Structural Analysis of a Triangle Zone Culmination, Comb Rock, Lewis and Clark County, Montana

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STRUCTURAL ANALYSIS OF A TRIANGLE ZONE CULMINATION,
COMB ROCK, LEWIS AND CLARK COUNTY, MONTANA

By

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A triangle zone is a structure commonly found at the leading edge of a thrust belt, characterized by a triangular cross-section of thrust faults. In the Montana triangle zone, west-dipping thrust faults intersect east-dipping ones above a regional detachment fault. Most studies of triangle zones focus on the structure in a cross-sectional sense, but little work addresses variations along the trend. The Canadian Rocky Mountain triangle zone has long been a productive petroleum province, so understanding the southern extent of this zone, where it enters Montana, is of interest for economic purposes as well as geologic understanding. Previous studies have concluded that the triangle zone continues into Montana, and this study interprets the triangle zone an additional 25 km farther south. This area is, however, more complex than previously thought.

The triangle zone in Montana undulates vertically in a system of culminations and depressions. The surface geology of the area was mapped in detail in the early 1960’s by the United States Geological Survey (USGS), but the subsurface interpretations were made before triangle zones were identified in the area. Multiple cross sections were created in this study to update these interpretations. Select areas from the USGS Comb Rock quadrangle in Lewis and Clark County, Montana, were studied in detail to locate, measure, and document a culmination of the triangle zone. Erosion of the culmination produced structural windows through the triangle zone, whereas the neighboring depressions preserve the overlying thrust plates. Strain accumulation in shale units, specifically the Marias River Shale, as well as thick igneous sills elevated the culmination. In addition, penetrative deformation styles and disharmonic folding were documented in three formations in the study area: the Telegraph Creek Formation, Marias River Shale, and Blackleaf Formation. This allowed for a new interpretation of triangle zone formation to be made that helps to explain the structurally thickened units that are commonly found near the apex of the blind thrust. This interpretation closely examined the geometries necessary to create a triangle zone and found a thrust angle discrepancy that can be accommodated by extra material being piled up on the thrust flat.
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1. INTRODUCTION

A triangle zone is a structure along the frontal edge of a thrust belt that is characterized by thrust sheets that were displaced in the same direction as overall thrust sheet emplacement to create a ‘duplex’ fault system, as well as an overlying, sub-regional ‘antithetic’ thrust sheet that was relatively displaced in the opposite direction (Jones, 1996). The area where these oppositely displaced thrust sheets meet creates a triangle in cross-section when combined with the detachment surface on the “floor” of the duplex. The antithetic fault forms when the thrust system becomes a ‘passive-roof’ duplex (Couzens and Wiltschko, 1996). Commonly, a shale unit at the base of the passive-roof allows the newly-formed tectonic wedge to split the rock layers and raise the roof thrust.

![Figure 1: Passive-roof duplex model (Banks and Warburton, 1986)](image.png)

Units in the passive-roof typically deform through folding as opposed to thrust faulting that is typical underneath (Fig. 1). Thrust faults do not propagate to the surface and begin to stack on top of one another underneath the roof. This lifts the roof upward and creates a prograding monocline on the limb of a ‘foreland syncline’. Foreland synclines occur in most areas that are hypothesized to have a triangle zone system present in the subsurface, such as the Alberta syncline in the foreland of the Canadian Rocky Mountains at the edge of the well-documented Canadian triangle zone (Price, 1981; Jones, 1982; Price, 1986; Sanderson and Spratt, 1992;
Skuce et al., 1992; Lawton et al., 1994; Jones, 1996; Skuce, 1996; Slotboom et al., 1996). The Alberta syncline continues south into Montana, becoming the Augusta syncline. In Montana, west-dipping faults define the western boundary of the triangular structure (closer to the Rocky Mountain front), and antithetic, east-dipping faults and a broad syncline define the eastern boundary of the zone. The Montana triangle zone structure trends roughly northwest and parallels the Rocky Mountain front. Though the areas of Montana and Alberta may be parts of the same overall structure, they differ due to changes in total displacement of the Rocky Mountain thrust system. Sears and Hendrix (2004) suggested that the thrust system rotated clockwise about an Euler pole located near Helena, MT (Fig. 2). The Montana triangle zone experienced about one fifth (~50 km compared to ~250 km) of the maximum thrust displacement of its Canadian counterpart. The triangle zone structure did not extend past the Euler pole, and therefore terminated somewhere near Helena.

Distribution of rock ages and plunges of fold axes indicate that the triangle zone in Montana undulates vertically. In the study area, the Comb Rock culmination has been preferentially eroded to expose the rock units that lie beneath the passive-roof. Northward, the structure
plunge downward and the passive-roof is preserved in a depression. To the south, deeper units are brought to the surface in a large north-plunging structure called the Craig Anticlinorium. These exposures allow for a deeper understanding of the system as a whole.

The origin of the Comb Rock culmination is unknown. Dolberg (1986) suggests that, in a nearby area of the triangle zone, units may have been lifted by strain accumulation in underlying shale units, especially the Marias River Shale, which developed small-scale internal fault duplexes that mimic the overall structure. These fault duplexes created bulges in the shale in some areas and allowed it to nearly pinch out in others (Fig. 4). These bulges will be referred to as MUSHWADs (Malleable, Unctuous Shale, Weak-layer Accretion in a Ductile duplex) (after Thomas, 2001). Another possible cause for the culmination could be additional faulting and imbrication of the overlying and underlying rock layers, in addition to the Marias River Shale. This type of faulting can raise the passive-roof upwards into a culmination. The local presence of thick and structurally competent igneous rocks provide another possible explanation for the Comb Rock culmination. Igneous intrusions are common in the area and could have inflated the strata to create the culmination. In addition, the Adel Mountain volcanics lie just to the east of

Figure 3 - Index map highlighting the area of the main study area relative to other geologic features in the region. Study area shown in red dashed box. Modified from Henry (2007) and Constenius (1996).
the triangle zone structure, adjacent to the culmination. Increased competency of the rocks in this volcanic field could have locally changed the dynamics of the thrust front as it rotated eastward.

In Canada, the triangle zone is valuable petroleum province (Jones, 1982). Thrust fault imbrications present in the subsurface of the passive-roof duplex created traps for buoyant hydrocarbons. To the east of the apex of the triangle zone, the passive-roof itself acted as a seal due to a shale layer that is invariably present at its base, and which lowers permeability sufficiently to stop hydrocarbon migration. Thermal maturity of the hydrocarbons correlates with proximity to the thrust front as the heat necessary for source rock maturation was linked to burial by overthrust sheets within the Rocky Mountains to the west. Heat contributions from the overlying hanging wall was sufficient to generate hydrocarbons. Source rocks too far to the east of the “disturbed belt”, as the Rocky Mountain front is commonly called, are immature, whereas those closer to the disturbed belt are more thermally mature and occupy the oil to wet gas temperature window (Clayton et al., 1983). Previous investigations attempting to demonstrate a relationship between the Montana and the better-known Canadian triangle zone stressed the economic and geologic significance of investigating its petroleum potential (Bradway, 2007; Henry, 2007).
Documentation of a culmination in the triangle zone has economic implications. Structural highs within a triangle zone will produce petroleum traps in three dimensions and the Rocky Mountain triangle zone is close enough to the disturbed belt to be thermally mature (Clayton et al., 1983). Furthermore, this culmination may be a response to strain accumulation and thickening of the Marias River Shale unit. In a source rock evaluation of the disturbed belt region units, sections of the Marias River Shale were noted to have the greatest quantity of organic matter, with an average of 2.4% by weight, and pyrolytic hydrocarbon yields in excess of 10,000 ppm (Clayton et al., 1983). Thickening of this unit moved additional source rock into a structural trap, and the shale unit could act as a seal as well, since multiple imbrications could have the layer repeated multiple times, between impervious fault zones (Dolberg, 1986). These fault duplexes create culminations in the shale in some areas and cause it to nearly pinch out in others (Fig. 4).

