STRATIGRAPHIC ARCHITECTURE AND DIAGENETIC EVOLUTION OF THE LATE DEVONIAN TO EARLY MISSISSIPPIAN STRATA IN WESTERN MONTANA

by

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of

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in

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ABSTRACT

Late Devonian to early Mississippian strata have been extensively studied in geologic literature both for academic and economic purposes. Lithostratigraphic intervals spanning this time in western Montana include the Exshaw, Banff, Three Forks and Lodgepole formations. These formations are generally composed of a lower organic-rich black shale, a medial calcitic and dolomitic siltstone to sandstone, and upper organic-rich shale. This siliciclastic-dominated rock package is anomalous in the carbonate-dominated Paleozoic of western North America. This study aims to address the following research question: where and what were the environments of deposition throughout the Late Devonian to Early Mississippian in western Montana and what is the diagenetic evolution of these rock packages?

To answer this question, multiple datasets were utilized including core, outcrop and geophysical well logs. A lithofacies scheme comprised of eighteen lithofacies was constructed based on rock attributes to interpret and correlate lithostratigraphic intervals as well as to establish a sequence stratigraphic framework from outcrop. The stratigraphic framework constructed from outcrop was then mapped throughout the subsurface of the study area where outcrop is absent. Finally, a diagenetic analysis was conducted according to significant sequence stratigraphic surfaces and rock bodies.

Lithostratigraphic and sequence stratigraphic surfaces are generally concurrent due to the low-accommodation epicontinental basinal setting of western Montana during this time. Sequence stratigraphic distribution indicates a long-term regression followed by a long term transgression that is overprinted by tectonically emergent features and third order cycles that are the primary concern of this project. Prominent structural features affecting sedimentary dispersal patterns include the Beartooth shelf, Sappington basin (that may be the incipient central Montana trough), the area near the Pendroy fault zone (possibly the incipient central Montana uplift), and western Canadian sedimentary basin

CHAPTER 1 – INTRODUCTION

Objectives

The objectives of this project are to describe and document facies distributions in southwestern Montana from the Late Devonian to Early Mississippian time, and correlate these data to equivalent strata in north-central Montana. Stratigraphic intervals recording the Devonian-Mississippian transition in Montana include the Banff and Exshaw formations in north-central Montana, and the Three Forks and lower Lodgepole formations in southwestern Montana (Figures 1 and 2). This study aims to answer the following question: how are depositional systems distributed in western Montana through Late Devonian to Early Mississippian time, and how does the diagenetic evolution of these strata affect reservoir quality.

This project emphasizes outcrop work of the Three Forks and Lodgepole formations of southwestern Montana. These strata were deposited in the Sappington basin (Figures 1 and 3). Data and concepts derived from outcrop study in the Sappington basin will be utilized to correlate and map intervals throughout the northern, subsurface portion of the project area that is the Western Canadian Sedimentary basin (WCSB) (Figure 2). This project aims to derive a coherent picture of the spatial distribution of depositional systems through time utilizing the techniques of lithostratigraphy, sequence stratigraphy, and linking sequence stratigraphy to diagenesis. These techniques will provide a detailed characterization of the Late Devonian to Early Mississippian reservoir on multiple scales, leading to a more complete exploration tool for the petroleum industry to exploit.

