions by the Rocky Mountain Trench (in Montana, this is the north-south trending topographic low occupied by highway 93). The eastern half can then be subdivided into a number of structural and physiographic provinces. From east to west, they are the Foothills, Front Ranges, Main Ranges and the Rocky Mountain Trench (Bally et al., 1966; Dahlstrom, 1970; Price, 1981). The Foothills lie on the eastern edge of the disturbed belt and mark the most forelandward zone of deformation. Stratigraphically, this region is dominated by upper and lower Cretaceous rocks. Moreover, the Foothills
can be subdivided into the outer and inner Foothills regions. The distinction between the two is made by the difference in topographic relief of the sub-regions based on their stratigraphic differences. The outer Foothills are marked by lower relief from predominantly Upper Cretaceous shales, while the inner Foothills have generally higher relief due to the abundance of competent Lower Cretaceous sandstone units (Dahlstrom, 1970) and are marked by a series of large culminations involving Paleozoic strata. Moving west, the next subdivision is the Front Ranges, showing decidedly higher relief and dominated by Upper Paleozoic carbonate rocks. This region is highlighted by imbricate zones and ridge-forming, large thrust sheets. Faults and folds are exposed at the surface and there is significant deformation visible at the macro and mesoscopic scales. The Main Ranges lie further west, and expose Paleozoic rocks at the surface. Structurally, broader folds with greater wavelength are observed in the east where carbonates are exposed while further west, the units are predominately shales and the structures are tighter with abundant cleavage (Dahlstrom, 1970). The Western Ranges (west of the Main Ranges) are made up of steep-dipping, highly-cleaved units. The Rocky Mountain Trench lies west of the Western Ranges and denotes the western boundary of this portion of the Rocky Mountains in Montana and Canada (Canada’s Eastern Cordillera) (Bally, et al., 1966; Dahlstrom, 1970). In Montana, the Rocky Mountain Trench abuts the eastern margin of the Salish Mountains and the western margin of the Swan and Whitefish Ranges, roughly 90 km west of the SRC.
The Northern Disturbed Belt encompasses the Foothills and Front Ranges (Mudge, 1970) and is approximately 50 - 65 km wide. Within these subdivisions, the Sawtooth Range lies within the Front Ranges. It is estimated that the timing of thrusting in the Northern Disturbed belt took place from mid to late Cretaceous (Albian) to Paleocene (72 - 56 Ma) (Mudge, 1972b; Hoffman et al., 1976; Larson, 2006; Fuentes, 2012). A study by Hoffman, et al. (1976) analyzed samples of metamorphosed potash bentonite through K-Ar dating, and found them to be of Late Cretaceous (Maastrichtian) age. The assumption is that these ages arise from the time that Mesozoic bentonite was converted to potash bentonite, and therefore indicate the time of thrust burial. They also noted that if there are inaccuracies in the data, it will lead to younger ages for thrust emplacement, thereby giving at the very least, a good constraint for the minimum age of thrusting (Hoffman, et al., 1976). Older ages from southern Canada determined through $^{40}$Ar/$^{39}$Ar dating of intrusions into Paleozoic shales are determined to be of Albian age (Larson et al., 2006; Fuentes et al., 2012).

**Stratigraphy**

Mesozoic rocks of the SRC are predominantly terrestrial in origin (Peterson, 1981). Mudstone, sandstone and siltstone tend to dominate the facies of the Cretaceous units in the SRC, where moving down-section, conglomerate begins to make an appearance. It is not until the basal-most units of the lower Cretaceous and into the upper and middle Jurassic portions of the section that marine sedimentary rocks appear
(Mudge and Earhart, 1983 geologic map). In contrast to the Mesozoic, the Paleozoic units of the Sawtooth Range and the SRC are dominated by carbonates. Limestone and dolomite abound while mudstone, siltstone, shale and sandstone can be observed as well; however, the dominant rock types of the Paleozoic section here are limestone and dolomite. Paleozoic rocks dominate the SRC with Mississippian, Devonian and Cambrian strata located west of the leading-edge thrust (Major Steele Backbone) of the structural complex. This is really the stratigraphic heart of the Swift Reservoir Culmination. In total, the mapped units of the SRC are more than 1,800 m thick (Figure 2).
Figure 2: Stratigraphic column of the units found within and around the Swift Reservoir Culmination (adapted from Singdahlsen, 1986).
Mississippian units observed in the field area are the Castle Reef Dolomite and Allan Mountain Limestone. The Castle Reef is divided into two members, the Sun River (upper Mississippian) and a lower unnamed member (lower Mississippian). The Castle Reef is a very light grey – white – bluish, sparry dolomite with a sugary texture and containing lenticular chert and locally abundant fossils. The fossils include crinoids, brachiopods, corals and bryozoans. The Allan Mountain is divided into three members (upper, middle and lower), is light grey – tan – dark brown/grey, and is thin-to-medium-bedded to slabby or platy in areas. It has a sparry appearance, is fine-grained and may contain crinoids. There is also an unconformity between the Mississippian Allan Mountain Limestone and the Devonian Three Forks Formation and the Devonian Jefferson Formation.

The Devonian strata include the Jefferson and Maywood Formations. The Jefferson Formation is divided into the upper Birdbear Member (Sandberg, 1955) and a lower unnamed member. The Birdbear Member is a very light grey to light yellow/tan dolomite, and is sparry in appearance. The lower member is fine-grained, brown-grey to chocolate brown, sparry dolomite and gives off a distinct fetid odor when broken to a fresh surface. The Maywood Formation is also divided into two unnamed members, the upper being a dark grey, sparry dolostone, while the lower is a green-grey to red-grey mudstone with yellow-grey dolomite beds within mudstone. An unconformity separates the Devonian Maywood Formation and the Cambrian Devils Glen Dolomite.
Cambrian units found within the SRC include the Devils Glen Dolomite, which is underlain by the Switchback Shale, followed by the Steamboat Limestone. The Devils Glen Dolomite is a very light grey, fine-grained, massive-bedded, sparry dolomite. The Switchback Shale is greenish-grey to reddish-grey and can contain oolitic lenses. It also has a tendency to be preferentially exposed at fault contacts in the SRC, often where the Steamboat Limestone is thrust over the Switchback Shale. The Steamboat is light grey, thin-bedded sparry limestone, where beds are divided by what appear to be algal-mat-like structures; intraformational conglomerate is also locally found (Figure 3). The Steamboat Limestone is the most extensively exposed stratigraphic unit within the SRC.
Figure 3: Intraformational conglomerates within the Cambrian Steamboat Limestone (Pencil for scale).
The Belt Supergroup comprises the western edge of the Sawtooth Range. Belt rocks are known to be more than 15,000 m thick to the west, but taper to nearly zero in the east (Peterson, 1981). It is this eastern edge of the Belt Supergroup that comes in contact with the Sawtooth Range; however, Belt Rocks are not observed at the surface within the SRC.
Major Faults

Thrust faults in the SRC strike predominantly northwest-southeast, and propagated to the east-northeast. Transport direction on faults was determined through available kinematic data (slickensides observed on fault contacts) and using the “bow-and-arrow” technique (Elliott, 1976). This yielded an overall transport direction for faults in the SRC of ~056°. For the most part these faults exhibit a classic stair-step or ramp-flat geometry, whereby they cut up-section and are younger in the direction of tectonic transport (west to east). There is also an observed stratigraphic control to placement of faults, juxtaposing more competent units onto less competent ones. The majority of the study area is made up of Paleozoic strata, and this is where the majority of faulting takes place. There are however, “major” faults found in both the Paleozoic and Mesozoic units. Regardless of where these major faults are found in the stratigraphy (Paleozoic or Mesozoic), they take the path of least resistance and find their way to lithologically incompetent units. Thrust faults in the field area are observed to cut up-section (footwall ramp) across lithologically competent units (sandstone, limestone, dolomite, etc.), and form flats within the incompetent units (shales). In the Cretaceous strata, there is a major décollement at the base of the Cretaceous Kootenai Formation, while in the Paleozoic section, flats develop at the base of the Cambrian Steamboat Limestone and within the Switchback Shale.
There are a number of major faults that dissect the north half of the culmination (Plate 1). These are, from east to west, the Mitten Lake thrust, Fish Lake thrust, Major Steele Backbone thrust, Lookout Ridge thrust, Haywood Creek thrust, Saddle Ridge thrust, Hungry Man Creek thrust, Jefferson Ridge thrust and the Killem Horse Creek thrust. In addition to these, there is also a major northeast-southwest trending fault (the Heart Butte thrust fault) that cuts across the structural grain of the culmination.

There are a number of other major faults in the southern half of the culmination (Singdahlsen, 1986), but they are generally not represented in the northern half. The Fish Lake and Major Steele Backbone thrusts are seen in both the northern and southern half; however, the remainder of the major faults from the southern half either merge into other thrusts, die out or plunge beneath the surface south of Birch Creek, or simply lie outside of the map area of the northern SRC.

The southern half of the SRC was mapped by Singdahlsen (1986) and the major faults there were mapped in Cretaceous and Mississippian strata. Singdahlsen (1986) mapped the Fish Lake thrust as the floor thrust of the Eagle Creek imbricate zone and, for convenience, it can be viewed the same to the north, even though the mapped imbricate thrusts of the Eagle Creek imbricate zone are more pronounced south of Birch Creek.
Fish Lake Thrust

The Fish Lake thrust was named by Singdahlsen (1986) for its proximity to Fish Lake just to the southeast of Swift Reservoir. The thrust is observed in both the southern and northern halves of the SRC. It extends north-northwest from Birch Creek for 9.8 km where it merges with the Major Steele Backbone thrust. It strikes 310° on average and dips ~20° southwest. The Fish Lake thrust transports the Cretaceous Kootenai Formation over the Cretaceous Marias River Shale creating almost 1,200 m of stratigraphic separation. This juxtaposition is noteworthy, because it is the easternmost example in the SRC of a major thrust utilizing a structurally incompetent shale unit for displacement; a pattern observed repeatedly throughout the SRC and much of the Sawtooth Range.