The present study was undertaken to test the hypothesis that the triangle zone continues southward toward the proposed Euler pole near Helena. The study area was chosen because the Comb Rock culmination and Craig Anticlinorium expose several stacked thrust sheets and windows, which permit examination of deeper levels of the putative triangle zone structure.
2. METHODOLOGY

1. *Field measurements of the Comb Rock culmination to better constrain the plunge of the structure.*

This study primarily focused on field mapping and structural measurement in the northern area of the 1:24,000 USGS Comb Rock Geologic Quadrangle (Schmidt, 1972a). An iPhone 5S with an application entitled *Field Move Clino* was used to take 1,421 measurements of exposed bedding planes and fold axes (Version 2.3.3, Midland Valley Exploration Ltd., 2016). This application enables measurements to be taken and geo-referenced quickly and accurately, using WGS84 datum. In addition to measurements, notes and photos were recorded and geo-referenced. A Brunton® compass and Garmin eTrex GPS unit were used to validate these measurements. Due to the fact that the rocks of the study area were commonly deformed by folding, the area provided many opportunities to record the orientation of the culmination as a whole. The measurements were input into a program called *Stereonet* which was created by Dr. Rick Allmendinger of Cornell University (Version 9.9.3, Allmendinger, 2017). This provided a lower hemisphere projection of the beds involved in the folds and of the axes of the folds. While in the field, measurements were plotted into a preliminary stereonet using the *Field Move Clino* software. Measurements were also sorted by location, formation, and type (bedding surface, lineation, cleavage, etc.) and then displayed on the iPhone 5S. This was used as an affirmation while in the field to resolve structures. All stereonets utilized in this study were created using the computer software *Stereonet 9.9.3* since it allows for
more fine-tuning and gives more information as to the attitude of the structures as a whole.

2. **Analyze well-log data from the area to determine if the Comb Rock culmination corresponds with thickening in the Marias River Shale.**

There are 127 wells with geophysical logs available in the study region. Data from 8 nearby wells calibrated cross sections. Formation tops were picked to better understand the subsurface structure and thickness variations in the Marias River Shale and Blackleaf Formation.

3. **Interpret geologic maps of the Comb Rock culmination.**

The currently available geologic maps of the culmination were completed by Schmidt, 1972a) before the triangle zone was recognized along the Rocky Mountain front. While the surficial geology shown on the maps is accurate, the structural interpretation was updated based on triangle zone geometry seen elsewhere on the Rocky Mountain Front in Montana.

4. **Construct geologic cross-sections of the triangle zone, Craig Anticlinorium, and Comb Rock culmination.**

Using the measurements taken at the surface and the data from well logs, balanced geologic cross-sections were constructed across the triangle zone structure to evaluate the culmination in the triangle zone. Plunge data were used to project structures from the Comb Rock culmination into the neighboring depressions.
3. STRATIGRAPHY

All rock units exposed in the field area are of Cretaceous age. However, older rocks have been identified in nearby well logs and were included in cross sections. They emerge to the SE in the core of the Craig anticlinorium, which plunges NW into the study area. The following stratigraphic column and field photos highlight the structural behavior of the units that are involved in the thrust structures of the area. For additional stratigraphic information, see Appendix 8.1 which describes all rock units in detail with field photos.
Figure 9 - Imbrications in the Marias River Shale in the Pishkun irrigation canal near Sun River Canyon, MT. Folds and faults can be traced by repetition of a triplet of white bentonite layers within the otherwise black shale. The Madison limestone of the Mississippian System can be seen in the background thrusted above this section of the Cretaceous System. The Mississippian limestones of the area deform brittely and create large, imbricated thrust sheets. Smaller-scale imbrications within the Marias River unit cause the shale to increase in thickness near the apex of a triangle zone which causes the mushwad. Canal is 10 meters deep and the triplet of bentonite layers is a meter thick.
Figure 10 - Stratigraphic column showing thicknesses of rock units in the study area and mechanical properties. Rocks exposed at the surface in the study area are outlined with a black rectangle.
4. STRUCTURAL ANALYSIS

This chapter describes and interprets the geologic structures found within the study area. This includes measurements and observations of the Comb Rock Culmination (field area) and subsurface reinterpretation of larger geologic structures to the south (study area). All of the structures observed in the study area and vicinity are folds and thrust faults, however, normal faults are interpreted to exist. The vast majority of the faults are east-vergent, however there is evidence for west-vergent thrust faults and folds. This study incorporates data from several previous studies of the area to create a better subsurface model of the triangle zone’s evolution along strike. To the north, two studies were conducted to evaluate the potential existence of a triangle zone along the Rocky Mountain front in Montana (Bradway, 2007; Henry, 2007). Throughout the study area for this project and farther to the south, USGS geologists created a stratigraphic handbook (Schmidt, 1978), mapped the surficial geology, and drew cross sections based on conventional knowledge during the 1960’s and 1970’s (Schmidt, 1972a; Schmidt, 1972b; Schmidt, 1972c; Schmidt and Strong, 1972). Since the development of the triangle zone concept post-dates these studies, a reinterpretation of the USGS surficial data is one of the goals of the present research.

![Image](image_url)

*Figure 11 - Cross Section A-A’ from Henry (2007) was created to explain the area just to the north of this study area. Left is southwest and right is northeast.*
4.1 Regional Triangle Zone Structure

The study area and adjacent regions to the north and south show that the Montana triangle zone contains a series of culminations and depressions, consistent with studies that show that a passive-roof duplex system can create windows and depressions depending on the degree of subsurface imbrication (Boyer and Elliott, 1982). A culmination can be raised by fault imbrication of units, by thickening of units through internal deformation, or by igneous intrusion. The Marias River Shale, Telegraph Creek Formation and Blackleaf Formation are all internally deformed, with steep dips at the surface across large areas of the study area. This implies that the units themselves are regionally flat, but horizontally shortened and internally crenulated, which generates steep dips and vertical thickening. Borehole data from eight wells within the study area show that the Marias River Shale and the Blackleaf Formation are much thicker (up to 200% of original mapped thickness) in the subsurface than would be expected given stratigraphic studies of the area (Viele, 1960; Viele et al., 1965; Schmidt, 1978). This implies not only internal deformation, but imbrication of the units; both of which act to thicken the rock units. In the Comb Rock Culmination field area, six igneous intrusions come to the surface only where the Marias River Shale or Blackleaf Formation are exposed.

Near the Auchard Creek anticline (northwest of field area 5-10 km), the Krone 31-32, Augusta Krone 31-32, and Soap Creek Cattle Co. A-1 wells reported the Blackleaf Formation, Kootenai Formation, and Jurassic, Mississippian, and Devonian systems at much shallower depths than predicted from the gentle regional westward dip of the undisturbed foreland (see Fig. 30 in the appendix for well locations). Units return to an expected location given regional dip in the Steinbach 1 well and the Milford Colony 1 well which lie 12.5 km to the southwest and 11.3
Figure 12 - Regional geologic maps showing the area surrounding the culmination field area (outlined in thin black), large thrust faults of the study area (traced in thick black with teeth), and the study area (area inside the 1:24,000 map extent). The background map is from the MBMG and was originally 1:100,000 and the 4 USGS geologic quadrangles in the lower right have been stitched together and were originally 1:24,000. The 1:100,000 map used data from the 1:24,000 maps so they have been overlaid to show more intricate structures. Well locations are seen as green dots. Well names can be seen in figure 30.
km east of the Soap Creek Cattle Co. A-1 respectively. The Steinbach 1 well and the Milford Colony 1 well are interpreted to represent the regional, undisturbed location of units. The interpretation for the area between these two well locations is that a large blind thrust fault duplicated the Devonian through Cretaceous section. The hanging wall anticline of that blind thrust is seen as the Craig Anticlinorium to the south. For simplicity, this thrust fault will be referred to as the “blind thrust” throughout this analysis.

In the Comb Rock culmination of the triangle zone, the Blackleaf Formation lies 1670 meters structurally higher than its regional depth. The majority of the imbrications lie within the Blackleaf and Marias River shales due to their tendency to deform disharmonically and their overall ductility, whereas the blind thrust fault rigidly duplicated the Devonian through Kootenai Formation section, as shown in Cross-Section A-A’ (Fig. 16).