Figure 1: Area of interest

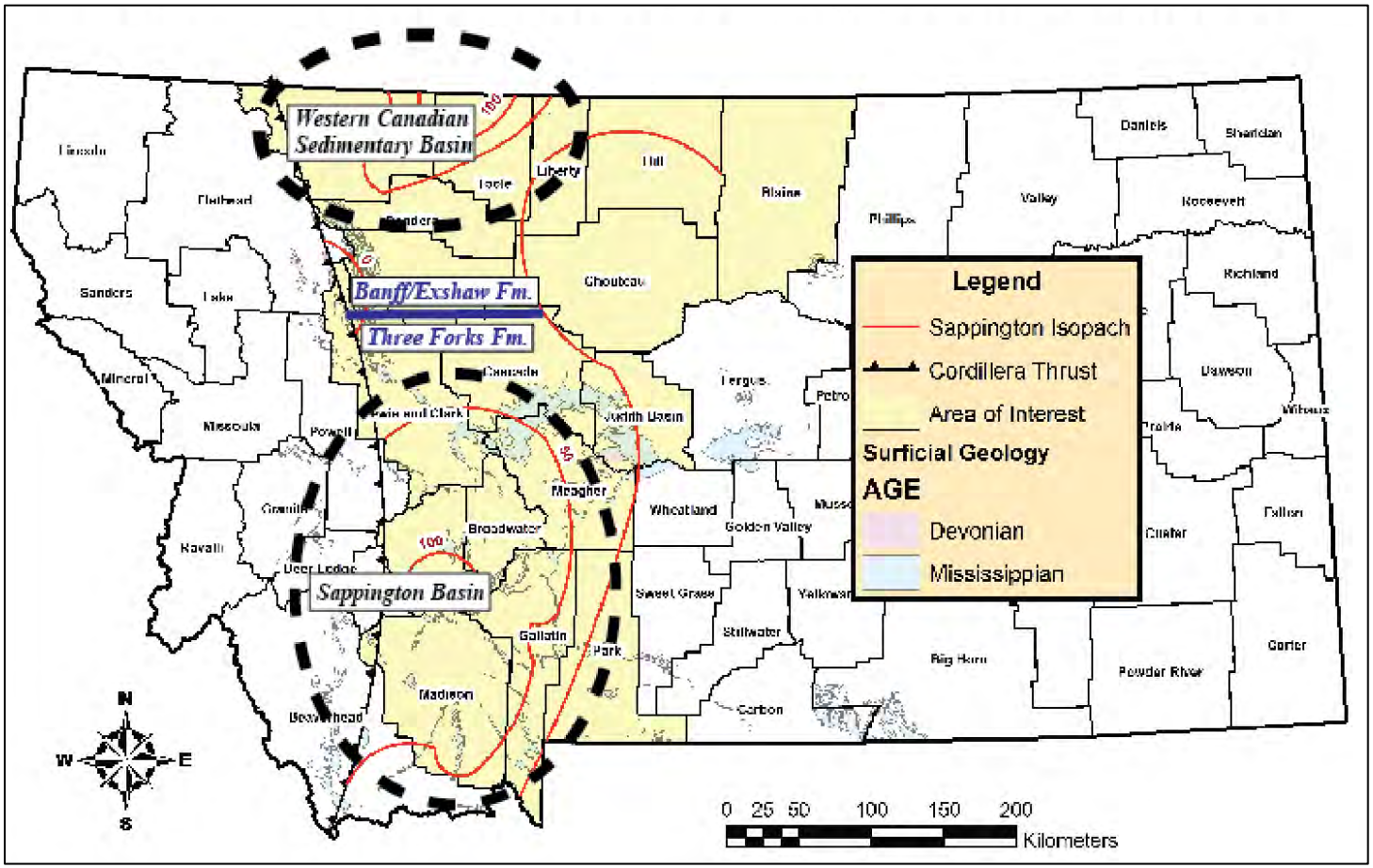


Figure 1: Area of interest. Counties of interest are highlighted in yellow. Red lines illustrate generalized isopach distribution of the Sappington Member of the Three Forks Formation (Macqueen and Sandberg, 1970). Isopach distribution is assumed to indicate ancient sedimentary basins. Thus, two discrete basins may be inferred: the northern Western Canadian Sedimentary basin (WCSB), and the southern Sappington basin. Stratigraphic nomenclature changes from the Sappington basin where the Three Forks Formation is utilized, to the Western Canadian Sedimentary basin, where the terms Banff and Exshaw formations are used (Sandberg, 1967). Purple and green polygons depict Devonian and Mississippian outcrop in Montana (Raines and Johnson, 1995).