Mitten Lake Thrust

The Mitten Lake thrust is a discontinuous thrust in in the northern SRC. It is exposed in the northern portion of the map area where it places Devonian, Mississippian and Jurassic rocks over the Cretaceous Marias River Shale, with a stratigraphic separation of 1,200 – 2,100 m. Tracing the fault south from the northern edge of the map area, the Mitten Lake thrust merges with the Heart Butte thrust along the eastern flank of Heart Butte. The Mitten Lake thrust continues south where it merges with the Fish Lake thrust, just north of Birch Creek. From Heart Butte to where it merges with the Fish Lake thrust, the Mitten Lake thrust is not observed at the surface, but is inferred to be there based not only on the abrupt change in strike of the
Mitten Lake/Heart Butte thrust at Heart Butte, but also on the extreme thickness of the Marias River Shale east of the Fish Lake thrust. It has an average strike of $331^\circ$, dips approximately $26^\circ$ SW and, along with the Fish Lake thrust, is the easternmost major thrust mapped in the northern half of the SRC.

Heart Butte (Figure 4) is a prominent outcrop of Paleozoic carbonates that rises abruptly along the front of the range to a height of over 1,800 m. It sits in the hanging wall at the confluence of the Mitten Lake and Heart Butte thrusts, with Devonian and Mississippian rocks on the Cretaceous Marias River Shale, with 1,600 to 2,100 meters of stratigraphic separation between hanging wall and footwall units.

Figure 4: View of Heart Butte looking south
North of Heart Butte, the units in the hanging wall of the Mitten Lake thrust range from Devonian and Mississippian to the Jurassic Sawtooth Formation (Ellis Group). From here to the edge of the mapped field area to the north, the Ellis Group is found in the hanging wall of the Mitten Lake thrust with the Cretaceous Marias River Shale in the footwall. The stratigraphic separation between these units ranges from 1,200 – 1,300 m. and the hanging wall units become progressively younger to the north until finally, the Marias River Shale is repeated (Mudge and Earhart, 1983). This underscores a stratigraphic discontinuity at Heart Butte where the fault steps from Cretaceous down to Devonian, but then gradually climbs up-section from Heart Butte to the northern edge of the map area (Figure 5).

![Stratigraphic separation diagram of the Mitten Lake thrust](image)

**Figure 5:** Stratigraphic separation diagram of the Mitten Lake thrust
**Major Steele Backbone Thrust**

The Major Steele Backbone thrust is mapped in both the north and south-halves of the culmination. Its name is derived from the prominent ridge that constitutes the front of the range just north of Swift Reservoir and south of Feather Woman Mountain. It is the range-bounding thrust in the north-half of the SRC, though this is not the case in the southern-half. Also, the Peak thrust merges with the Major Steel Backbone thrust at Swift Reservoir and is not represented in the northern-half. In the north-half of the SRC, the Major Steel Backbone thrust places Cambrian over Cretaceous strata, while in the south-half it frequently places Cambrian over Mississippian. In the map area for this study, the Major Steel Backbone thrust places Cambrian Steamboat Limestone over the Cretaceous Kootenai and Blackleaf Formations, with a stratigraphic separation of 1,500 to 2,000 m. The thrust strikes approximately 325°, and using Elliott’s (1976) “bow-and-arrow” rule, where the direction of maximum displacement is determined by constructing the normal bisector to a straight line connecting two ends of a thrust on a map, a transport direction of 056° can be calculated. South of Swift Reservoir, the fault is mapped to the north fork of Dupuyer Creek (Singdahlsen, 1986). In the north-half of the SRC, the Major Steele Backbone thrust continues along the Major Steele Backbone (a prominent ridge just north of the reservoir) for roughly 8 kilometers, to the base of Feather Woman Mountain. There the fault wraps around the Major Steele Backbone peak making an abrupt 90° turn to the west-southwest where it brings Steamboat
Limestone in contact with the Devonian Maywood, creating 365 m of stratigraphic separation (Figure 6).

![Stratigraphic separation diagram of the Major Steele Backbone thrust.](image)

**Figure 6**: Stratigraphic separation diagram of the Major Steele Backbone thrust.

**Lookout Ridge Thrust**

The Lookout Ridge thrust is another northwest-striking, southwest-dipping thrust that runs from the northwest edge of Swift Reservoir to the northwest edge of the map area. It is mapped for more than 16 km in the SRC, and from the west-southwest side of Feather Woman Mountain to the northwest out of the field area. It is the easternmost thrust transporting Cambrian rocks to the northeast. The fault is named for the prominent ridge of Cambrian strata in the northwest portion of the field area. The fault becomes the major bounding fault of the Cambrian suite of rocks in the northern portion of the SRC.
For roughly 4.3 km from Birch Creek to the northwest the fault has an average strike of 329°. Along this segment of the fault, it is somewhat difficult to determine exactly which fault would be considered the Lookout Ridge thrust. This is due to the fact that the fault merges/branches into a number of imbricate splays involving the Cambrian Steamboat Limestone and Switchback Shale. To the northwest though, the fault takes on more defined characteristics, for the next 1.9 km to the northwest, it places Steamboat onto Switchback (150 m of stratigraphic separation), then Steamboat onto Devils Glen Dolomite (271 m of stratigraphic separation), and finally Switchback onto Devils Glen (200 m of stratigraphic separation). Continuing to the northwest for the next 5.6 km, the fault begins to superimpose Cambrian onto Devonian strata (300 to greater than 600 m of stratigraphic separation). The fault strikes an average of 310° for about 4 km where it then takes a turn to the north striking, 350° through the remainder of the Devonian section in outcrop. For the next 1.9 km the fault places Cambrian Steamboat Limestone on Mississippian strata (880 – 1,160 m of stratigraphic separation). For 1.1 kilometers of this the fault continues its strike at 350°, but for nearly the next kilometer makes an abrupt turn to the northeast striking ~020°. The next 2.4 km brings the Cambrian Steamboat Limestone up to the Jurassic creating upwards of 1,160 m of stratigraphic separation; this juxtaposition continues until the Lookout Ridge thrust brings the Steamboat Limestone in contact with the Mississippian again, just before exiting the field area. Where the fault is in contact with the Jurassic
section, it curves in a concave-eastward trend for the next kilometer until making another abrupt turn to the northwest, striking 310° until it exits the map area.

What this trend of gradually increasing stratigraphic separation signifies is that while the thrust cuts to a depth capable of extruding Cambrian rocks, longitudinally, the thrust is gradually stepping up section as the fault trace moves to the northwest (bringing Cambrian rocks in contact with continually younger strata). This is an excellent example on a gradual scale of what is believed to be occurring on an overall trend within the SRC and beyond.

**Haywood Creek Thrust**

The Haywood Creek thrust is named for the creek that starts at a confluence just to the south-southeast of the Major Steele Backbone, and drains southeast into Birch Creek at the point where the north fork of Birch Creek empties into the Swift Reservoir. From Birch Creek north throughout the map area, the Haywood Creek thrust places Cambrian on Cambrian, primarily Steamboat on Steamboat creating upwards of 73 m of stratigraphic separation. It lies within the heart of the culmination and, while not necessarily a thrust that runs the length of the field area as some of the other major thrusts do, it is one that bounds an important imbricate zone within the culmination. Following the trace of the fault to the northwest, it extends approximately 3.8 kilometers before branching into two splay faults, and has an overall strike of approximately 325°. This branch point occurs at the convergence of the two streams
that form the confluence of Haywood Creek. The eastern branch of the fault places the Steamboat Limestone on top of the Switchback Shale, creating upwards of 150 m of stratigraphic separation, while the western branch continues to place Steamboat on top of Steamboat. Each of these branches continue to the northwest for another 1.5 km, where they either die-out, or merge into another Cambrian-involved thrust. In this portion of the culmination, this system of branching, merging and dying-out of faults creates a pattern of an anastomosing array of faults that significantly complicates the overall system of structures.

**Saddle Ridge Thrust**

The Saddle Ridge thrust is an arbitrarily named fault in this study. The name is not associated with any specific ridge or peak in the field area, but a prominent accessible saddle in the middle of the map area. However, the thrust is one of the major faults found within the SRC. Its average strike is 323° from Birch Creek for nearly 12 km to the northwest, where it continues beyond the western edge of the map. It repeats the Cambrian Steamboat, creating ~75 m of stratigraphic separation. It is one of the more continuous thrust faults found in the SRC and acts as the sole fault for the westernmost imbricate zone.

**Hungry Man Creek Thrust**

The Hungry Man Creek thrust is herein named for the northwest-southeast trending creek that the thrust follows. The fault is mapped in only the north-half of the
SRC. It strikes 327° from Birch Creek to the western edge of the map area (approximately 9.5 km) and beyond. It places Cambrian over Cambrian strata creating approximately 150 m of stratigraphic separation. There is a slight step-over or lateral displacement along the fault about 3 kilometers north-northwest of Birch Creek that occurs at the confluence of three drainages that comprise the headwaters of Hungry Man Creek. From there, the fault extends another 6.5 kilometers to the edge of the map area. At the step-over, there is a slight overlap, where the Steamboat Limestone is thrust over the Devonian Maywood Formation, creating > 365 m of stratigraphic separation. Beyond this to the northwest, the Hungry Man Creek thrust continues to place Cambrian on top of Cambrian strata. This anastomosing/overlapping pattern of thrust faults signifies a structural tear and may be attributed to a localized discontinuity in the basement, as described in later sections.

**Jefferson Ridge Thrust**

The Jefferson Ridge thrust takes its name from an unnamed ridge that has a prominent exposure of Devonian Jefferson Dolomite. It has an average strike of 322° and is mapped for roughly 7.2 kilometers from Birch Creek to the western edge of the map area. Adjacent to Birch Creek, the thrust carries Cambrian Steamboat Limestone over the Devonian Jefferson Formation, creating over 600 m of stratigraphic separation. However, to the northwest the thrust branches off, with the eastern branch placing Devonian on top of Devonian creating up to 365 m of stratigraphic separation; the
western branch carries Steamboat Limestone over the Devonian Jefferson until it dies-out into the eastern limb of a major anticline in the western portion of the map area.