The large Craig anticlinorium lies to the south of the Comb Rock culmination. This NW-plunging structure is defined by a steeply-dipping west limb, a mildly-dipping east limb, and a core of Marias River and Blackleaf shales. There has been little work done to interpret the internal structure of the feature, and it is commonly interpreted as simply a large anticlinal feature. Through analysis of multiple bore-holes and geologic maps of the area, the anticlinorium is here interpreted as the result of fault bend folds above the ramp and flat of the blind thrust fault. On the western edge of the Comb Rock Quadrangle geologic map (Schmidt, 1972a), multiple klippen of Cambrian strata are remnants of large thrust faults along the Rocky Mountain front. One such klippe overlies the Willow Creek Formation in a deep structural depression between the Rocky Mountain front and the anticlinorium. The depression defines the flat at the base of the footwall ramp of the blind thrust. At the surface, a west-dipping homocl ine of units from the Willow Creek Formation down to the Telegraph Creek Formation defines strata tilted to
the west over the west-dipping footwall ramp. The homocline passes eastward into a broad region of disharmonic folds that overlie the footwall flat where the blind thrust overrides the Kootenai Formation in the subsurface. This flat continues east for about 10 km whereupon the units tilt eastward in a hanging wall cut-off fault-bend fold. The blind thrust therefore has some 11.25 km of eastward displacement. At the nose of the blind thrust, the top of the Kootenai Formation dips to the east into the foreland syncline which is commonly associated with triangle zone structures. This syncline preserves the Adel Mountain Volcanics, whose east edge is essentially autochthonous with respect to the foreland basin. Therefore, the 11.25 km displacement of the blind thrust must be accommodated by its insertion into the foreland basin beneath the Adel Mountain Volcanics. The east-dipping thrust fault that defines the triangle zone was not mapped in this area by earlier workers, but likely follows the west edge of the Augusta syncline, as it does farther to the north (Bradway, 2007). The western edge of the Adel Mountain Volcanics was reported to be much more deformed than the rest of the formation (Schmidt, 1978), which would be expected given the structural conditions shown in Cross Section A-A’ (Fig. 16).
Displacement increases to the north along the Rocky Mountain Front. On a large scale, this equates to about 50 km of displacement throughout the study area and 250 km of displacement at the maximum in Canada (Fig. 2). On a smaller scale, displacement increases from the south to north within the study area. This increase in displacement is accommodated by an increase in the number of imbrications in the foreland. At the southern extent, near the town of Wolf Creek, there is just one blind thrust in front of the larger thrust sheets carrying Precambrian rocks. Seven km to the northwest, this thrust splits its displacement as the Two Medicine Formation begins to duplicate at the surface (Fig. 15). This displacement split also affects the Craig anticlinorium as its northwesterly plunge immediately lessens at the same point. The fault, here referred to as “imbricate thrust” continues to the northwest and gains displacement as the Two Medicine Formation is almost completely duplicated (Fig. 17). Both the blind thrust and imbricate thrust sheets have separate klippen of Cambrian strata in structural lows (visible in Fig. 14) which are interpreted as the flat-ramp transition. This implies that the two thrust sheets have individual ramps that are defining these separate structural lows. The imbricate thrust turns westward near the lower third of the Comb Rock Quadrangle (Schmidt, 1972a) and leaves the higher resolution (1:24,000) mapping. However, the imbricate thrust can be traced to the northwest on the larger, lower resolution map. For the first 40 km of the fault (measured from the original split), the imbricate thrust appears to do little more than duplicate the Two Medicine Formation at the surface. After 40 km, displacement increased sufficiently for the imbricate thrust to carry Mississippian rocks to the surface. This transition appears to happen somewhat rapidly as the imbricate thrust surficially stays within the Two Medicine for the entire study area, but when it crosses the Dearborn River near Brown’s Lake to the north of the study area, it emerges from the mapped Quaternary alluvium carrying the Kootenai Formation and the
Mississippian System (Fig. 12). This is interpreted as a lateral ramp along the fault that allows the deeper units to become involved in the thrusting. At the split of the blind thrust and imbricate thrust, this study interprets the imbricate thrust to originate in the Blackleaf Formation due to its widespread involvement in deformation throughout the study area. The lateral ramp allows the thrust to propagate deeper and to begin carrying the Kootenai Formation and ultimately the Mississippian System. Dolberg (1986) interpreted these imbricates farther to the north and determined that these many of these thrusts plunge beneath the larger thrust plates carrying Precambrian rocks. The imbricate thrust does not seem to follow this overall trend as it lies in front of the Precambrian-bearing thrust sheets.

Between the Craig anticlinorium and the Comb Rock culmination, a ~10 km strike length of Two Medicine Formation is discretely folded and faulted. Erosional windows expose deeper units (Marias River Shale and Blackleaf Formation) that are penetratively deformed as opposed to the discrete deformation in the overlying rocks (Fig. 13). This change in deformation style implies one detachment must lie between the brittlely deforming rocks of the Virgelle Sandstone and Two Medicine Formation and the penetratively deforming rocks of the Telegraph Creek Formation, Marias River Shale, and Blackleaf Formation, and another must underlie the Blackleaf Formation. These detachments define the shear zone at the apex of the triangle zone as shown in Cross Section A-A’ (Fig. 16).
Figure 14 - Composite geologic map created from Schmidt (1972a and 1972b) with annotations showing Cross Section A-A', the Culmination Study Area (purple outline), local highway names, and the fold axis of the Augusta syncline. The Adel Mountain Volcanics are seen on the east side of the map in pink and red, the Craig Anticlinorium is seen in the south center of the map plunging to the northwest, the Kevin Member of the Marias River Shale is brown and is easily traced through the Anticlinorium and in the culmination. Areas of light green represent the eastern facies of the Two Medicine Formation, but the pinks, reds, and purples present on the western side of Cross Section A-A' represent the western facies of the Two Medicine Formation. Cambrian klippen from earlier thrust sheets are visible on the western edge of the map in olive color surrounded by the light blue of the Willow Creek Formation and the gray of the St. Mary’s River Formation. Igneous intrusions are shown as white with red stipple (coarse-grained) and bright yellow (fine-grained). Cross Section B-B' is seen in the northern part of the map and runs across the Comb Rock Culmination.
Figure 15 - Composite geologic map from Schmidt (1972a and 1972b) with annotations showing the surface expressions of the Blind Thrust Ramp (dark blue), Shear Zone (Blind Thrust Flat)(green), and the Passive Roof of the Triangle Zone (light blue). In addition, map shows approximate location of the suspected igneous intrusives underneath the Comb Rock Culmination which are the cause of that culmination. Intrusives flowed from SW to NE in the red shaded area and first come to the surface at the SW edge (white with red stipple). Later expressions are seen in the Comb Rock Culmination where Comb Rock and subsequent igneous intrusives create high topography and a structural high as well. This map also shows the location and plunge direction of the Craig Anticlinorium which is here interpreted to represent a mushwad within the shear zone of the triangle zone structure.
Figure 16 - Cross Section A-A’ across the Craig Anticlinorium showing Blind Thrust geometry
Figure 17 - Cross Section D-D' is a composite section with Cross Section A-A'. This cross section crosses the Eldorado Thrust fault which carries Precambrian rocks on top of Cretaceous rocks. This section also crosses the imbricate thrust which duplicates the Two Medicine Formation at the surface. The bend in section is located right at the apex of the triangle zone and the remainder of the section is also part of Cross Section A-A'.
4.2 Comb Rock Culmination

Sitting roughly seven km NW of the Craig anticlinorium is a unique rock formation referred to as Comb Rock, due to its resemblance to the hair-care product. This quartz monzonite dike is ~25 meters thick, stands ~100 meters over the surrounding grasslands, and extends for about a kilometer along strike. It has vertical fractures that resemble columnar joints on its
southern edge. These fractures combined with its long, tall, and thin appearance helped to give the rock its name.

Comb Rock stands alone as the sharpest dike standing in the area, but in the vicinity, 5 other quartz monzonite dikes or sills are exposed, but none are preserved with the same rigidity. These rocks support some of the highest topography around, but where the rock itself is fractured and broken the hills are rounded instead of sharp, like Comb Rock. Comb Rock is phaneritic, while the other dikes or sills are porphyritic (Schmidt, 1972a).

Well logs from the surrounding area report stacks of as many as 5 igneous sills in section from the Devonian Jefferson Formation through the Cretaceous Blackleaf Formation, with a prominence in the Blackleaf Formation. The igneous intrusions are here interpreted to be responsible for raising the structural levels of the triangle zone in the Comb Rock culmination.

Local wellsite geologists confirm numerous sills in the area; the Augusta-Krone 31-32 well 8.4 km to the northwest of Comb Rock encountered over 400 meters of igneous rock, similar in composition to the exposed dikes and sills in the area of the Comb Rock culmination (Large, personal communication, 2017). This rock was reported to grade from solid white to a greenish hue nearer to the bottom. This color change could potentially be evidence of a large igneous body that fractionated as it cooled. It is not known whether one large body sourced the Comb Rock dikes and sills upward, or if multiple sills broke toward the surface, but the majority of intrusive igneous bodies in the area are split into multiple dikes and sills as opposed to one large laccolith.

To better describe the structural geology of the Comb Rock culmination, the area is divided into Comb Rock West, Comb Rock Central, and Comb Rock East. These subdivisions
reflect changes in fold structures on either side of Comb Rock, and changes in rock units exposed at the surface.

Figure 19 - Map showing the culmination study area with subdivisions highlighted.