Figure 2: Sappington Basin Data

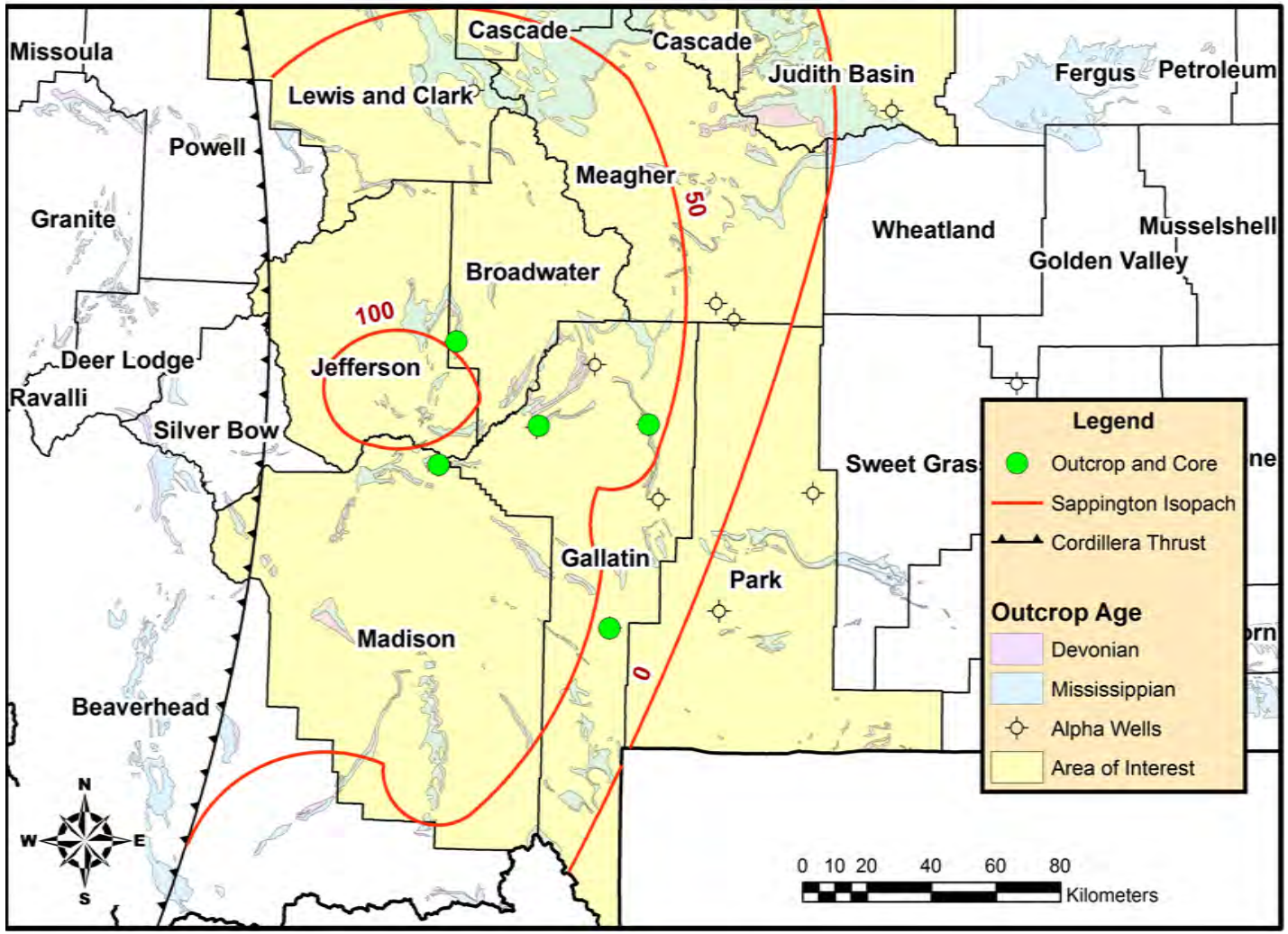


Figure 2: Sappington Basin Data: The southern portion of the study area hosts dominantly outcrop data, shown with green dots. Few well penetrations are in the area, and even less with associated geophysical data-- depicted by a dry well symbols (Macqueen and Sandberg, 1970: Raines and Johnson, 1995).