**Killem Horse Creek Thrust**

The Killem Horse Creek thrust is named for the creek that begins at Mt. Poia and drains down to Birch Creek. There is a small splay fault where the fault branches off to the south creating an isolated outcrop of Steamboat Limestone; the splay is interpreted as a small backthrust, creating a small “pop-up” structure (McClay, 1992) of Steamboat Limestone.

Following the fault northwest from Birch Creek, once it diverges from repeating Cambrian units, it begins to cut up through the Paleozoic section from the Steamboat Limestone to the Mississippian Castle Reef Dolomite, and then back down to the Devonian Jefferson before it exits the map area. As this cutting up-section takes place, the fault transitions from truncating the western limb of a major anticline (Cambrian and Devonian), to the western limb of a major syncline involving Devonian and Mississippian units (Plate 2, Section C-C’), across the core of that syncline (Mississippian) and finally across its eastern limb. This overprinting of major structures is unusual for thrusts in the SRC, and shows it to be an out-of-sequence thrust. Furthermore, as this is the hindward-most thrust carrying Cambrian strata (in the SRC) it is clearly one of the major thrusts in the immediate vicinity.
Heart Butte Thrust

The Heart Butte thrust fault is a northeast-southwest striking thrust that connects the Major Steele Backbone thrust with the Mitten Lake thrust. The Heart Butte thrust differs dramatically from the other major faults found within the culmination in that it trends perpendicular to the overall structural grain. Where the majority of faults strike in a NW-SE direction, the Heart Butte thrust strikes NE-SW, at 230°, and dips shallowly to the northwest at 08°. Moreover as the overall transport direction of units in the culmination is east-northeast, this signifies that there is right oblique-slip on the fault. The Heart Butte thrust links the Major Steele Backbone thrust to the Mitten Lake thrust, and in doing so, transfers displacement from the Major Steel Backbone thrust to the Mitten Lake thrust. Along with all of this, the dip-separation component of the Heart Butte thrust brings Mississippian and Devonian units in contact with the Cretaceous Marias River Shale, thus creating a stratigraphic separation of roughly 1,500 m.

Imbricate Zones

One of the most distinguishing features of the SRC, specifically the northern-half, is the presence of four imbricate zones (IZ’s), each bounded by a major thrust. From east to west, they are the Eagle Creek, Major Steele Backbone, Haywood Creek and Saddle Ridge imbricate zones. The Eagle Creek imbricate zone was originally mapped by Singdahlsen (1986), while the others named here are from this study.
**Eagle Creek Imbricate Zone**

The Eagle Creek imbricate zone is the easternmost zone in the SRC. It was named for the creek that runs from the southern end of the Major Steele Backbone ridge south into Birch Creek just, downstream of Swift Dam. The Eagle Creek IZ is a collection of northwest-striking, southwest-dipping imbricate thrust faults with a footwall décollement – the Fish Lake thrust. The Eagle Creek imbricate zone involves the Cretaceous Kootenai and Blackleaf Formations, with more mapped thrusts south of Birch Creek compared to the area north of the creek; this imbrication produced a number of tight folds adjacent to Birch Creek as well. Singdahlsen, (1986) raised the question as to whether there is another bounding thrust to the west that caps the series of imbricate thrusts – a roof thrust for the zone – thus creating a duplex structure (Boyer and Elliott, 1982). The interpretation from this study, as well as that by Singdahlsen (1986), is that this is a duplex fault system (Figure 7). Singdahlsen hypothesized that the thrust carrying the Jurassic Ellis Group acted as the roof thrust for the system. If so, the roof thrust picks up a short section of Cretaceous Blackleaf Formation as it continues to the north before the Jurassic Ellis is truncated. The imbricate thrusts involving Cretaceous strata in the Eagle Creek IZ are interpreted to sole-out asymptotically into both the Fish Lake thrust (floor thrust) and upwards into the thrust carrying the Jurassic Ellis Group (roof thrust), leaving an array of imbricate thrusts exposed at the surface today after unroofing.
Figure 7: Map view of the Eagle Creek Imbricate Zone north of Birch Creek. Image centered at 48.1838298°, -112.8685564°.

**Major Steele Backbone Imbricate Zone**

The Major Steele Backbone imbricate zone is directly west of the Eagle Creek imbricate zone. It is about 1 km wide at its maximum, but on average, has a width of roughly 0.8 km and runs from Swift Reservoir NNW for ~ 4 km along the Major Steele Backbone ridge. It is bounded by the Major Steele Backbone thrust to the east and the
Lookout Ridge thrust to the west, and involves the Cambrian Steamboat Limestone and
the Cambrian Switchback Shale. This zone repeats a succession of Steamboat Limestone
and Switchback Shale. Moving north, many of these thrusts merge into each other
within a few kilometers, thus confining the Major Steele Backbone imbricate zone.

Haywood Creek Imbricate Zone

The Haywood Creek imbricate zone is directly west of the Major Steele Backbone
imbricate zone. Its floor thrust is the Haywood Creek thrust on its eastern margin, while
the thrust defining its western edge is the Saddle Ridge thrust. The Haywood Creek
imbricate zone is a collection of thrust faults that repeat the Cambrian Steamboat
Limestone. It is interpreted from the construction of cross-sections to be a leading
imbricate fan. The lack of evidence for faults merging or branching underscores this
interpretation.

Saddle Ridge Imbricate Zone

The Saddle Ridge Imbricate Zone is at the western flank of the SRC. It is
observed from Birch Creek to the western edge of the field. The Saddle Ridge thrust is
at its leading-edge, while the Hungry Man Creek thrust forms the trailing-edge carrying
Cambrian and Devonian units. Faulting within Saddle Ridge imbricate zone tends to
repeat Cambrian Steamboat Limestone, but closer to Birch Creek there are sections of
the Cambrian Switchback Shale that are incorporated into the zone with repeated
sequences of Steamboat topped by Switchback. Interestingly, of the four occurrences
where Switchback Shale is observed adjacent to Birch Creek here, there is a progressive lateral discontinuity that characterizes the unit. From east-to-west, packages of Switchback Shale are progressively cut-off, leaving the Saddle Ridge imbricate zone with regular intervals of Switchback at Birch Creek, while the unit is absent from the IZ just a few kilometers north. This strike-parallel elimination of the Switchback Shale narrows the zone significantly, compressing it from ~ 1.5 to 0.3 km wide and may be attributable to a lateral ramp in the subsurface (Figure 8).

Figure 8: En echelon-style cut-offs of Switchback Shale within the Saddle Ridge Imbricate Zone. Image centered at 48.1825075°, -112.9338306°.
Folds

Folds within the SRC differ from what is observed at the surface in the rest of the Sawtooth Range. This uniqueness stems from the extensive exposure of Cambrian units at the range-front. The fold styles exhibited by the Cambrian section in the SRC differ not only from those seen in overlying Paleozoic and Mesozoic rocks, but also from Cambrian outcrops found elsewhere in the Sawtooth Range. This difference can be attributed to stratigraphic variations (mechanical stratigraphy) as well deeper structural controls within the basement.

Fold Types

There numerous fold types found within the SRC. Based on Ramsay’s fold classification scheme using dip isogons, there are class 1, 2 and 3 folds (Ramsay, 1967, Ramsay and Huber 1987). Different fold types may be preferential to different parts of the culmination which will be discussed later, and are grouped into structural domains. These domains are characterized by the deformational features and stratigraphy found within them.

Fold Development

In the northern-half of the SRC, the fold styles mentioned above often have variation within a given fold. This is the result of primarily two factors; the scale at which they are observed (mesoscopic) and the developmental history of the folds.
Previous studies in the region focused more on the timing of folding in relation to thrusting, i.e. thrust first, fold first or, contemporaneous. Singdahlsen (1986) discusses the formation of Swift anticline in terms of a fault-propagation fold, where the shortening that takes place during the growth of the anticline is transitions from a folding to thrusting scenario. This relationship is also seen in the northern SRC in an anticline in the western portion of the map area between the Jefferson Ridge and the Killem Horse Creek thrust (in-between cross-section lines B-B’ and C-C’). The anticline is cored by Cambrian Steamboat Limestone in the hanging wall of a thrust that is the lateral termination of a splay from the Jefferson Ridge thrust. This fold-thrust relationship is comparable to that seen along the Walling Reef thrust in the southern SRC as well. The propagation of the thrust likely facilitated the development of the anticline, where at some point the thrust became locked and the Lookout Ridge thrust propagated forward. In map view, the Paleozoic units in the crest of the anticline form a composite fold composed of Cambrian Steamboat Limestone, Switchback Shale, Devils Glen Dolomite and Devonian Maywood Formation. Calculating dip isogons for the Switchback, Devils Glen and Maywood shows an interesting relationship of folding (Figure 9).
Figure 9: Map image of varying fold classifications within an anticline. Image oriented with the center of the map at 48.1882916°, -112.9762158°.

The most incompetent unit of the three, the Switchback Shale, is a Class 3 fold where dip isogons diverge and layer thickness is decreased on the limbs of the fold. The middle layer, the Devils Glen Dolomite forms a Class 1C fold with a weakly convergent isogon pattern concentrated at around the hinge zone. Along the west limb, the isogon furthest from the hinge shows a strong convergence, indicating a possible transition to a Class 1A fold. Along the eastern limb, isogons show the weakly convergent pattern of a Class 1C fold before the unit is truncated by the Steamboat Limestone. The Devonian Maywood is folded into a complex isogonal pattern where the western limb forms a Class 3 fold with a sub-parallel isogon pattern near the hinge zone, with diverging isogons and decreasing layer thickness toward the limb. The eastern limb is parallel to
sub-parallel near the hinge zone, with isogons then beginning to converge in the manner of a Class 1C fold, while the easternmost isogon shows a possible diverging trend as the limb appears to begin to thin and is truncated by the Steamboat Limestone and the Jefferson Ridge thrust. This highlights the variable geology within the folded layer, showing a transitioning of the fold from a Class 2 to 3 on the western limb and a Class 2 to 1C along the eastern limb, with an indication that it may have been transitioning back to a Class 2 and possibly Class 3 fold were the unit not truncated. Observing these three folded units together is also interesting as it demonstrates how mechanical heterogeneity of folded layers can create different classes of folds (and fold geometries) in a single deformational event. Incompetent units tend to show exaggerated limb-thinning and hinge-thickening in comparison to the more competent units. However, it should be noted that this construction of dip isogons was made from the map pattern of these folds, and not from a perfect down-plunge profile view of the units. This inherently leads to some distortion of the isogons, but doesn’t necessarily invalidate the observations.