4.2.1 Comb Rock West

Comb Rock West covers over 8.5 km$^2$ and extends to the north and west boundaries of the Melaney Ranch. Comb Rock West is dominated by the Two Medicine Formation, Virgelle Sandstone, and Telegraph Creek Formation. It extends southeast to the area where the Marias River Shale and Blackleaf Formation become the dominant rock units exposed at the surface. This transition is blurred by the lack of outcrop but the boundary is based on the outcrops seen in this study and those mapped by Schmidt (1972a). To
the southwest, the boundary was based on the overall trends of the folds in the area and divides
the folds into NW plunging and SE plunging domains.

Stereonet plots of beds in Comb Rock West define large-scale folds (100’s of meters) that
plunge northwest (Fig. 20). Synclinal folds are typically cored by Two Medicine Formation and
anticlinal folds are cored by Telegraph Creek Formation. Plunging Syncline 1 was defined by 90
bedding plane measurements. A stereonet plot shows the trend and plunge of its axis (Fig. 20).
The resistant beds that outline this fold in the satellite view are sandstone beds within the
Telegraph Creek Formation, Virgelle Sandstone, and Two Medicine Formation (Fig. 21). The
anticline to the west of Plunging Syncline 1 appears to have a similar trend and plunge, but the
ridge which defines the western edge did not provide useable measurements for stereonet
analysis. In addition, the poorly exposed core of the anticline did not yield many measurements.
It is likely that the shallow dipping beds in the crest of the anticline were severely fractured. A
dendritic gulley system transects the anticline but skirts the edge of the syncline. At the southern
extent of Figure 21, the anticline is cored by Marias River Shale as it intersects Comb Rock. The
folds in this subdivision of the Comb Rock field area are projected onto an inset of Cross Section
B-B’ (Fig. 25).
Figure 21 - Satellite view of Plunging Syncline 1 clearly shows folding as the more resistant rock units create topography expressed on the surface. There is a plunging anticline to the west of Plunging Syncline 1, but the western margin of the fold is not well exposed which yielded poor, one-sided stereonet results. Strike and dip measurements are shown as blue dots.

4.2.2 Comb Rock Central

Comb Rock Central extends from the northern boundary of the Melaney Ranch to Comb Rock. This subdivision covers over five km². A large percentage of the surface area of the central subdivision exposes different members of the Marias River Shale. Near Comb Rock and Auchard Creek, the Marias River Shale contacts the Vaughn member of the underlying Blackleaf Formation. The stratigraphy steps up eastward from Comb Rock, indicating an overall eastward
dip of the units. Nearer to Black Rock (in the northeast corner of the study area), the Marias River Shale exhibits sharply disharmonic folds in which steep, oppositely dipping beds are common (Fig. 22). Disharmonic folding within the Marias River Shale farther north in Sun River Canyon and Pishkun Canal and is attributed to a complex stress regime within the apex of the Triangle Zone (Sears et al., 2005). Bedding measurements in 47 different locations in Comb Rock Central define folds that plunge both to the northwest and the southeast (Fig. 22). The stereonets for Comb Rock West and East outline individual large folds with regional trends, but the Comb Rock Central stereonet encompasses numerous small, outcrop-scale folds because of the incompetent nature of the Marias River Shale and Blackleaf Formation. Due to the easily erodible nature of the Marias River Shale, outcrops throughout Comb Rock Central are few. Many of the measured planes within this section are from thin sand beds that lie within the shale or from gullies where erosion allowed the orientation of the shale itself to be determined.

4.2.3 Comb Rock East

Comb Rock East covers just under 13 km². It extends from the northern boundary of the Melaney Ranch to the Dearborn River at its southern terminus. On the east, it is bound by Highway 287, and on the west it is bound by the western boundary of Dearborn Ranch, and the boundaries between Comb Rock Central and Comb Rock West. This southern area is comprised predominantly of the Two Medicine
Formation, Virgelle Sandstone, and Telegraph Creek Formation. There are many east-vergent thrust faults in this area that imbricate the Virgelle Sandstone at the surface. Synclinal folds are typically cored by Two Medicine Formation and anticlinal folds are cored by Telegraph Creek Formation. Stereonet plots of beds in this area clearly define a dominant SE plunge. One particular fold that has a large areal extent in Comb Rock East is here named “Broken Syncline” because of the way that the axis appears to have been faulted (Fig. 24). A stereonet of the beds involved in this syncline was plotted from 227 bedding plane measurements (Fig. 23). In the southern part of Comb Rock East, folding gives way to fault imbrication. Near the Dearborn River, there are many long north-south trending ridges that are capped by resistant sandstone or volcanics units within the Two Medicine Formation or by the Virgelle Sandstone. These ridges extend for kilometers without much variation in trend. The majority of the folds seen in this area are small-scale (10s of centimeters to meter scale), tight to isoclinal, and disharmonic, and reside within the Telegraph Creek Formation.
Figure 24 - Broken Syncline. The broken axis can be seen here just left of center in the satellite photo.
4.2.4. Geometry of Comb Rock Culmination

The structural analysis clearly defines the geometry of the Comb Rock culmination (Fig. 25). The culmination is 5.5 km long, in the NW-SE direction. It plunges 26.2 degrees to the NW on its NW end, and 27.4 degrees SE on its SE end. It represents a structural uplift of 850 meters relative to the adjacent domains (Fig. 26). To the north, the culmination plunges into a set of 2 imbricated thrust sheets of the Two Medicine, Virgelle, and Telegraph Creek formations (projected in figure 25). To the south it plunges into a set of 8 imbricated thrust sheets of the
same formations. Some of these appear to be the same sheets, interrupted by erosion of the culmination. A composite plunge projection shows that the thrust sheets are broadly folded into the synclines and anticlines measured for the stereonet analyses. The deeper exposures of the culmination show that the steep, disharmonic folds in the Blackleaf, Marias River, and Telegraph Creek formations lie beneath the broader folds and imbricated thrust sheets of the Virgelle and Two Medicine Formations. The overall horizontal shortening exhibited within the culmination is 11.25 km, as shown by thrust replications and vertical thickening. That shortening is a function of the insertion of the blind thrust wedge into the foreland basin, and detachment of the shaly Cretaceous units off the structurally more rigid strata of the wedge.

Well logs from the Augusta-Krone 31-32 well 8.5 km to the northwest show that a composite total of 400 m of igneous sills inflated the foreland strata, mostly within the Blackleaf and deeper formations. This is interpreted to represent a NE trend of inflated sills across the culmination (Fig. 27). The composite thickness of igneous rock in the Augusta-Krone 31-32 well is less than the structural amplitude of the culmination, therefore it is likely that the culmination has additional igneous intrusions and these sills enabled the uplift. The sills were injected pre-deformationally (Schmidt, 1972) and the structurally strong sills increased the thickness and strength of the blind thrust plate, which then elevated the overlying part of the triangle zone as the blind thrust was inserted into the foreland basin. The upper part of the Blackleaf through Two Medicine formations were sheared off in the movement zone.
Figure 26 - Cross Section C-C' shows an along-strike view of the Comb Rock Culmination. This culmination represents a structural anomaly of about 850 meters. Although it is represented here as a single, laccolith-shaped body, the igneous intrusion is likely split into multiple dikes and sills that add up to a composite thickness of about 850 meters. Local wells find sills predominantly in the Blackleaf Formation, though they do exist deeper.
Figure 27 - Cross Section B-B’ Full shows a full interpretation of the Comb Rock Culmination from SW to NE. An inset cross section was created to show greater detail and project folds from off of the culmination. It is interpreted that the igneous rocks responsible for the culmination originate as sills in the Blackleaf Formation and travel up the ramp of the blind fault at which point dikes become prevalent at the surface. The Blackleaf Formation is commonly inflated with sills in nearby wells so it is thought to be the main conduit of the igneous intrusives in the study area. A Cambrian klippe is present at the SW corner of the cross section near point B.
5. DISCUSSION

There are some inherent difficulties with triangle zone identification. These zones occur at the leading edges of fold-and-thrust belts such as the Rocky Mountains, where blind thrusts split strata as they are inserted into foreland basins sediments. The blind thrusts deform the younger overlying rocks even though it never breaks across them. The surface boundary of a triangle zone is a bedding-parallel shear zone that does not duplicate or omit stratigraphic section, so it is not readily observable at the ground surface. The majority of information about triangle zone geometry comes from boreholes and seismic reflection lines. Since they are difficult to identify, many triangle zones have only recently been documented at the fronts of mountain systems.