Figure 3: Western Canadian Sedimentary Basin Data

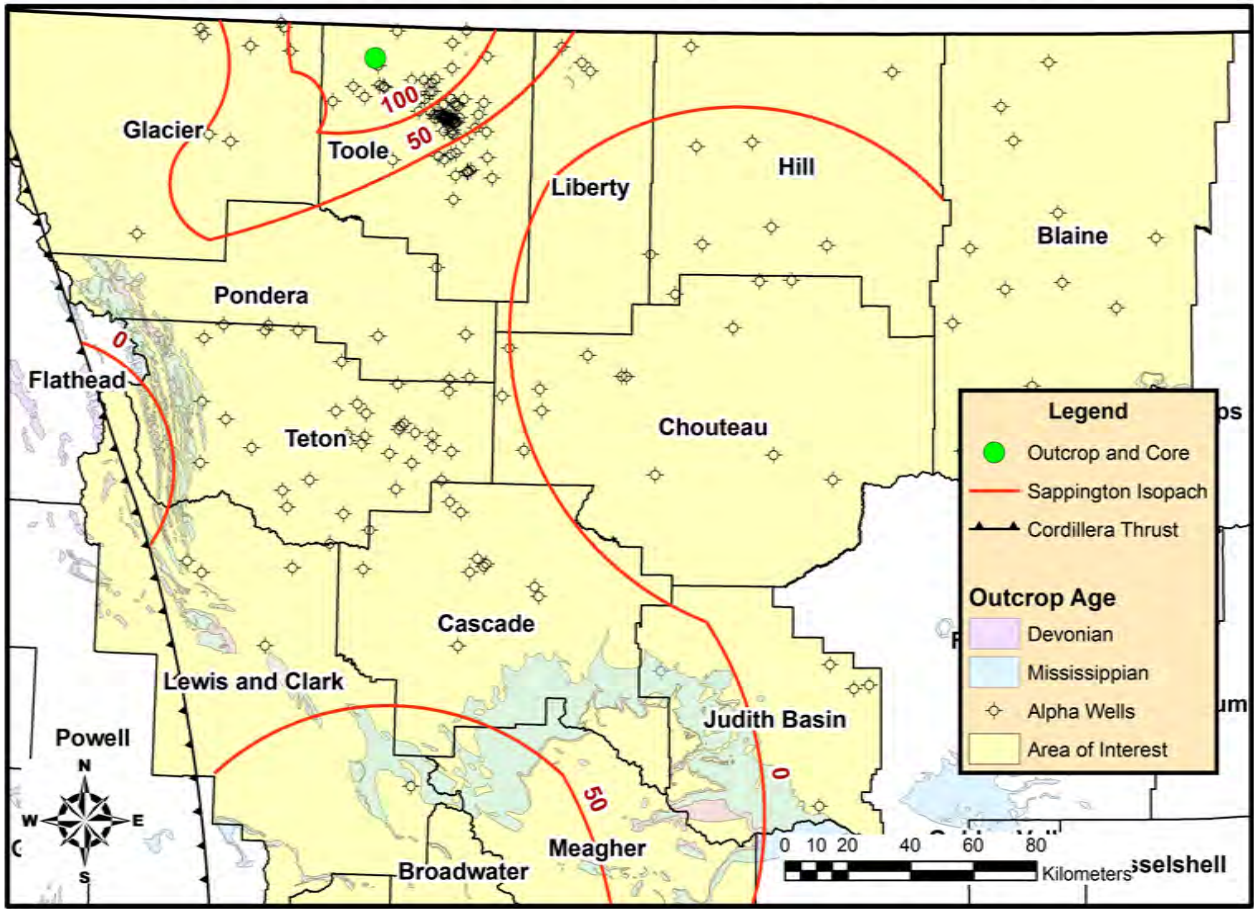


Figure 3: Western Canadian Sedimentary Basin Data: The northern portion of the study area hosts subsurface petrophysical data, shown with dry well symbol (Macqueen and Sandberg, 1970: Raines and Johnson, 1995). This map shows alpha wells with associated geophysical well logs. These "alpha wells" have been specifically selected according to their penetration depth and quality of geophysical logs. Dominantly gamma ray, bulk density, resistivity and the photoelectric factor were utilized in correlation.

Significance of Research

Strata equivalent to the interval under study are known to be economically important. The stratigraphically-equivalent Bakken/Three Forks interval in the Williston basin has been assessed to contain an estimated mean of 7,375 million barrels of oil, 6,723 billion cubic feet of natural gas, and 527 million barrels of natural gas liquids that are technically recoverable (Gaswirth et al., 2013). Additionally, the stratigraphically equivalent Exshaw/Banff interval in north-central and northwest Montana is currently being assessed as a possible unconventional reservoir (Hansen, 2012). However, these strata are preserved in the subsurface, and do not allow outcrop observation.