An argument can be made that some of the folding in the Cambrian Steamboat Limestone follows the fold-first hypothesis, especially in folds proximal to Swift Reservoir. Adjacent to the reservoir, Steamboat Limestone is folded into very tight, disharmonic buckle folds, thrusted over Switchback Shale (Figure 10).
Figure 10: Isoclinal folds in the Cambrian Steamboat Limestone in the hanging wall of the Major Steel Backbone thrust.

Closer examination shows that they appear to be almost “fish-hook” style folds (Sorby, 1879; Ramsay and Huber, 1987) (Figure 11). Fish-hook style folds develop as a series of folds with adjacent synclines and anticlines demonstrating marked asymmetry between them, which is what is observed along the south shore of Swift Reservoir.
Figure 11: Fish-hook-style folds in the Cambrian Steamboat Limestone along the south shore of Swift Reservoir (Google Earth image oriented south-southwest).

Examining the isogon pattern of one of these folds (Figure 12) shows the fold to be Class 2 where dipisogons are parallel to sub-parallel at the hinge zone, while beginning to converge farther from the hinge (Class 1C). As can be seen along the eastern (left) limb, the isogons then begin to become less convergent appearing to move towards a divergent pattern, and the layer thickness of the limb begins to decrease. While not shown on the image, what appears as isogons beginning to diverge, actually demonstrates a transition to the adjacent fold where isogons are
converging. Moreover, this marked asymmetry between adjacent folds highlights the mechanical heterogeneity between units.

Figure 12: Isogon pattern on “fish-hook” fold of Steamboat Limestone along the south shore of Swift Reservoir (Google Earth image oriented south-southwest)

Ramsay and Huber (1987) suggest a deformation sequence for the creation of fish-hook folds like those seen at Swift Reservoir (Figures 11 and 12). In this scenario, there are three different layers with different competencies (μ) where $\mu_1 > \mu_2 > \mu_3$. In terms of the SRC, $\mu_1$ could be thought of as the Steamboat Limestone, $\mu_2$ as the lower shaley portion of the Steamboat and $\mu_3$ as the Switchback Shale. When the units are shortened, the difference in competencies of the layers causes $\mu_1$ to fold with an initial
vertical asymmetry. As shortening continues, the folded layer begins to rotate transforming the 1B folds to 1C and creating further asymmetry between folds. Finally, as the stress and shortening continues, shear zones may develop between the folds creating the characteristic “fish-hook”-style folds (Figure 13) (Ramsay and Huber, 1987). The units involved in the referenced example are limestone (competent) and highly cleaved slate (incompetent). And while the fold classes involved in Ramsay and Huber’s example are slightly different than what is observed at Swift Reservoir, the deformational sequence coincides with what is observed at the SRC.

Figure 13: Deformational sequence of units with differing competencies suggested by Ramsay and Huber (1987) for the development of fish-hook folds. (Ramsay and Huber, 1987)
Eyelid Windows

A tectonic window in a thrust belt forms through the erosion of an upper layer of thrusted rock leaving the rocks beneath exposed. An “eyelid window” (Oriel, 1950, 1951) is a unique form of a tectonic window wherein the map pattern gives the overall impression of an eyelid. These windows are often observed through the erosion of a thrust culmination (Boyer and Elliott, 1982). The tectonic processes that set up the pre-erosional phase of a window’s formation may also be the same processes responsible for the formation of the culmination itself (Figure 14) (Boyer and Elliott, 1982).

Figure 14: Example of an idealized duplex eyelid window. Stratigraphic packages bounded on all sides by thrusts resulting in the development of a culmination and ultimately a window (Boyer and Elliott, 1982).
In the absence of stratigraphic variability within a thrust system – namely along-strike variations within units – a thrust system that is bounded by ramps at the leading edge (frontal) as well as on either side (lateral/oblique) can lead to the development of a culmination that when subsequently eroded may form an idealized duplex eyelid window (Figure 14) (Boyer and Elliott, 1982). Furthermore, they argue that a culmination formed by the folding of an imbricate fan that is then eroded could also result in a characteristic eyelid window map pattern (Figure 15) (Boyer and Elliott, 1982).

Figure 15: Example of an idealized "Eyelid Window" formed by a folded imbricate fan. (Boyer and Elliott, 1982).

It is this unique case of an eyelid window that is observed in the SRC, where the Cambrian units are highly imbricated and surrounded by younger Paleozoic and
Cretaceous units of the culmination. Moreover, a combination of the ramp-bounded system coupled with folding can facilitate the development of an eyelid window (Figure 15). Figure 16 shows how a duplex with folding in the roof thrust can create an eyelid window very similar to Boyer and Elliott’s folded fan scenario. SRC is likely a product of a ramp-bounded system and may very well be the product of a folded duplex. Evidence for this is demonstrated in the abrupt changes in stratigraphy along-strike (e.g. Cambrian to Mississippian or Cretaceous to Mississippian), coupled with faults that strike perpendicular to what is observed regionally (The Heart Butte thrust and the Split Mountain Tear to the south). Were the boundaries of the window derived from gradual stratigraphic changes within units, the boundaries of the window would not be so distinct and there would not be the sharp strike-parallel cut-offs of units.

Figure 16: An idealized eyelid window formed by a duplex structure with a folded roof thrust. Dashed grey line represents the erosional surface
Mechanical Stratigraphy

Mechanical stratigraphy is the division of rocks based on the rock’s mechanical properties (Cooke, 1997, Laubach et al., 2009), and knowledge of these mechanical properties is key in understanding how rocks will deform. In the SRC, these properties can be easily observed in the distinct deformational characteristics between units. For example, there is an observable variation between the way the predominantly carbonate rocks of the Paleozoic succession deform versus the clastics of the Mesozoic succession. Paleozoic rocks are significantly more deformed than the Mesozoic rocks of the SRC, with a greater occurrence of imbrication, and folds that are frequently tighter and of higher frequency than those found in the Mesozoic succession. Within the Paleozoic suite of rocks, the Mississippian and Devonian units are more competent than the Cambrian which is demonstrated by Mississippian and Devonian rocks having a more open style, and reduced frequency of folding than what is observed within the Cambrian units.
Figure 17: Fold in Mississippian strata showing inter-limb angle 96°. View looking northwest along the western edge of the field area.

This is seen in folds, where the inter-limb angles are greater in the Mississippian and Devonian units (~>90°, open) than the Cambrian (<90°, frequently tight to isoclinal) (Figure 17), as well as in the formation of huge thrust sheets (tens of kilometers) of Mississippian rocks that characterize the Sawtooth Range (Figure 18).
Figure 18: Photo showing adjacent Mississippian units forming a large fold and thrust sheet at Swift Reservoir, MT.
Within the Cambrian section, there are distinct deformational styles and relationships between units as well. The Steamboat Limestone often forms tight, isoclinal folds and is faulted and imbricated to the point to which the Switchback Shale and Devils Glen Dolomite are all but eliminated from large portions of the culmination (Figure 11). The Devils Glen Dolomite forms more open folds than the Steamboat with inter-limb angles upwards of 100° in places. Switchback Shale, the weakest of these three units deforms, ductilely often forming crenulations. The Switchback is often sandwiched between layers of Steamboat Limestone, and there is a marked ductility contrast between the units highlighted by the Switchback exhibiting flexural flow (Donath and Parker, 1964) between layers of Steamboat (Figure 19).

Figure 19: Displaced limestone beds within the Cambrian Switchback Shale. Limestone (highlighted) deforms via minor imbrications and duplex structures, while crenulations can be observed within the shale.
As the culmination formed, these properties came into play as faults cut up-section across more competent packages of rock (Mississippian, Devonian, etc.) creating ramps, while weaker units like the Switchback Shale formed thrust flats. Internal weaknesses also accommodated differential deformation. For instance, weaker beds found within the Mississippian Castle Reef Dolomite allowed for flexural-slip within a fold (Donath and Parker, 1964), while shale at the base of the Steamboat Limestone likely acted much like the Switchback Shale by creating a zone of weakness within the Cambrian section.
Mudge’s (1972) survey showed nine sub-belts within the vicinity of the Sun River Canyon portion of the Disturbed Belt, while Singdahlsen (1986) had four “domains” classified in his field area. Four distinct domains or lithostratigraphic packages are observed in the northern portion of the SRC (Figure 20). While there is some overlap in what was designated by Singdahlsen (1986), there are significant differences as well.

Figure 20: Structural Domain map of the northern Swift Reservoir Culmination.
Domain 1

Domain 1 (Figure 21) is similar to Singdahlsen’s (1986) Domain I, in that it consists of folds and faults east of the range front, involving Cretaceous and Jurassic strata. These are siliciclastic rocks, in marked contrast to the predominantly carbonate outcrops of the SRC. It is bracketed to the west by the Major Steele Backbone thrust, to the north by Feather Woman Mountain and Heart Butte, and to the east is the eastern margin of the map area. The faulting in Domain 1 consists of low-angle thrusts on the order of 30°W, and contains the Eagle Creek Imbricate Zone.

Figure 21: Map of Structural Domain 1, highlighting major faults.
Folding in Domain 1 shows predominantly open synclines with inter-limb angles greater than 90° observed at the southern end of the field area. When looking at Domain 1 from south-to-north, there is increased folding (and faulting) at the southern end, proximal to Birch Creek. As faults merge to the north, there is a direct relationship to the number of observed folds. Comparatively, Domain 1 shows the least amount of folding and faulting of any domain in the SRC. The domain is also in the structurally forward-most portion of the culmination, making up the eastern margin of the SRC. Bordering the north end of the domain is the Heart Butte thrust. It strikes 230°, essentially perpendicular to almost all the faults in the SRC and parallel to the overall direction of thrust propagation within the culmination. This is likely associated with a lateral ramp bringing the Mississippian and Devonian strata in contact with the Cretaceous. Unfortunately, kinematic indicators were not able to be measured. This does not however eliminate evidence of a ramp, as the fault surface is likely buried. Dip data of units on the northwest (hanging wall) side of the fault show units dipping shallowly to the northwest. These dip directions are in direct contrast to what is observed throughout the rest of the SRC and signal the possibility of a subsurface lateral ramp.