Due to the propagation of the tectonic wedge of material, formations are delaminated as the wedge propagates towards the foreland. Since the passive roof is separate from the blind thrusts underneath, the formations can appear to be continuous, as the wedged material remains in general stratigraphic order. The main evidence for wedging is replication of the deeper units in shallow blind thrust slices that lift them above their regional depth. At the apex of a triangle zone, even though the stratigraphic order is generally uninterrupted, stratigraphic units lie over a thousand meters above their regional structural depths, which implies thrust repetition at depth, even though there is no surface thrust trace (Fig. 28); therefore, a blind thrust is required. Furthermore, the stratigraphic section is greatly thickened at the apex of a triangle zone to accommodate the shortening represented by the blind thrust (Fig. 29 and 16). Six km south of the culmination study area, deeper units exhibit significant repetition on blind thrusts where exposed in the core of the NW-plunging Craig anticlinorium, which represents a complex hanging wall anticline on a blind thrust system. That structure traces northwest into the study area, where the
Augusta-Krone 31-32 borehole encountered Paleozoic units 1000 m above their undisturbed regional depth.

In order to draw a cross section for an area such as this with limited subsurface data available many assumptions about stratigraphic and structural thicknesses are required. Unit thicknesses are highly variable on available well logs. Although there have been several stratigraphic studies of the area (Viele, 1960; Viele et al., 1965; Schmidt, 1978), the units are highly deformed in the study area. This causes structural thickening as units are disharmonically kink folded (Fig. 6, Fig. 9). The Marias River Shale is known to dramatically change thickness with deformation (Dolberg, 1986), and basing a uniform thickness from any one location would be unreliable. In general, units were assigned reported stratigraphic thicknesses at depths where there was less internal deformation, but thicknesses varied with complex shearing between the blind thrust and the passive roof.

For construction of the cross-section of the blind thrust (Fig. 16 and 17), the main constraints available are a few well logs and surface exposures. Well logs interpreted to intersect the blind thrust show units at a shallower-than-regional depth, but well logs to the west of the blind thrust show units 1000-1200 meters deeper, at their regional levels. This was correlated with surface geologic maps which show the youngest strata at the surface occupy the same areas where the wells reported the subsurface Paleozoic units being at their deepest, and in stratigraphic order. Towards the east, where the blind thrust is interpreted to rise up a footwall ramp, exposed strata dip westward across a broad homocline. Wells intersect those same deep Paleozoic units at shallower levels to the east, above the footwall flat. Since the passive roof was interpreted to be beneath the Two Medicine Formation, its presence at the surface dipping eastward was evidence that the blind thrust ended at a hanging wall cut-off along the west
margin of the Augusta syncline. Units in the syncline descended to their appropriate regional
depths, east of the tip of the blind thrust. The total displacement of the blind thrust fault in the
subsurface is given by the map distance between the footwall ramp and the corresponding
hanging wall ramp, or 11.25 km as shown in the cross-section (Fig. 16).

The passive roof is not directly seen in the area or interpreted by the geologist who
mapped the area 40-50 years ago (Schmidt, 1972a and 1972b), but with the evidence for a blind
thrust, the geometry of the system implies that the passive roof must exist. At the tip of a blind
thrust, the unbroken strata above will be folded. Once the thrust ramps up completely to a flat,
the passive roof is created. The regional cross section created for this project shows 11.25 km of
displacement for the blind thrust.

Although many of the wells in the area are dry holes, there are some wells with
hydrocarbon shows, and the most promising came from BNV Eagle 1. This well found shallow
gas and oil (<300 meters TVD) in the Virgelle Sandstone and also found multiple imbrications of
the Marias River Shale. The well log was not available, but information was gathered from the
wellsite geologist (Large, personal communication, 2017). This well is located about 10 km
north of the Comb Rock Culmination. The potential for hydrocarbon exploration is one of the
main drivers for subsurface understanding on the Rocky Mountain Front. The Virgelle Sandstone
is one of the most promising reservoir rocks in the area due to it being the thickest sandstone in
the stratigraphic column. The Marias River Shale is a proven seal when imbricated above the
Virgelle Sandstone (seen in the BNV Eagle 1 well), and is also noted by Clayton et al. (1983) to
have sufficient TOC to be a potential source rock as well. The triangle zone system worked well
to capture hydrocarbons as the thrust system advanced into the foreland. As thrusting
propagated, the triangle zone at the farthest extent of deformation continued to grow in front of
the larger thrust sheets. In this manner, hydrocarbons generated at depth within the thrust system could be trapped at the front of the deformation. In Canada, the triangle zone is well documented and is a major hydrocarbon resource.

This study has shown that inside these triangle zone systems, there can be a subsystem of culminations and depressions. These structural features can be created by imbrication of the strata in the subsurface, thickening of the strata due to plastic internal deformation, and by syntectonic igneous intrusions. The first two two methods are very similar in that internal imbrication inside a formation can thicken it, but also imbrication of the entire formation will thicken it with regards to the surrounding strata. It seems that the Marias River Shale shows both kinds of imbrications throughout the study area and beyond. This is the grounds for application of the mushwad hypothesis of Thomas et al. (2001) to this area. As the triangle zone evolved, intense shearing deformed the rocks between the blind thrust and the overlying rocks within the passive roof. This shearing intensely deformed the Blackleaf, Marias River, Telegraph Creek, Virgelle and Two Medicine formations. Due to the lack of structural rigidity within the Marias River Shale, when subjected to this shearing, a mushwad was built up. The shaly section accumulated and structurally bulged up the overlying rocks of the triangle zone to help create a

Figure 28 - Cross section of the Canadian triangle zone in southwestern Alberta (MacKay, 1996). Similar imbrications and thickening can be seen in the apex of the triangle zone in this Canadian example as those interpreted to exist here in Montana.
culmination. In order for the culmination to rise to its current structural height, igneous intrusions inflated the Blackleaf Formation and Marias River Shale even further to the point where these rock units and the igneous intrusions are exposed at the surface today.

Another factor that causes mushwad formation is the change in thrust angle from the initial breaking and ramping of units to the flat. When rock units break in response to a sub-horizontal maximum stress direction, the fault would likely break at an angle of around 30 degrees to horizontal (Sibson, 1985). As this 30-degree angle is rotated onto the thrust flat, it increases. This steeper angle is not stable so a different fault plane breaks to re-establish a 30-degree angle. The area between the new fault plane and the original fault plane becomes a zone of excess material and gets intensely deformed into the mushwad seen at the apex of the triangle zone (Fig. 29).

Cross Section A-A’ shows that the units in this mushwad have been thickened (Fig. 16). Any attempt to quantify the shortening seen in a zone of penetrative deformation such as this needs to incorporate area balancing as opposed to strictly line-length changes. The area of the mushwad in cross section is here interpreted to be roughly 6.8 million m². If this is converted to a rectangle with an original stratigraphic thickness of 625 meters, the original length of that rectangle would be 10934 meters. Given that the current length and thickness are 8750 meters and 1656 meters respectively, this calculation shows a shortening or 2184 meters and a thickening of 1031 meters at the mushwad’s thickest point (a shortening value of 20% and thickening of 165%). This original quantity of rock fits reasonably well along the nose of the blind thrust where it would have been peeled off the passive roof and deformed into its current triangular shape.
Figure 29 - Schematic of Triangle Zone formation showing where extra material comes from for mushwad.
6. CONCLUSION

Given the results from field work, borehole data, cross sections generated from this study, and the results from similar studies throughout the region, it can be concluded that there is a culmination of the triangle zone near Comb Rock. It can also be concluded that this culmination was partially caused by a large blind thrust fault that placed deeper stratigraphic units structurally higher than would be expected given regional dip of the foreland basin stratigraphy in the area. When interpreting the area on a regional scale, the Comb Rock culmination stands out starkly on a geologic map, but its limited regional extent does not work well with the one large fault being the only answer.

There is evidence for Marias River shale thickening due to lateral distribution, steeply dipping beds, and well log reports. In addition, there is evidence for internal deformation thickening other units such as the Telegraph Creek Formation, and the Blackleaf Formation. Small-scale imbrications come to the surface in the Craig anticlinorium as well, which show that they are not only a possibility, but a probability in defining the structure above them. This paper concludes that the Comb Rock culmination was not only caused by formation thickening and imbrications in the subsurface driving the strata higher but also from a NE-trending swarm of Cretaceous dikes and sills which elevated a swath across the triangle zone beneath the Comb Rock culmination.
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7.1 Map References


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7.2 Software

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Midland Valley Exploration Ltd. Field Move Clino. Computer software. Digital Field Mapping. Vers. 2.3.3.

7.3 Personal Communications

Large, J., 2017. Local wellsite geologist.

8. APPENDIX

Figure 30 – Map of local well locations
8.1 Stratigraphy

All rock units exposed in the field area are of Cretaceous age. However, older rocks have been identified in nearby well logs and were included in cross sections. They emerge to the SE in the core of the Craig anticlinorium, which plunges NW into the study area. The following discussion highlights the structural behavior of the units that are involved in the thrust structures of the area. The stratigraphy analysis by Schmidt (1978) was modified for this section unless noted otherwise.