An increased understanding of stratigraphically equivalent outcrop analogs in the Sappington basin of southwest Montana will lead to better characterization of the Late Devonian to Early Mississippian petroleum depositional system. Depositional environments and their distribution through space and time exert a strong control on many components of the petroleum system, including source, seal, and reservoir. Accordingly, high resolution characterization of Late Devonian to Early Mississippian strata may lead to enhanced exploration success in the petroleum industry. Specifically, this study aims to characterize reservoir properties on multiple scales.

Project Area

General Statement

The area of interest is contained in the western Montana counties of Glacier, Toole, Liberty, Hill, Blaine, Pondera, Choteau, Lewis and Clark, Cascade, Judith Basin,

Meagher, Broadwater, Jefferson, Madison, Gallatin, and Park (Figure 1, 2, and 3). The project is principally divided into two distinct areas: 1) southwest Montana (Figures 1, 2, and 2) north-central Montana (Figure 1). These two areas are delineated by the data sets present in each respective area as well as what has been hypothesized to be two discreet Devonian-Mississippian sedimentary basins (Macqueen and Sandberg, 1970).

Southwest Montana

The Devonian-Mississippian transition in southwest Montana is represented by the Three Forks and Lodgepole formations (Figure 4). These formations were deposited in the Sappington basin. The Sappington basin as defined by Gutschick et al. (1976) is an epicontinental basin that lies in southwest Montana where several Devonian-Mississippian outcrop exposures are present (Figure 2).

North-central Montana

The Devonian-Mississippian transition in north-central Montana is represented by the Banff and Exshaw formations. The northern project area is defined as the southernmost extent of the Western Canadian Sedimentary basin (Figures 1 and 3). Due to the subsurface nature of these rock intervals, geophysical well logs are the primary dataset utilized within this area (Figure. 3).