Originally, the Heart Butte thrust was thought to be a “secondary transverse tear fault” (Figure 22) (Dahlstrom, 1970), though upon further investigation, evidence supports the theory of a lateral ramp.
A secondary tear fault implies emplacement of the original thrust sheet prior to rupture of the tear fault, and often a steep dip to the fault. Both scenarios (tear fault versus lateral ramp) allow for differential deformation on opposite sides of the fault, which is observed here, but the dip of the fault makes the ramp hypothesis more likely. A three-point problem constructed along the fault shows the fault dipping shallowly to the northwest at a slightly lower angle than bedding. While such a low angle fault is not what is to be expected from a lateral ramp of this size, it disputes the idea of a near-vertical tear fault, and allows for the possibility of the angle of the fault plane to increase at depth, and be more in-line with traditional ideas of a ramp-bounded thrust system.

Figure 22: Example of formation of secondary transverse tear faults (modified from Dahlstrom, 1970).
Domain 2

Domain 2 (Figure 23) contains the Devonian through Cretaceous section from Feather Woman Mountain and Heart Butte at the southern end of the domain, to the northwest beyond the field area. This suite of rocks is deformed into a series of northwest-trending anticlines and synclines bounded to the east by the Mitten Lake...
thrust, south by the Heart Butte thrust, and to the west by the Lookout Ridge thrust. While there is a distinct reduction in folding from south-to-north in Domain 1, there is a dramatic increase where Domain 1 ends and Domain 2 begins. Domain 2 is consistently folded from south-to-north. Fold hinges here trend and plunge to the northwest (Figure 24), yet folds become more closely-spaced (decreasing wavelength) in the northern portion of the domain as opposed to the southern end (increased wavelength). This is due to a change in stratigraphy from south-to-north, where the rocks transition from the more competent Paleozoic carbonates to the Mesozoic clastics.

Figure 24: Stereonet of the easternmost syncline in Domain 2, showing the pi-girdle (best-fit great circle of poles-to-bedding-planes) and the pi-point (fold axis).
A number of the folds on the western edge of Domain 2 are truncated by faults. There is one fault in the western portion of Domain 2 that is likely an imbricate splay off of the Lookout Ridge thrust that carried a small section of Jurassic over the Kootenai, manifesting itself in a series of tight isoclinal folds with west-dipping axial surfaces (Figure 25).

Figure 25: Image of isoclinal folds in Jurassic strata. Colors indicate differing stratigraphic units from the foreground and background of the photo (looking northwest).
Figure 26: Cross-section of the fold shown in Figure 25 (elevation in meters).

The fault juxtaposes the Jurassic Swift and Cretaceous Kootenai Formations (Figure 26) which are locally conformable. Further south, the splay dies-out and the footwall-units are overturned and comprise the western limb of a syncline. This shows that the fold developed at the same time as the fault. As the Lookout Ridge thrust propagated relatively eastward, units in the footwall of the LRF were being progressively folded; eventually, folded units in the footwall of the LRF reached a point where a splay fault ruptured, thereby leaving the southern end of the syncline’s western limb overturned, while further north shortening was accommodated by faulting. This splay
constitutes a back-limb fault of an overturned syncline, thus leaving the appearance of inverted stratigraphy in the hanging-wall of the splay.

The Easternmost fold in Domain 2 (the syncline that runs through Heart Butte, along the eastern edge of the domain to the north) is the most pronounced structure of the domain and is observable over the length of the domain. It sits at the leading edge of the décollement bringing Paleozoic rocks up to Cretaceous. This may also be a back-limb thrust, though representing an upright limb of a fold similar to the back-limb thrust represented in Figure 27.

Figure 27: Fault-block diagram showing fold-fault relationships of upright fold limbs (Dahlstrom, 1970).
Overturned folds are observed along the western margin of the domain in conjunction with an increase in the frequency and intensity of folding and are consistently found in the footwall of the LRF. The overturned orientation of the folds is interpreted to be the result of overriding thrusts found proximal to the folds.

Figure 28: Structural domain map of Domain 3, highlighting major faults.
Domain 3

Domain 3 is made up predominantly of the Steamboat Limestone with a small section of Devonian found at Major Steele Backbone Peak, and is equivalent to Singdahlsen’s (1986) Domain IV. Numerous imbricate thrusts are observed striking longitudinally throughout the domain, repeating sequences of either Steamboat on Steamboat, or Steamboat on Switchback Shale (Figure 28). It is bounded to the east by the Major Steele Backbone thrust from Birch Creek, north to the base of Feather Woman Mountain. There, it steps back to the west where the Lookout Ridge thrust becomes the leading edge thrust and continues northward. The domain is bracketed to the west by the Hungry Man Creek thrust. This is the domain with the most closely spaced folding within the SRC. There are numerous concentric, isoclinal and overturned folds (Figure 11). There is a surprising amount of variation to the folding, even though it is comprised of one suite of rocks. However, this variation is due largely to the mechanical variability of the units as well as the proximity of folds to faults. Cambrian strata are comprised of limestone, shale and dolomite and the mechanical properties of these units allow for the diverse style of disharmonic deformation. Many of folds seen in Domain 3 are tight, isoclinal folds; moreover, these fold styles are predominantly found in the Cambrian Steamboat Limestone and Switchback Shale. The overall lack of competency of the Cambrian rocks allows them to deform in a more “ductile” manner than Mississippian and Devonian strata, often developing into Class 3 folds with layer thickness increased in the hinge zone and reduced on the limbs, as well as flexural flow
between Cambrian units in tight folds. However, where the Cambrian Devils Glen Dolomite crops out within the domain, there is a distinct shift in the style of folding due to its greater competency. Just south of Major Steele Backbone peak along the MSB ridge, on the eastern margin of Domain 3, the Devils Glen forms a syncline cored by structurally competent Devonian rocks. This fold style contrasts with what is seen throughout the SRC in folded packages of Steamboat Limestone and Switchback Shale, and while inter-limb angles of the folded Devils Glen are less than what is observed in Mississippian and Devonian units, they are greater than those seen elsewhere in the Cambrian. Moving east along the fold past its inflection point, it transitions from a syncline to a box anticline (inter-limb angle $133^\circ$), though only a portion of it is visible as the units terminate here at the range front (Figure 29). This marked difference in fold styles between adjacent units highlights the mechanical variabilities between units, and accounts for much of the structural variability found within domain 3.
Figure 29: Portion of a box anticline along the Major Steele Backbone. There is a gap in perspective between the units in the foreground and units in the background, creating the illusion of an undulating contact between Devonian and Cambrian.

The Switchback Shale acts as a detachment for the numerous imbricate thrusts found within Domain 3, and in the subsurface these faults are interpreted to sole-out into minor décollements within the Switchback Shale (Plate 2). The basal (shaley) portion of the Steamboat Limestone has been interpreted to be a separate unit incorporated as part of the Pentagon Shale (Ihle, 1988), which likely acts in the same manner as the Switchback Shale allowing faults to sole into it. However, as it was included as part of the Steamboat in this study, the map pattern just shows Steamboat thrust on Steamboat (as opposed to seeing an additional unit involved in deformation). Within the imbricate zones found in Cambrian units of Domain 3, variation in folding can
be attributed to the proximity of folds to major thrust faults found within the SRC. Folding intensifies proximal to these faults, as folds become tighter, inter-limb angles are less and the frequency of folding increases. The clearest example of this can be seen when looking at the units of Domain 3 as a single package, and observing the increased deformation as units approach the leading thrust of the domain, the Major Steele Backbone thrust (Figure 30). To the west the Steamboat Limestone takes on a concentric-style folding and folds are significantly more symmetrical; to the east however, the units become asymmetric, overturned and isoclinal where the Steamboat is thrust up in the hanging wall of the Major Steel Backbone thrust (Figure 30).
Figure 30: Photos showing spatial relationship between fold style and proximity to major faults. As Cambrian units get closer to the leading edge of the thrust system (Major Steele Backbone thrust (MSBT) and Swift Reservoir), deformation increases. Cartoon of fold transitions modified from (https://thehiddenwater.wordpress.com/geology/geological-structures/folds/)
Figure 31: Stereonets showing differences between folds and their proximity to major faults. A-C correspond to a fold in Figure 30 b. D-F correspond to the fold in Figure 30 c. A and B. Poles plotted along with pi-girdle and pi point showing orientation of fold axis. B and E. Poles plotted with 1% area contours designed to show symmetry / asymmetry of folds. C and F. Best fit planes of fold limbs designed to show differences in inter-limb angles of folds. Inter-limb angle in C. 13.4°. Inter-limb angle in F. is 121°.
Domain 4

Domain 4 (Figure 32) is comprised of the Paleozoic suite of rocks (Cambrian through Mississippian) and makes up the western portion of the map area. It is
bounded to the east by the Hungry Man Creek thrust, and to the south by Birch Creek.

The folding is somewhat diverse, owing to the relative diversity of stratigraphy. As seen previously in the other structural domains, there is a marked change in the fold and fault style between the units found within the SRC. The Cambrian Steamboat Limestone and Switchback Shale form tight, asymmetrical and isoclinal folds, while folds in the Devils Glen Dolomite show increased inter-limb angles. And where folding occurs in the Devonian and Mississippian units, inter-limb angles are further increased (Figure 33).