8.1.1 Devonian

From the base up, Upper Devonian rocks in the study area comprise the Souris River Formation, Jefferson Formation, Three Forks Formation, and the Sappington Formation. The 70-meter thick Souris River Formation is a system of fine-medium grained, red and green marine shales that grades upwards into fossiliferous carbonates of the Jefferson Formation. The Jefferson Formation is about 240 meters thick and is dominated by 2- to 3-m thick dolomite beds with interlayered shale. The 70-meter thick Three Forks Formation contains red and green shale and evaporite beds of the Potlatch member. The Devonian system is capped by organic-rich shales of the Sappington Formation (stratigraphic equivalent of the Bakken Formation of the Williston basin of eastern Montana) which is less than 10 meters thick in this area (Peterson, 1986).

Mechanical Properties- Although the Jefferson dolomite beds are structurally strong, the Potlatch anhydrite and other evaporites within the Three Forks Formation can act as a detachment surface for fault propagation. The Devonian system is therefore fairly heterogeneous which could allow for slip between formations during deformation. A major blind thrust fault in
the study area appears to have soled in the Souris River shales and ramped across the Jefferson dolomites.

**8.1.2 Mississippian**

The Madison Group dominates Mississippian section in this area. It totals 350 meters thick in outcrop (Roberts, 1966), but some wells penetrated over 365 meters. The Madison Group is divided into two units in the study area: the Lodgepole Limestone and the Mission Canyon Limestone. The Lodgepole Limestone comprises the lower 150 meters and is an interlayered mixture of thin to medium limestone beds and calcareous shale. The upper 200 meters of the Madison Group is assigned to the Mission Canyon Limestone, which has thick-to-massive crinoidal to oolitic limestone beds capped by a thick bed of dolomitized limestone, referred to as the Sun River Dolomite from exposures in the Sun River Canyon farther to the north (Peterson, 1984).

**Mechanical Properties**- In general, the thick-bedded Mississippian limestones deform as a strong structural unit. In the map area, a major blind thrust ramp cuts across the Madison Group.

**8.1.3 Jurassic**

The Jurassic system in the study area includes the middle to late Jurassic Ellis Group, which comprises the middle Jurassic Sawtooth Formation and the middle-late Jurassic Swift Formation. The late Jurassic Morrison Formation lies atop the Ellis Group and represents terrestrial clastics of the foreland basin. The Jurassic formations have a total thickness of 143 meters, and represent
three transgressive-regressive eustatic cycles (Peterson, 1986). The Sawtooth Formation is about 30 meters thick and consists of marine limestone, shale, siltstone, and sandstone. Disconformably overlying the Sawtooth Formation is the Swift Formation which is of similar thickness (30 meters) and made up of marine conglomerate, shale, and sandstone. The Morrison Formation conformably overlies the Swift Formation. It is about 80 meters thick and consists of continental sandstone, siltstone, mudstone, and limestone.

**Mechanical Properties** - The Jurassic system is very fine-grained overall, but there is some heterogeneity with sandstone and limestone beds scattered throughout. It is faulted and intensely folded in the center of the Craig anticlinorium to the south of the study area (Schmidt, 1972c), which shows that it is subject to deformation. Those faults interleave units of Jurassic and Cretaceous Kootenai Formation, so the two are commonly grouped together on cross sections across the area.

**8.1.4 Cretaceous**

From the base up, the Cretaceous units in the area comprise the Kootenai Formation, Blackleaf Formation, Marias River Shale, and the Montana Group (Telegraph Creek Formation, Virgelle Sandstone, and the temporally equivalent Two Medicine-Adel Mountain Volcanics-Horsethief formations). The Saint Mary River Formation lies to the west of the study area, but is included in the regional cross-section.
8.1.4.1 Kootenai Formation

The Early Cretaceous Kootenai Formation is not exposed in the field area, but crops out 20 km to the south in the Craig Anticlinorium. The Kootenai Formation is commonly divided into three sedimentary units: a lower sandstone, a middle shale and limestone, and an upper sandstone and limestone. The lowermost part of the formation is a hard, massive, quartz-chert sandstone which averages 8-15 meters in thickness. The middle member of the Kootenai Formation is made up of mudstone, siltstone, sandstone, and limestone and averages around 130 meters thick. The mud and siltstone are red and purplish red with flakes of white mica common on bedding surfaces. Near the middle of the unit are several beds of massive limestone (3-4 meters thick) that contain abundant freshwater gastropods and pelecypods. The upper 70 meters is made of sandstone, siltstone, mudstone, and limestone. The sandstone is massive and forms lenticular beds as much as 15 meters thick. A few feet from the top is a massive detrital limestone which is around 1.2 meters at its thickest point. This bed locally contains abundant gastropods and pelecypods.

**Mechanical Properties**—The Kootenai Formation contains massive sandstones and thick shale beds. The heterogeneity allowed it to deform internally where exposed in the Craig anticlinorium to the south.

8.1.4.2 Blackleaf Formation

The Blackleaf Formation is composed of three members (bottom to top): the Flood Member, the Taft Hill Member, and the Vaughn Member. Of these, only the Vaughn Member crops out in the field area.
The Flood Member rests on top of the Kootenai Formation with a slight disconformity. The thickness averages about 60 meters but is noted to vary due to deformation. It can be split into three separate sections of marine origin: a lower quartz-rich sandstone, a middle shale and siltstone, and an upper carbonaceous sandstone.

The Taft Hill Member represents the medial part of the Blackleaf Formation. The thickness of this member is noted to vary due to deformation, but it averages around 60 meters. The lower two thirds of the member are made up of a dark gray silty shale while the upper third has thin sandstone beds as thick as 60 centimeters. The majority of the rocks in this member are olive-gray in color.

The Vaughn Member is exposed in the study area in the Comb Rock Central region in cut banks of Auchard Creek as well as gullies to the east-northeast of Comb Rock. It is also exposed at the center of the Craig Anticlinorium and exhibits chevron folding (Fig. 29). This member rests conformably on top of the Taft Hill Member and has an average thickness of 114 meters. More than half of this member consists of thin sandstone and siltstone beds (several centimeters to 1-2 meters thick) that are greenish-gray. Conglomerate, bentonite, and ash-fall tuff are also present in the Vaughn Member. Fossils are not abundant, but some woody plant material has been preserved. In the study area, multiple leaf fossils were recovered from the Vaughn Member.
Figure 31 - Leaf fossils found within the Vaughn Member of the Blackleaf Formation. Hammer for scale.

**Mechanical Properties** - The Blackleaf Formation is heterogeneous with many interbedded sandstones and shales. Some of the shales within the formation vary in thickness with deformation which implies multiple detachment zones to allow for imbrication and disharmonic folding within the shales. The Blackleaf Formation has chevron folds in the center of the Craig Anticlinorium which imply a tendency for folding as opposed to brittle fracture.
The Marias River Shale is made up of four members (bottom to top): the Floweree Shale Member, the Cone Member, the Ferdig Member, and the Kevin Member. The average thickness of the formation is 177 meters although it varies due to deformation. The Marias River Formation is exposed throughout the central part of the field area, although it is commonly covered with soil and grass due to its slope-forming nature. All members of the Marias River Shale are marine in origin.
The Floweree Shale Member is disconformable with the underlying Vaughn Member of the Blackleaf Formation. It varies greatly in thickness due to deformation. Although the average thickness is about 20 meters, it thins out to zero in some areas. The Floweree Shale Member is mostly a dark-gray shale with local thin beds of gray siltstone or sandstone.

The Cone Member is conformable with the underlying Flower Shale Member. Its average thickness is 20 meters, but it also varies greatly due to deformation and can be thinned out to zero. The base is an olive-gray siltstone with limestone concretions capped by a 1-meter thick bentonite bed. The majority of the Cone Member (~15 meters) is thinly laminated gray shale and siltstone, although the top contains a 3-meter thick sandstone with less common thin limestone.
beds above that. The Cone member is equivalent to the second white specks member of the Alberta Group, which is a borehole marker bed and a source rock.

The Ferdig Member is conformable with the underlying Cone Member and has a more uniform thickness of 49 meters. However, some thickness variation due to deformation does occur. Overall, the member defines a coarsening-upward sequence that begins with a lower shale unit and grades up to a siltstone or fine-grained sandstone unit at the top. The lower shale is about 11 meters thick, is non-calcareous in nature, and contains scattered beds of siltstone and sandstone which are generally less than 5 centimeters in thickness. The upper unit is about 38 meters thick and mostly contains thin beds of sandstone and siltstone which are thinly laminated. The sand content increases upward in this unit and there are scattered ripple marks on some of the bedding planes.