Figure 4: Generalized Chronostratigraphic Framework

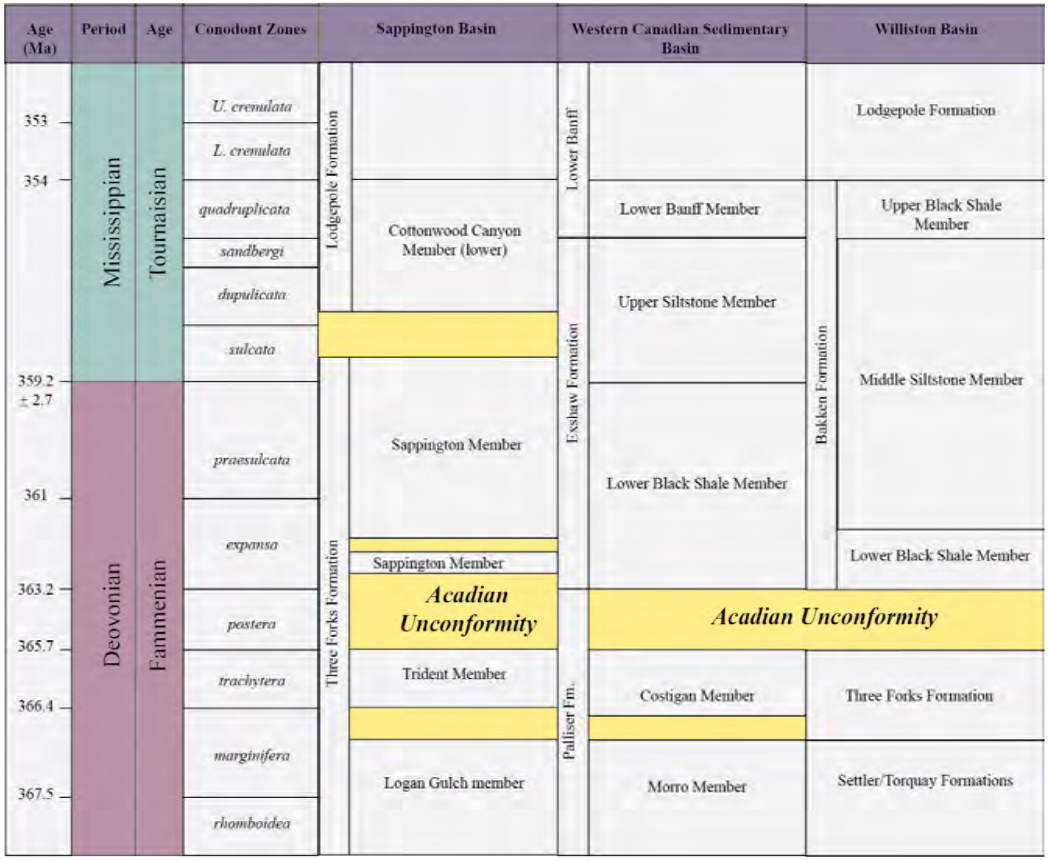


Figure 4: Generalized Chronostratigraphic Framework. Framework extends between the Sappington basin and southern Western Canadian Sedimentary basin and the Williston basin. Time-equivalency is inferred via conodont zonation defined by Kaufmann (2006) and Johnson et al. (2010). A regionally-significant unconformity exists within the interval of interest that was originally recognized by Wheeler (1963), with several other relatively minor unconformable events. This unconformity separates Sloss's (1963) Kaskaskia Sequence into two separate sequences: Kaskaskia I and II.

Devonian-Mississippian Lithostratigraphic Units in Western Montana

General Statement

Definition of stratigraphic terms is confusing in the area of interest due to the convergence stratigraphic nomenclature that differs in the three adjacent basins. These basins include 1) Sappington basin where Three Forks Formation and Lodgepole Formation terminology is used 2) Western Canadian Sedimentary basin where Exshaw Formation and Banff Formation terminology is used, and 3) Williston basin where Three Forks Formation and Bakken Formation terminology is used (Figures 1, 4, and 5). This nomenclature convergence occurs in north-central Montana near the 49th parallel (Macqueen and Sandberg, 1970; Bamber and Mamet, 1978). Figure 4 serves as a generalized chronostratigraphic framework of the time-space distribution rock bodies and associated nomenclature. Chronostratigraphic bodies have been constrained by the use of conodont biostratigraphy (Figure 4) (Sandberg and Poole, 1977; Kaufmann, 2006; Johnson et al., 2010).

Lithostratigraphically all three packages of rock somewhat resemble each other in that they all contain a carbonate-cemented, siliciclastic-dominated interval sandwiched between two organic-rich mudstone intervals (Sandberg, 1962; Smith et al., 1995; Angulo and Buatois, 2012). However, chronostratigraphy indicates that lithostratigraphic bodies are not time-equivalent (Figure 4). Chronostratigraphic relationships are discussed in the following section.

Three Forks and Lodgepole Formations

The Devonian-Mississippian contact within southwestern Montana has been the subject of much geologic debate. It can be confidently stated from brachiopod and conodont biostratigraphy that the Devonian-Mississippian boundary lies somewhere within the Sappington Member of the Thee Forks Formation (Sandberg and Poole, 1977; Kaufmann, 2006; Johnson et al., 2010).

Although the area was first documented by early USGS surveys (Hayden, 1873; Hayden 1876), the term Three Forks was coined by Pearle and Merrill (1893). These authors divided the Three Forks interval into lower and upper shale units separated by a band of limestone 15-20 ft. thick. Although Devonian and Mississippian fossils were discovered through the interval, an abundance of Devonian fossils led the authors to place this interval in the uppermost Devonian. Raymond (1907) later suggested that the Three Forks interval contains the Devonian-Mississippian contact.

Conversely, Sloss and Laird (1947) and Sloss and Moritz (1951) interpreted the Sappington interval to be the uppermost member of the Three Forks Formation--the upper boundary of which was marked by an extensive black shale interval. The interval crops out along the Gallatin River near Logan, MT which Sloss and Laird (1947) proposed to be the type section.

Sandberg and Hammond (1958) proposed a division of the Three Forks Formation into three members: a lower evaporitic member, a medial shale member, and an upper Sappington Sandstone Member. Sandberg (1965) renamed these members in ascending order: Logan Gulch, Trident, and Sappington Sandstone members. The authors

suggest that the Sappington Member straddles the Devonian-Mississippian boundary, yet fail to locate an exact contact. Gutschick (1966) defines the Sappington interval as an individual formation separate from the underlying Three Forks Formation, leading to some nomenclature confusion.