Figure 33: Mississippian Castle Reef Dolomite forming a syncline in the footwall of the Lookout Ridge thrust (faults shown in blue, folds in red; interlimb angle of syncline shown previously as 96°, photo facing northwest).
This again is due to the Devonian and Mississippian units consisting of more competent limestones and dolomites. There are two major faults that run through the domain (Jefferson Ridge thrust and the Killem Horse Creek thrust). These faults are distinguished by their direct involvement with large folds found in Domain 4. The branch point in the southern portion of the Lookout Ridge thrust facilitates the transport of the forelimb of a major anticline bracketed by the Jefferson Ridge and Killem Horse Creek thrusts. This is another example of the contemporaneous relationship between the growth of a fold and a fault as described by Dahlstrom (1970). Here, as the fault propagated to the east-northeast, the anticline was likely developing along the thrust as well as a fault-propagation fold. As shortening increased, eventually the fault ruptured in a splay and the displacement was transferred to the eastern limb of the Lookout Ridge thrust. This transfer of displacement accommodates shortening in thrust zones and can be seen in map view as an en echelon pattern of faulting.

Heart Butte Thrust Fault

The Heart Butte thrust is a key feature of the SRC. This one fault links Domains 1, 2 and 3 in its transfer of thrust displacement. At first glance, the Heart Butte thrust and its relationship to the Major Steele Backbone thrust and the Mitten Lake thrust could be thought of as a secondary transverse tear fault (Figure 22) (Dahlstrom, 1970). However, a number of factors work against the interpretation of a tear fault and point to that of a lateral ramp. The two scenarios are similar in that there is still a transfer of
displacement along the fault, differences in deformation styles can be observed on either side of the fault, and there may be a significant amount of stratigraphic separation. However, in a tear fault scenario, the Heart Butte thrust would likely have a steep dip, and a three-point problem from map data determined the thrust to be very low-angle (≈8 - 13°). Moreover, while there is a significant amount of Devonian and younger strata on the northwest (hanging wall) side of the fault, there is almost none to the southeast along strike of the Major Steele Backbone and Lookout Ridge thrusts, except for that seen at Major Steele Backbone Peak. Were the Heart Butte thrust a tear fault, it would be expected for there to be more indication of a block of upper Paleozoic rocks similar to those seen in Domain 2 that they would have “torn” away from.

However, as the abrupt change is likely due to the presence of one or more ramps, the units in Domain 3 were likely locked up by steep ramps, while the units north of the thrust had a gentler ramp angle to overcome.

Interestingly, this deformational sequence and the units involved bears a striking resemblance to the relationship between the Walling Reef thrust, Split Mountain tear fault and the Old Man thrust in the southern half of the SRC (Figure 34) (Singdahlsen, 1986). When interpreting those faults, the Walling Reef could be thought of as the Major Steel Backbone equivalent, the Split Mountain tear as comparable to the Heart Butte thrust, and the Old Man thrust representative of the Mitten Lake thrust. The Split Mountain tear transfers the displacement from the Walling Reef thrust to the northeast to the more forward Old Man thrust. In both settings Mississippian and Jurassic units
are juxtaposed against Cretaceous on opposite sides of the tear fault, as well as that of the leading edge faults (Mitten Lake and Old Man thrusts). There is also a marked distinction between the deformation styles on opposite sides of the tear fault; the north side showing a higher degree of imbrication, while the south side exhibits more folding. While there is a greater degree of imbrication directly adjacent to the Split Mountain tear fault, these imbrications appear to be truncated by the Split Mountain tear at nearly 90°. It is also worth noting is the contrasting displacement orientations of the Heart Butte thrust and the Split Mountain tear – the Heart Butte thrust having a right-lateral offset component, while the Split Mountain tear fault has left lateral. This distinction is significant in that it may imply a link between the development of these faults and the possible control rendered upon them from the subsurface geometries of the basement rocks.
Aside from the anomalous location of the Cambrian rocks in the SRC (along the range front), the pattern of their surface exposure is unique as well, forming an eyelid window (Figure 15 and Plate 1). This window is complicated by the fact that it is actually two eyelid windows, one to the southeast and one to the northwest of Feather Woman Mountain, thus forming a compound eyelid window. The map area comprises the majority of the southern window, which from here on will be referred to as the Swift Reservoir Eyelid Window (SREW). The bounding features of the SREW are the Swift
anticline and Birch Creek to the south, Cretaceous strata to the east, Feather Woman Mountain to the north, and Middle-Upper Paleozoic strata of the Devonian-Mississippian rocks to the west. The mapped area of Cambrian units that comprise the SREW is approximately 23 km², and while the units continue further to the southeast (Mudge and Earhart, 1983), Swift anticline forms a strike-parallel cutoff to the easternmost Cambrian units, thereby forming the southern cutoff for the eyelid structure; Feather Woman Mountain forms the northern cutoff. The northern window, hereby referred to as the Lookout Ridge Eyelid Window (LREW), has an area of ~10 km² with ~7 km² mapped from this project and an additional 3 km² inferred from Mudge and Earhart (1983). What characterizes these windows as eyelids are the cutoffs formed by the relative encroachment of the large Middle-Upper Paleozoic structures on the Cambrian thrust sheet. From south to north these are Swift anticline, Feather Woman Mountain and Little Plume Peak. The term “relative encroachment” is used, because while they are not thrust onto the Cambrian units, their presence is affecting the spatial distribution of Cambrian units at the surface. Each of these structures forms a strike-parallel cut-off to the northwest-southeast-striking Cambrian suite of rocks, and helps create the characteristic pseudo-eyelid map pattern found within the SRC. This is not to say that structures like Feather Woman Mountain are the only features controlling the structural development of the SRC, much of this may be due to the presence of subsurface ramps.
Figure 35: Example of a compound eyelid window similar to what is seen at the Swift Reservoir Culmination. Thrust faults are “cut-off” along-strike, disrupting the formation of a more classic eyelid window structure. Teeth on the fault traces represent the hanging wall of the fault.

The window structure observed at the SRC is significantly more complex than this, but the image in Figure 35 helps to visualize the complexities observed on the map in a simplistic manner.
Basement Anomalies

On a regional scale, research has shown that the development of the Northern Disturbed Belt has been affected by the geometry of the basement rocks (Mudge, 1982). Specifically, the development of the Sweetgrass Arch, directly to the east of the Disturbed Belt of Montana. When looking at the South Arch (a portion of the Sweetgrass Arch) there are two features, the Pendroy fault zone and the Scapegoat-Bannatyne trend, which are regional structural anomalies that trend roughly perpendicular to the overall structural trend of the Disturbed Belt. The Pendroy fault zone, Scapegoat-Bannatyne trend and the South Arch involve Precambrian basement rocks, and the Scapegoat-Bannatyne trend, when traced to the southwest, has been thought to have affected the development of the Northern Disturbed Belt (Mudge, 1982). The Scapegoat-Bannatyne trend may have impacted the development of the Disturbed Belt, as there is a marked change in the structural trend of faults where the Scapegoat-Bannatyne trend meets the Disturbed Belt west of Haystack Butte, MT. At this point there is a change in strike of the Disturbed Belt from north-south to northwest-southeast. The implication is that when the forward development of the Disturbed Belt encountered this anomaly, there was an adjustment to the overall structural trend of the units in the Disturbed belt (Reinecke, 1989). This adjustment is likely due to the presence of the Scapegoat-Bannatyne trend, a northeast-southwest trending collection of structural anomalies in the basement (Kleinkopf and Mudge, 1972). If anomalies within the basement have the ability to influence the development
of a mountain belt on a regional scale, smaller discontinuities within the basement may also affect the development of individual faults. Specifically, if preexisting features in the basement were encountered by a forward-progressing thrust sheet, these anomalies could influence the depth to which a décollement would cut, thus affecting the expression of stratigraphic units at the surface. Interestingly, these NE-SW trending features generally coincide with the Great Falls Tectonic Zone. The Great Falls Tectonic Zone has been thought to be a crustal suture zone between the Medicine Hat Block and the Wyoming Province (O’Neill and Lopez, 1985). Work by Lemieux et al. (2000) using high resolution magnetic data attempts to show that its role as a suture zone may be somewhat overstated. While looking at the zone at a larger scale, Foster et al. (2005) analyzed U-Pb zircon, as well as Sr, Nd and Pb isotopic data and concluded that the processes that formed the Proterozoic provinces surrounding the Wyoming craton were different from those that worked to form the craton itself. Regardless of whether or not the Great Falls tectonic zone is a crustal suture zone, there appears to be a correlation to the basement magnetic and gravity anomalies seen in northwest Montana.

With regards to whether these anomalies affected the development of the Disturbed Belt and the SRC, without the availability of seismic reflection data, one way to visualize the subsurface is through the analysis of magnetic and gravity data. Magnetic and gravity data was obtained from Montana’s Natural Resource Information System (NRIS) and the state’s GIS clearinghouse, and magnetic color maps were generated. On these maps, “warmer” colors represent positive anomalies, while
“colder” colors represent negative anomalies. These anomalies correspond to the relative densities of the rocks, whereby, the higher the anomaly value, the denser the rock. This allows for a certain degree of interpretation as to the basement structures.

When looking at the Sweetgrass Arch for example, there are observable magnetic anomalies that can be directly associated with the Pendroy fault zone as well as the Scapegoat-Bannatyne trend (Figure 36). These translate to southwest-northeast trending linear features on the map. “Hot” colors on the map represent increased magnetism, and are likely due to mafic sills and dikes that intruded into the basement.

Figure 36: Tectonic map of the northern Disturbed Belt and surrounding area with associated magnetic data. “Warmer” colors signify increased magnetism likely due to intruded mafic sills and dikes.
One of the most striking features is that of the magnetic relationship to the trace of the Lewis thrust, specifically surrounding Marias Pass. Following the trace of the Lewis thrust to the north, it makes an abrupt ~90° turn to the northeast at Marias Pass, and then another ~90° turn back to the northwest where it returns to following what is essentially the overall structural trend of the features found within the Northern Disturbed Belt. North of Marias Pass, there is a significant change in the magnetic signature of the rocks, where the magnetic field decreases directly west of the fault, while there is an increase to it just east of the Lewis thrust. As the Lewis thrust carries the Mesoproterozoic Belt rocks in its hanging wall, this change in the magnetic field could be due to the extreme thickening caused by the uplifting of the Belt Rocks, thereby increasing the distance (thickness) between the surface and the basement. Just southeast of the pass where the fault makes its abrupt change in strike to the northeast, there is an increase in the magnetic field in the footwall of the Lewis thrust, with an abrupt low to the northwest of the pass. If this increase to field is indeed a structural high of the basement with a structural low directly to the northwest, this could act as a lateral ramp in the basement, thus accounting for the abrupt change in strike of the Lewis thrust at Marias Pass.