The Kevin Member of the Marias River Shale overlies the Ferdig Member with a mostly conformable surface, but there may be a slight disconformity. This member averages 90 meters in thickness, but varies considerably due to deformation. The Kevin Member is made up of shale, siltstone, sandstone, limestone, bentonite, and conglomerates, but is 90% black shale. Many of the other lithologies occur as thin, discontinuous beds. Marine invertebrate fossils are abundant within in Kevin Member.

**Mechanical Properties:** Almost every member of the Marias River Shale has been noted by Schmidt (1978) to vary in thickness when deformed. This variability is enough to completely pinch out a member that is otherwise tens of meters in thickness. On the contrary, this variability with deformation can thicken members to be several times thicker than originally. This commonly occurs when small-scale detachments form within the rock units and allow for imbrication that mimics the larger-scale tectonic activity. This imbrication can repeat rock beds
and therefore increase the structural thickness of the unit. This is especially evident within the
Pishkun Canal 60 km to the northwest, since it gives a much larger viewing window than is
commonly available in an undisturbed setting. Imbrications within the Marias River Shale can be
traced out using a pattern of white bentonite beds that lie within the black shale that is commonly
found within the Marias River Shale. The Marias River Shale detaches from the Blackleaf
Formation and folds disharmonically into 'mushwad' culminations. It also seems to be the
horizon into which the stronger units were wedged in this section of the triangle zone.

Figure 34 - View of the imbricated Bentonite beds within the Marias River Shale. Photo taken at the Pishkun Canal by Jim Sears.
Montana Group

The majority of the rocks exposed at the surface throughout the field area are assigned to the Montana Group. This group consists of the Telegraph Creek Formation, Virgelle Sandstone, the Two Medicine Formation, the Horsethief Formation, and the St. Mary River Formation. This group represents two regressive sequences of the Cretaceous Interior Seaway and wedge of sediment that thins eastward toward the Rocky Mountain foreland bulge.

8.1.4.4 Telegraph Creek Formation and Virgelle Sandstone

The Telegraph Creek Formation and Virgelle Sandstone together represent a regressive marine system that coarsens upward from the offshore marine strata of the Marias River Shale. The Telegraph Creek Formation is made up of interbedded sands and shales with oscillation and current ripple marks as well as ripple cross-laminations (Viele et al., 1965). Structurally, the Telegraph Creek Formation has many small-scale (< 1 meter) folds that allowed measurement of overall trends across the culmination. The thickness of the Telegraph Creek varies with deformation, but averages 100 meters.
The Virgelle Sandstone is one of the primary ridge-forming units in the field area. It is characterized by an iron-rich caprock that varies in thickness from 0.5-2 meters (~1 meter in field area) which overlies a tan, friable, massive, lenticular cross-bedded sandstone. The Virgelle Sandstone is 45 meters thick in the study area. The sandstones contain tan concretions around 50
centimeters in diameter. Structurally, the Virgelle Sandstone commonly shows closely spaced fractures and also commonly has calcite veins on fracture planes. Due to the high degree of cross-bedding throughout the sandstone, many measurements were taken in order to obtain a better average. The Virgelle Sandstone is stratigraphically (not temporally) equivalent with lower members of the Eagle Formation of central-eastern Montana on the other east side of the Rocky Mountain foreland bulge.

Figure 36 - A ridge formed by the Virgelle Sandstone. Darker, iron-rich caprock is seen on top. Bushes growing on the ridgeline are 20-30 centimeters in height. View is looking northwest.
Figure 37 - Lenticular cross beds of the Virgelle Sandstone. Darker, iron-rich caprock is seen on top. Hammer for scale. View is looking Southeast.

**Mechanical Properties:** The Telegraph Creek Formation is highly heterogeneous with many interbedded sandstones and shales, allowing a high degree of internal deformation. Throughout the field area the Telegraph Creek formation is involved in small-scale folds. The small folds were measured in great detail to attempt to define larger-scale folding patterns. Steep beds are preferentially exposed with natural erosive processes in this grassland. Large areas of steeply dipping Telegraph Creek Formation are mapped. However, the formation is too thin to be exposed across such large areas if it were dipping uniformly at such steep angles. Therefore, it is
likely that the formation is disharmonically folded, accordion-style, above the underlying Marias River Shale.

The Virgelle Sandstone is a homogeneous, massive sandstone body that, when deformed, acts as a singular layer. It deforms brittlely without small-scale folds or imbrications, commonly forming imbricated thrust packages between the underlying Telegraph Creek Formation and overlying shaley Two Medicine Formation. In outcrop, the Virgelle Sandstone is commonly filled with calcite veins in closely-spaced fractures. Many of these fractures do not align along any particular axis of folding.

3.4.5 Two Medicine Formation

The Two Medicine Formation is widely exposed rock in the field area and throughout the Disturbed Belt region to the north. Stratigraphically, the Two Medicine Formation is equivalent to the Upper Eagle and Hell Creek formations of central Montana. Its base is defined as the first coal-bearing unit above the Virgelle Sandstone. This is a necessary distinction as the lower Two Medicine Formation also has large cross-bedded sandstones similar to those found in the Virgelle Sandstone (Viele, 1960). Schmidt (1978) divided the formation into an eastern facies and western facies. The study area lies near the division between the two, but is exclusively within the eastern facies.

Western Facies

The western facies is divided into a lower sedimentary member and an upper volcanic member. In the study area, it is noted to reach a total thickness of over 830 meters. The sedimentary member is about 160 meters thick and is conformable with the Virgelle Sandstone. Sandstone makes up 60% of the sedimentary member and beds are lenticular and vary from a
few centimeters up to 15 meters thick. The sands range in color from gray to green to tan. They are fine-to-medium-grained, and locally crossbedded. Some of the thick sandstone beds in the lower part have a thin magnetite-rich layer at the top which closely resembles the Virgelle Sandstone. Mudstones in this member are gray, tan and green. They are silty to sandy and form thin beds of several centimeters to 1-2 meters thick. Thin beds of carbonaceous shale, lignite, coal, and bentonite are also found in the lower member. Some fossiliferous mudstone beds are also found in the lower member. They are less than a meter thick and consist of small brackish-water pelecypods and gastropods. The beds can be made up almost entirely of shell material in places.

The volcanic member is about 700 meters thick in the study area and rests upon the sedimentary member with a slight disconformity. This member is made up of an assemblage of clastic volcanic rocks and lava flows all of continental origin. It is divided into nine different units by Schmidt (1978), but these will not be outlined here.
Eastern Facies

The Eastern Facies rests conformably on top of the Virgelle Sandstone and is roughly 600 meters thick. This facies represents many different types of sedimentary and volcanic rocks which are mainly of continental origin. The lower 120 meters is equivalent to the Western Facies and is made up of sandstone, mudstone, conglomerate, carbonaceous shale, lignite, coal, bentonite, and fossiliferous mudstone. The sandstones are gray, green, and tan and are as thick as 12 meters. Most of the sand is calcareous and some beds contain large concretions. The mudstones are green and gray, present in thin beds, and commonly silty or sandy. Small lenses of conglomerate are present and are less than 0.5 meters thick. These conglomerates have smoothly rounded pebbles of chert, quartzite, limestone, and porphyritic volcanic rocks. Thin (several centimeters to 2 meters) beds of black carbonaceous shale, lignite, and coal are present. Fossiliferous mudstones are as much as 2 meters thick and contain brackish water species of pelecypods and gastropods. The mud in these layers is green or gray mudstone or a brown carbonaceous mudstone.

Above these beds is 50 meters of mixed volcanic sandstone, siltstone, mudstone, and ash-fall tuff. The sandstone ranges from several centimeters to 5 meters thick, is coarse-grained, and is dark gray-green in outcrop. The base is marked by a conglomerate of rounded pebble-sized clasts. The volcanic siltstone and mudstone range from several centimeters to 2 meters thick, have indistinct bedding, are gray-green in outcrop, and are sandy in nature. The top of this
sequence is commonly marked by a white and pink ash-fall tuff. This bed ranges from several centimeters to 2 meters in thickness, is hard, and has conchoidal fracture.

Atop the volcanic sequence just outlined lies ~250 meters of nonvolcanic sandstone, siltstone, mudstone, limestone, and bentonite. The sandstone is as thick as 6 meters, is green-gray in color, fine-medium grained, and locally cross-bedded. The siltstone and mudstone are blocky in areas and green-gray in color. Bentonite and limestone beds are sporadically located in this sequence.

The upper 185 meters of the eastern facies of the Two Medicine Formation is made up of clastic volcanic rocks of which a majority are volcanic sandstone which can be as thick as 10 meters. The sandstone is fine to coarse grained, thick-bedded, and cross-bedded in areas. Some of the sands contain evidence of channelization such as rounded pebbles (Fig. 36) and wood fragments. Siltstone and mudstone beds are as thick as 2 meters and are interbedded with the sandstone. Four separate ash-fall tuffs were recorded throughout this sequence. They are white-gray, hard, and as thick as 1 meter.

**Mechanical Properties:** The Two Medicine Formation is very thick and extremely heterogeneous throughout its entirety. Due to its terrestrial deposition, it is not only heterogeneous vertically but also horizontally as fluvial channels carved its paleo-depositional surfaces. This heterogeneity allows for many potential glide planes to develop where shale lies between more
rigid volcanics or sandstones. It is also thought that this heterogeneity could be the cause of one of the delaminations that make the triangle zone theory work here (Sears, personal communication). The deformation differences between malleable shales and brittle volcanics allow for gliding as well as many of the imbrications that are observed throughout the Rocky Mountain Front.

Figure 40 - Outcrop on the Dearborn River showing the heterogeneity within the Two Medicine Formation. River is ~5 meters wide and bed of sandstone in outcrop is ~2 meters thick.
8.1.4.6 Adel Mountain Volcanics

Though there is some uncertainty as to the exact age of the Adel Mountain Volcanics, it is thought to be Late Cretaceous-Paleocene in age. This formation reaches a maximum thickness of about 880 meters, and lies to the east of the majority of the area included in the regional interpretations of this study. Its western boundary is reported to have been subjected to intense deformation, its eastern boundary is much more quiescent and its southern boundary appears to structurally overlie larger, deeper thrust faults. The formation consists of clastic volcanic rocks and lava flows which are all of terrestrial origin. There are five major lithologic units within the Adel Mountain Volcanics: volcanic breccia, trachybasalt flows, trachyandesite flows, lacustrine deposits, and a volcanic conglomerate.
**Mechanical Properties:** The Adel Mountain Volcanics are not structurally significant due to lack of subsurface existence and are used as a stratigraphic marker on the surface for this study. They comprise the passive roof of the triangle zone.

*Figure 41 –* Photo taken from a Virgelle Sandstone ridge toward the southeast. All of the high topography in the distance is Adel Mountain Volcanics and represents its resistance to denudation. Dearborn River in background. Car for scale.
8.1.4.7 Horsethief Formation

The Horsethief Formation present to the north of the study area for this project (north of Montana Highway 200). It represents a marine, coarsening upward sequence from a shaly sand upwards to massive sands. It has a reported thickness of 20-70 meters, is volcanic-rich, and represents many different facies (Viele et al., 1965). The Horsethief Formation is Late Cretaceous and is thought to be the northern facies of the Adel Mountain Volcanics (Sears, personal communication). There is a structural separation of the two at MT 200 and different mapping parties split them into different units. For the purpose of this study, the Horsethief Formation will be regarded as the stratigraphic equivalent of the Adel Mountain Volcanics. Since it is equivalent, the shallow marine fossils allow for it as well as the Adel Mountain Volcanics to be dated as Late Cretaceous.

**Mechanical Properties:** The Horsethief Formation is not present in any cross sections for this project so it does not have structural importance.

**Special Notes:** Though the Late Cretaceous volcanic rocks that occupy separate thrust plates were divided into different formations when mapped by Schmidt (1972a), it is thought that most of these changes are not due to different rock units but instead due to facies changes within a common formation, telescoped by thrusting (Sears, personal communication). The complex nomenclature resulted from field parties mapping different structural areas not realizing the stratigraphic equivalency of the units at the time. For cross sections created in this project, the Two Medicine Formation is regarded as a single unit but differing thicknesses will be maintained.
8.1.4.8 St. Mary River and Willow Creek Formations

Though they will be discussed separately, there has been reasonable doubt expressed as to the mappability of the contact between the two formations. Viele et al. (1965) reports a potential combined thickness of 880 meters by structural analysis of allowable space inside “Middle Fork Syncline”, though combined thicknesses reported by Schmidt (1978) are slightly less (~800 meters). Schmidt (1978) does mention that erosion has likely removed some of the upper part of the Willow Creek Formation which could account for the difference in thickness. Neither the St. Mary River Formation nor the Willow Creek Formation is seen in the mapped part of the field area though it is present on geologic maps of the region. Its presence on the surface usually signifies a structural depression that has allowed for young rocks to be preserved.

St. Mary River Formation

The majority of this formation lies conformably on top of the Western facies of the Two Medicine Formation though a small amount of the basal part of the formation is reported to exist beneath the Adel Mountain Volcanics farther to the east. It is about 360 meters thick and of mostly terrestrial origin. Forty percent of the formation is sandstone that lies in beds as thick as 6 meters. The other sixty percent of the formation is made up of siltstone and mudstone with occasional, discontinuous, and thin ash-fall beds.

**Mechanical Properties:** This formation is essentially insignificant in the structural regime of the area except as a marker bed for stratigraphic level.
**Willow Creek Formation**

There is a gradational contact between the top of the St. Mary River Formation and the bottom of the Willow Creek Formation that has been questioned as a suitable, mappable contact (Viele et al., 1965). Though the maximum exposed thickness is 430 meters, it is commonly exposed at the surface due to its young age and an unknown amount has likely been weathered and eroded away. The Willow Creek Formation is of terrestrial origin and, similar to the St. Mary River Formation, 40 percent is sandstone. The beds are red, green, gray, and brown tuffaceous sand which are as thick as 6 meters. The other sixty percent of the formation is made up of red, purple, green, and gray siltstone and mudstone. Although fossils were not found in the Willow Creek Formation in the Comb Rock region to help determine its age, the lower part of the Canadian Willow Creek Formation is Cretaceous while the upper is Paleocene in age (Tozer, 1956).

**Mechanical Properties:** Similar to the St. Mary River Formation, the Willow Creek Formation is of minimal structural importance and is most useful as a stratigraphic marker.

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| Marias River - Ferdig                         | 1086     |
| Marias River - Cone                           | 1184     |
| Marias River - Floweree                       | 1250     |
| Blackleaf - Vaughn                            | 2250     |
| Blackleaf - Flood                             | 2432     |
| reverse fault                                 | 2866     |
| Blackleaf - Vaughn                            | 2866     |
| Blackleaf - Flood                             | 3078     |
| Quartzite?                                    | 3194     |
| possible fault                                | 3280     |
| igneous                                       | 3510     |
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| possible fault                                | 3830     |
| sedimentary rock - Blackleaf                  | 4384     |</p>
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8.3.1 Stereonets – Plunging Syncline 1 – Comb Rock West

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8.3.2 Stereonets - Broken Syncline – Comb Rock East

--------- Poles from Planes | 11/14/2016 at 1:54 PM --------
calculated from 227 planes from Data set: 'Broken_Syncline_LARGER_Extent.txt'

----- Bingham Analysis | 11/14/2016 at 1:54 PM-----
Data set: poles to Broken_Syncline_LARGER_Extent.txt

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Best fit great circle (strike, dip RHR) = 254.8, 62.6
### Measurements – Broken Syncline

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8.3.3 Stereonets – Doubly Plunging Folds - Comb Rock Central

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Best fit great circle (strike, dip RHR) = 225.9, 81.2

calculated from 47 planes from Data set: 'Folds_NE_CombRock.txt'
Measurements - Doubly Plunging Folds in Comb Rock Central

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8.3.4 Stereonets – River Crossing Folds – Comb Rock East

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Poles from Planes | 10/18/2016 at 2:19 PM

Calculated from 45 planes from Data set: 'River_Crossing_Folds_Dearborn_Ranch.txt'

Bingham Analysis | 10/18/2016 at 2:19 PM

Data set: poles to River_Crossing_Folds_Dearborn_Ranch.txt

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Best fit great circle (strike, dip RHR) = 255.0, 59.7
Measurements – River Crossing Folds

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Cross Section A-A' with projected well locations

Shane Fussell

Legend
- Willow Creek Formation
- St. Mary's River Formation
- Adel Mountain Lacustrine Deposits
- Adel Mountain Volcanics
- Two Medicine Formation
- Virgelle Sandstone
- Telegraph Creek Formation
- Marias River Shale
- Blackleaf Formation
- Kootenai Formation and Jurassic System
- Mississippian System
- Devonian System
- Cambrian System

Deformed

Approximate location of measurements: Augusta Core Rock Calibration

Undeformed

Projected Augusta-Krone 31-32
Projected State 1
Projected Milford Colony 1
Topographic Profile

Legend
- Willow Creek Formation
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-10
-11
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Thousands of Feet
0 km 5 km 10 km 15 km 20 km 25 km
Meters

0 km 5 km 10 km 15 km 20 km 25 km
Meters