The resolution of the magnetic data available for this project does not allow for a local/culmination-scale interpretation of structures. However, working on the assumption that basement anomalies are capable of affecting development of the Disturbed Belt on regional scale, it is fair to assume that similar features could exhibit
control on structural development at culmination-scale. A conceptual model of these possible basement anomalies is seen in Figure 37. The model is intended to demonstrate a stair-step pattern in the basement that could account for the expression of the units at the surface. The diagram depicts the levels to which the basal décollement would be able to cut to. Recesses shown at the Mississippian act as ramp-bounding systems for the Cambrian rocks where eyelid windows develop, while the bend along the base of the Cambrian level signifies the Lewis thrust’s turn at Marias Pass.

Figure 37: Schematic model representing depths to which the basal décollement may be controlled by subsurface features in relation to the Rocky Mountain Front, the SRC, the Lewis thrust and Marias Pass (not to scale) (Modified from Wilkerson et al., 2002).
While magnetic signatures of basement anomalies at the SRC are not visible for a culmination-scale interpretation, strike-parallel cut-offs observed in conjunction with the compound eyelid window structure observed in the Cambrian point towards some type of basement control on the geometries of the culmination.

**Cross-Sections**

Transverse cross-sections were plotted out perpendicular to major fold axes within the SRC in a grid-pattern, and spaced out to target significant structural features within the culmination (Plate 1). Features observed in outcrop were represented throughout the subsurface in cross-section. This is most apparent in the mechanical variability seen between units.

Section A-A’ (Plate 2) is in the southern end of the field area, and involves predominantly Mississippian-Devonian and Cretaceous units. Mississippian dominated rock packages show more fault-bend folding and less imbrication than the Cambrian and Cretaceous units near the surface. Moreover, out-of-sequence thrusts are interpreted where sections of Mississippian to Cretaceous units are truncated by the Mitten Lake thrust and the Cretaceous is thrust over by the Major Steele Backbone thrust. Moving north, the next cross-section is B-B’ (Plate 2). Here the Cambrian units are seen in much greater abundance, as well as their propensity for imbrication. The Major Steel Backbone thrust transports the Cambrian units over the Cretaceous succession of rocks, and there are distinct deformational differences between the units, highlighted by the
Cretaceous units suffering far less imbrication. Also notable is the absence of Mississippian and Devonian Rocks at depth. This is interpreted to be a result of strike parallel cut-offs of the Upper Paleozoic units, and possibly a lateral ramp at Swift Dam.

Section C-C’ (Plate 2) is the next northernmost cross-section. It has the most abundant amount Cambrian strata and some of the most structural variability observed in section. Sections C-C’ and B-B’ show good visual correlation between sections a sense of how the culmination varies at depth from south-to-north becomes clear. The relationship between the Major Steele Backbone and Lookout Ridge thrusts shows how to the north, Devonian and upper Cambrian are carried by the hanging-wall of the Major Steele Backbone thrust, and essentially capped by the Lookout Ridge thrust in its footwall. The hanging-wall units of the Lookout Ridge thrust become rotated to a steeper angle in a piggy-back fashion and west of the Lookout Ridge thrust the Cambrian units are highly imbricated. In the hanging-wall of the Lookout Ridge thrust, the development of a fault-propagation fold is observed, while the back limb of an associated syncline is truncated by the Killem Horse Creek thrust in an out-of-sequence fashion.

Section D-D’ shows decidedly different geometries, which are attributable to the abrupt change in stratigraphy within the section. This section is dominated by the Upper Paleozoic and Cretaceous rocks of the SRC. The Mitten Lake thrust is seen transporting Paleozoic over Cretaceous rocks, while the Lookout Ridge thrust is truncating the back-limb of a syncline in Domain 2. The units in the hanging-wall of the
Mitten Lake thrust are deformed into one large series of folds that appear to have experienced strong deformation by the Lookout Ridge thrust, where the units were being folded until the Lookout Ridge thrust cut across units and truncated the back-limb of the fold carrying the highly imbricated Cambrian rocks.

Section E-E’ is a longitudinal cross-section that runs in-between Heart Butte and Feather Woman Mountain. While it doesn’t show a large amount of structural variability, it crosses the Heart Butte thrust and helps to visualize the how the fault may steepen as it continues to the north.

**Out-of-Sequence Thrusting**

Throughout the cross-sections, there are numerous interpretations of out-of-sequence faults. While this runs contrary to the view that thrusts propagate in a hinterland to foreland progression, these occasions of out-of-sequence faults are localized, yet may shed light on how the culmination developed. However, while the regional sense of thrust progression may have been getting younger towards the foreland, localized sections showing out-of-sequence thrusts may have developed at the same time as the overall culmination. A number of these are seen truncating large folds (Plate 2, section A-A’, C-C’ and D-D’) and in each of those cases, the truncated folds involve Upper Paleozoic units. This model of simultaneous thrusting and development of the culmination is outlined by Boyer (1992) and uses the northern Sawtooth Range as an example of this sequencing. Specifically, he describes the development of the northwest end of the culmination just out of the field area where the Mississippian is
bounded on either side by Jurassic as being indicative of the synchronous thrusting model. There, the forelimb of a Mississippian fold is overlain by an imbricate stack of Jurassic, while on the back limb Jurassic units are observed over the Mississippian, but not in a tight stacking pattern. A similar relationship is seen on the western portion of the map area where Devonian rocks are seen at the surface in a fault-cored anticline with Cambrian units imbricated to a high degree on the forelimb (east side), while just to the west, are Devonian and Mississippian units that are not imbricated like the Cambrian. Another indication of simultaneous thrusting pointed out by Boyer (1992) is the presence of imbricate thrust faults in the hanging wall of the roof thrust of a duplex. This is witnessed in the hanging wall of the Major Steele Backbone thrust just north of Swift Reservoir.

**Petroleum Geology**

There are applications of this research relative to the petroleum industry. Specifically, the RMF continues to be an area rich in exploration, especially within the region of the inner foothills. The SRC may serve as an excellent outcrop analogue to other subsurface duplex structures along the RMF, specifically Shell's Waterton gas field in Alberta Canada (Figure 38).
There have been two wells drilled within the northern SRC (Blackfeet Tribal 12-1 and Mittens 1) and, further north just beyond the culmination, there were two more wells drilled as well (Kiyo 1 and Kiyo 1A). Each of these is located along the front of the range with the Mittens 1 well in the most structurally forward (eastern) position. These wells targeted the Mississippian Madison formation, which are the same units found to produce roughly 5.5 million cubic meters of raw sour gas on a daily basis. Shell’s field was discovered in 1957, and lies along the RMF in a similar tectonic setting as what is found in the SRC along the foothills of a major northwest-southeast striking thrust belt. In Waterton, structural traps were created when the Mississippian and Devonian rocks were thrust into duplex structures, with an overlapping anticlinal pattern (Mitra, 1986). Likewise, geometries of the Mississippian and Devonian units at Swift Reservoir (Plate 2, section A-A’) are interpreted to form similar structures in the footwall of the Major Steele Backbone thrust. Inter-beds of shale and impermeable limestones acted as seals for these traps while migration of the hydrocarbons took place via fault pathways (Hannigan et al., 1993). Ideally, when these wells were targeted in the area surrounding the SRC, the hope was for a similar discovery. While the potential source and reservoir
rocks are present in the SRC and below, the results of drilling did not produce. In this sense, the practicality of the SRC becomes its potential as a structural analogue to other productive structures along the RMF. The fact that the Mississippian carbonates found in the subsurface of the Waterton field are exposed at the surface of the SRC, as well as interpreted to be folded and stacked in the subsurface of the culmination in a similar fashion can be useful in interpreting the potential for similar structures along the RMF. As far as a source rock evaluation of the units is concerned, the presence of the Lewis thrust might have been a major factor with regards to burial versus maturity of the rocks. Clayton (1982) produced a source rock hydrocarbon evaluation of the Disturbed Belt, and notes a distinct lateral change in the maturity of the source rocks found east and west of the Lewis thrust plate. As the Lewis thrust carries the extremely thick section of the Belt rocks there is a significant change in the thermal history of the rocks when considering those that have been buried by the thrust versus those that have not. The Waterton field is essentially overlapped by the Lewis thrust, while the SRC is not. Moreover, Clayton’s (1982) study showed through lateral changes in the maturity of saturated hydrocarbons that the Lewis thrust would have extended at least 16 km further east than its present location. While the SRC is more than 16 km east of the Lewis thrust, the thrust may have continued further east at this latitude as opposed to the Waterton. The conclusion being that where the Waterton field is presently partially buried by the Lewis thrust (Keating, 1965), it likely was completely buried in the past, and this could very well have influenced the maturity of the source rocks found in each
setting. However, while there are similarities between the settings of both Waterton and the SRC, when assessing the hydrocarbon investigations conducted around the SRC factors other than maturity are likely to have had a significant impact. Notably, there is a lack of subsurface data in the region surrounding Swift Reservoir. Waterton and the region surrounding it have had numerous wells drilled as well as seismic investigations conducted, which has allowed for a very detailed picture of the subsurface compared to that of the SRC. There are numerous factors that may have curtailed success in the area. Subsurface geometries may be more complex leading to smaller pay zones, or an increased chance of missing a trap when drilling. Unknown fault arrays or subsurface karst topographies may have breached reservoirs, or at least influenced the migration pathways of hydrocarbons. There are many unknown factors could have affected potential reservoirs. However, there have been successful endeavors to the south and east of the SRC involving similar units, indicating that the lack of successful investigations in the area are likely due to more than just a lack of maturity of the source rocks. Regardless, due to the complex structural nature of the SRC coupled with the lack of subsurface data, when compared to Waterton it should be viewed as a structural analogue at best.
CONCLUSIONS

The Swift Reservoir Culmination has an extensive and complex deformational history. Its development is a result of contractional forces from the Sevier orogeny that formed the Disturbed Belt as well as the Sawtooth Range, which the Culmination is a part of. As the region was deformed, the numerous northwest-southeast striking thrust faults developed and contributed a considerable amount of east-west shortening that is found across the Sawtooth Range. These tightly-spaced west-dipping imbricate thrusts are the signature feature of the SRC and the Sawtooth Range. Moreover, while the SRC is littered with these imbricate thrusts, there are ten “major” faults that divide the culmination. A number of these major faults sole-out into décollements for the four imbricate zones (Eagle Creek, Major Steele Backbone, Haywood Creek and Saddle Ridge) that define a large part of the Culmination. The combination of these major thrusts and imbricate zones likely helped contribute to the formation of a subsurface duplex structure in the footwall of the MSB thrust sheet. Moreover, within the SRC, these imbricate zones and thrusts are supplemented by numerous folds found within the culmination. These folds exhibit an increasing amount of deformation where proximal to major faults and there is a generalized increase in deformation from west to east, especially where proximal to the leading edge of the culmination as a whole.

Deformation of the units within the SRC is controlled primarily by the mechanical properties of the stratigraphic units found within the culmination. This stratigraphic control on the culmination’s deformation history is exemplified by the
compartmentalization of the culmination into structural domains. These domains are
defined not only by their stratigraphic makeup but also by the deformational styles
found within them. Domain 1 is made up of Cretaceous rocks of the foothills and is
dominated by low angle thrusts and broader inter-limb angles of folds than found
elsewhere in the culmination. Domain 2 consists of Cretaceous and Jurassic strata,
dominated by northwest southeast striking folds. This domain is unique in the relative
lack of faulting that takes place within it, yet deformation is markedly increased with
proximity to the major faults that define its structural boundaries. This increase in
deformation comes in the form of overturned folds, decreased wavelength between
folds, and the truncation of folds by faults.

Domain 3 is dominated by the Cambrian suite of rocks with a small occurrence of
the Devonian section. The signature of this domain is the myriad of northwest-
southeast striking faults found throughout it. Moreover, not only is there the greatest
occurrence of thrust faulting found in Doman 3, but the greatest number of major faults
running throughout it. This in turn accounts for the largest amount of imbricate zones
found in the culmination. The folding in Domain 3 is significantly tighter than what may
be observed in the other domains, with many folds becoming isoclinal and overturned.
Here too, there is a distinct increase in the amount of folding where proximal to major
faults, and especially where close to the Major Steele Backbone thrust. From west-to-
east, folds in the Cambrian Steamboat Limestone can be observed transitioning from a
more symmetrical and pseudo-concentric style of folding to asymmetrical and
overturned as the Cambrian units ramp up onto the Major Steel Backbone thrust.

Furthermore, it is within Domain 3 that we see the characteristic strike-parallel cutoffs of faults that are a hallmark of the northern half of the SRC. These cutoffs shape the surface exposure of the Cambrian units into what can be described as a compound eyelid window, and may be attributed to structural geometries of basement rocks.

Domain 4 is characterized by the Paleozoic suite of rocks and has a wide array of faulting and folding. Here there is decreased imbrication as compared to what is seen in Domain 3. This is due again to the change in stratigraphy, and therefore a change in the mechanical properties of the units found within the Domain. The Mississippian and Devonian units found here are more competent than the Cambrian. This leads not only to reduced imbrication, where units are not soling-out into detachments with such frequency, but also, units are observed longitudinally for greater distances throughout the domain. This is in opposition to the Cambrian units of Domain 3 that form more of an en-echelon fault pattern which may be attributed to lateral displacement transfer between faults. The folds of Domain 4 also have increased wavelengths and inter-limb angles when compared to those found in Domain 3.

In each of these structural domains, where similar units outcrop, there are distinct similarities to the deformational styles found in those zones. For example, where the more competent units of the Devonian and Cambrian Devils Glen outcrop in Domain 3, we see an abrupt change in fold style in the form a box anticline. Moreover, where the Cambrian Steamboat Limestone and Switchback Shale outcrop in Domain 4,
there is a change in the frequency of faulting (increased imbrication) as well as their
surface expression, resulting in en-echelon and even anastomosing map patterns at
times.

While the Sawtooth Range and the Swift Reservoir Culmination are dominated
by northwest-southeast striking faults, within the SRC, the Heart Butte thrust is
antithetical to the regional structural trend. Domains 1 and 2 are separated by the
Heart Butte thrust Fault which brings Devonian and Mississippian units over Cretaceous,
in an orientation that is perpendicular to the overall structural trend observed
throughout the SRC and the Sawtooth Range as a whole. This creates a right-lateral
oblique component of offset to the thrust and transfers displacement from the Major
Steel Backbone to the Mitten Lake thrust. These attributes of the fault, coupled with
the amount of stratigraphic separation created via thrusting leads to the interpretation
that this fault reflects a subsurface lateral ramp as opposed to a secondary transverse
tear fault. This ramp is important because it allows the Mississippian units to cut-off the
exposure of Cambrian rocks. Furthermore, the Cambrian units form a compound eyelid
window that is for all intents and purposes created by the presence of subsurface lateral
ramps in the basement. These ramps were features present in the basement rocks prior
to the development of the SRC and the Sawtooth Range. Large-scale structures and
features in the basement are observable through magnetic and gravity maps.

Basement-associated structures directly east of the Northern Disturbed Belt such as
Kevin Dome and the South Arch are able to be delineated through these magnetic and
gravity maps, along with features such as the Pendroy fault zone and the Scapegoat-Bannatyne Trend. The Scapegoat-Bannatyne Trend has been shown to have impinged upon forward development of the Disturbed Belt resulting in a change in strike of faults where they came in contact with the trend. Large-scale basement features such as these give evidence for the effectiveness of preexisting basement structures to not only be visualized by magnetic and gravity data, but to be able to shape the development of the Sawtooth Range and the Disturbed belt. These were used as proxies for the presence of basement anomalies within the SRC and along the RMF northwards towards Glacier National Park and Marias Pass. Contour maps of magnetic data along the RMF and around the SRC show possible magnetic anomalies that could account for the presence of basement structures, though at a culmination-scale resolution of the contours magnetic data was insufficient for appropriate interpretation. These potential basement anomalies may in turn be accountable for the strike parallel cutoffs found adjacent to Swift Anticline, Feather Woman Mountain, and little Plume Peak, as well as the two 90° turns the Lewis thrust makes at Marias Pass. Thus, the fault-cutoffs found within the SRC could be thought of as a miniature analog to what is seen regionally in regards to the trace of the Lewis thrust and its relationship to Marias Pass and Glacier National Park. Moreover, these discontinuities found within the basement rocks along the RMF effectively control the depth to which the basal décollement is able to cut. This creates an undulation to the décollement along the range front, where, moving north-northwest from Swift Reservoir along the regional structural trend, the décollement
effectively cuts up-section in a stair-step fashion before plunging to a depth capable of bringing the Precambrian Belt rocks to the surface in the hanging wall of the Lewis thrust at Glacier national Park. Additionally, this model of coupling available magnetic and gravity data along with preexisting geologic maps in order to identify strike-parallel fault-cutoffs associated with magnetic anomalies can be an effective means of identifying subsurface geometries where seismic and well-data are not available.

Finally, while the potential for petroleum exploration in and around the SRC has so far been unsuccessful, its greatest asset may be as a structural analog for other subsurface duplex systems along the RMF. The rocks present in the culmination have been proven productive in other petroleum systems, while the exposure and diversity of structures found within the SRC are second-to-none in both complexity and the fact that these same structures have been successfully tapped in other areas of the Disturbed Belt.
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APPENDICES
APPENDIX A

STEREONETS
Figure 39: Stereonet of fold in Cambrian Steamboat Limestone at Station SR-151

Figure 40: Stereonet of fold in Cambrian Steamboat Limestone at station SR-165
Figure 41: Stereonet of fold in Mississippian Castle Reef Dolomite at station SR-170

Figure 42: Stereonet of fold in Cambrian Steamboat Limestone at stations SR-173
Figure 43: Stereonet of fold in Cambrian Steamboat Limestone at station SR-177
Figure 44: Stereonet of fold in Cambrian Steamboat Limestone at station SR-183

Figure 45: Stereonet of fold in Mississippian Allan Mountain Limestone at station SR-194
Figure 46: Stereonet of fold in Cambrian Steamboat Limestone at station SR-205

Figure 47: Stereonet of fold in Cretaceous Kootenai Formation at station SR-210
Figure 48: Stereonet of fold in Cretaceous Kootenai Formation at station SR-239
APPENDIX B

DIP ISOGON DATA
Figure 49: Class 1A fold in Mississippian rocks below Swift Dam showing dip isogons
Figure 50: Plot of normalized orthogonal thickness vs the difference between isogon and axial trace angle for fold in Figure 49
Figure 51: Class 1C fold in Mississippian rocks in Domain 4 showing dip isogons
Figure 52: Plot of normalized orthogonal thickness of limbs vs the difference between isogon and axial trace angle for fold in Figure 51
Figure 53: Class 3 fold in Cambrian Steamboat Limestone along Birch Creek showing dip isogons
Figure 54: Plot of normalized orthogonal thickness of limbs vs the difference between isogon and axial trace angle for fold in Figure 53
Figure 55: “Fish-hook” fold in Cambrian Steamboat Limestone showing dip isogons
Figure 56: Plot of normalized orthogonal thickness vs the difference between isogon and axial trace angle for fold in Figure 55
Figure 57: Class 3 fold in Cambrian in domain 3 showing dip isogons
Figure 58: Plot of normalized orthogonal thickness of limbs vs the difference between isogon and axial trace angle for fold in Figure 57
Figure 59: Class 1B to 1C fold in Cambrian rocks in Domain 3 showing dip isogons
Figure 60: Plot of normalized orthogonal thickness of limbs vs the difference between isogon and axial trace angle for fold in Figure 59
APPENDIX C

PLATES