This study subscribes to terminology prescribed by the USGS, with the Sappington interval defined as the uppermost member of the Three Forks Formation. Overlying the Three Forks Formation is the basal, organic-rich, lower tongue of the Cottonwood Canyon Member of the Lodgepole Formation (Sandberg and Gilbert, 1967).

The Sappington and Cottonwood Canyon members were deposited in the Sappington basin. The Sappington Member is lithostratigraphically equivalent to the Lower Black Shale and Middle Siltstone members of the Bakken Formation, yet are chronostratigraphically equivalent only to the middle member of the Bakken Formation (Figure 4). Additionally the Sappington Member is lithostratigraphically equivalent to the entire Exshaw Formation, while chronostratigraphically equivalent only to the Lower Black Shale Member and part of the Upper Siltstone Member. The Cottonwood Canyon Member is lithostratigraphically equivalent to the Lower Banff Member and the Upper Black Shale Member of the Bakken Formation, yet is chronostratigraphically equivalent to the part of both Upper Siltstone Member of the Exshaw Formation and Lower Banff Member, and part of the Middle Siltstone member, and Upper Black Shale Member of the Bakken Formation.

Banff and Exshaw Formations

The Exshaw Formation was first proposed by Warren (1937) to be the lower black shale previously considered the basal part of the Banff Formation. However, he did not provide a description of a type section, and therefore the stratigraphic extent of the newly-proposed Exshaw Formation remained nebulous. Clark (1949) proposed the lower part of the siltstone interval be included in the Exshaw Formation, yet still failed to detail a type section. Finally, Harker and McLaren (1958) were able to provide a suitable type section description for the Exshaw Formation. Later, Macqueen and Sandberg (1970) refined the work of Harker and McLaren (1958) to include the entire siltstone unit in what is today termed the Exshaw Formation.

The Exshaw Formation is originally of Canadian nomenclature. However, Sandberg (1967) proposed that the Exshaw nomenclature be utilized throughout the subsurface in north-central Montana, namely in the counties of Toole, Glacier, Pondera, and upper Teton. A nomenclature change was proposed to exist due to an erosional area in the area of Teton county about 40 miles wide which separates the Sappington Formation to the south from the Exshaw Formation to the north.

The “Banff Series” was first proposed as a thick succession of upper Paleozoic to lower Mesozoic siliciclastic and carbonate rocks (McConnell, 1887). The stratigraphic definition was later confined to the lower shale units of those defined by McConnell (1887). These lower shale units were further refined by Warren (1937) with his designation of the lower shale and siltstone units as the Exshaw Formation. The modern

designation of the Banff Formation exclusively includes a basal shale unit, and overlying mixed siliciclastic and carbonate units (Mcqueen and Sandberg, 1970).

The Exshaw and Banff formations were deposited in the Western Canadian Sedimentary basin. This package of rock lithostratigraphically resembles the Three Forks and Bakken formations, yet chronostratigraphic contacts are do not follow lithostratigraphic contacts. The Lower Black Shale Member of the Exshaw Formation is chronostratigraphically equivalent to most of the Sappington Member, and the Lower Black Shale and part of the Middle Siltstone Member of the Bakken Formation (Figure 4). The Upper Siltstone Member of the Exshaw Formation is chronostratigraphically equivalent to part of the Cottonwood Canyon Member of the Lodgepole Formation, and part of the Middle Siltstone Member of the of the Bakken Formation. Finally, the Lower Banff Member is chronostratigraphically equivalent to part of the Cottonwood Canyon Member, and the Upper Black Shale Member of the Bakken Formation.

Bakken Formation

The Bakken Formation was deposited in the intracratonic Williston basin, currently in eastern Montana, western North Dakota, and southern Saskatchewan (Gerhard et al., 1982) (figure 5). During early exploration in the Williston basin, several names were given to an organic-rich mudstone/siltstone interval below the Madison Group including the Englewood and Exshaw (Fuller, 1956). However, it was eventually named the Bakken Formation in reference to Amerada Petroleum Corporation H.O. Bakken 1 well (Nordquist, 1953). The Bakken Formation is divided into three members

Figure 5: Devonian Paleotectonic Reconstruction

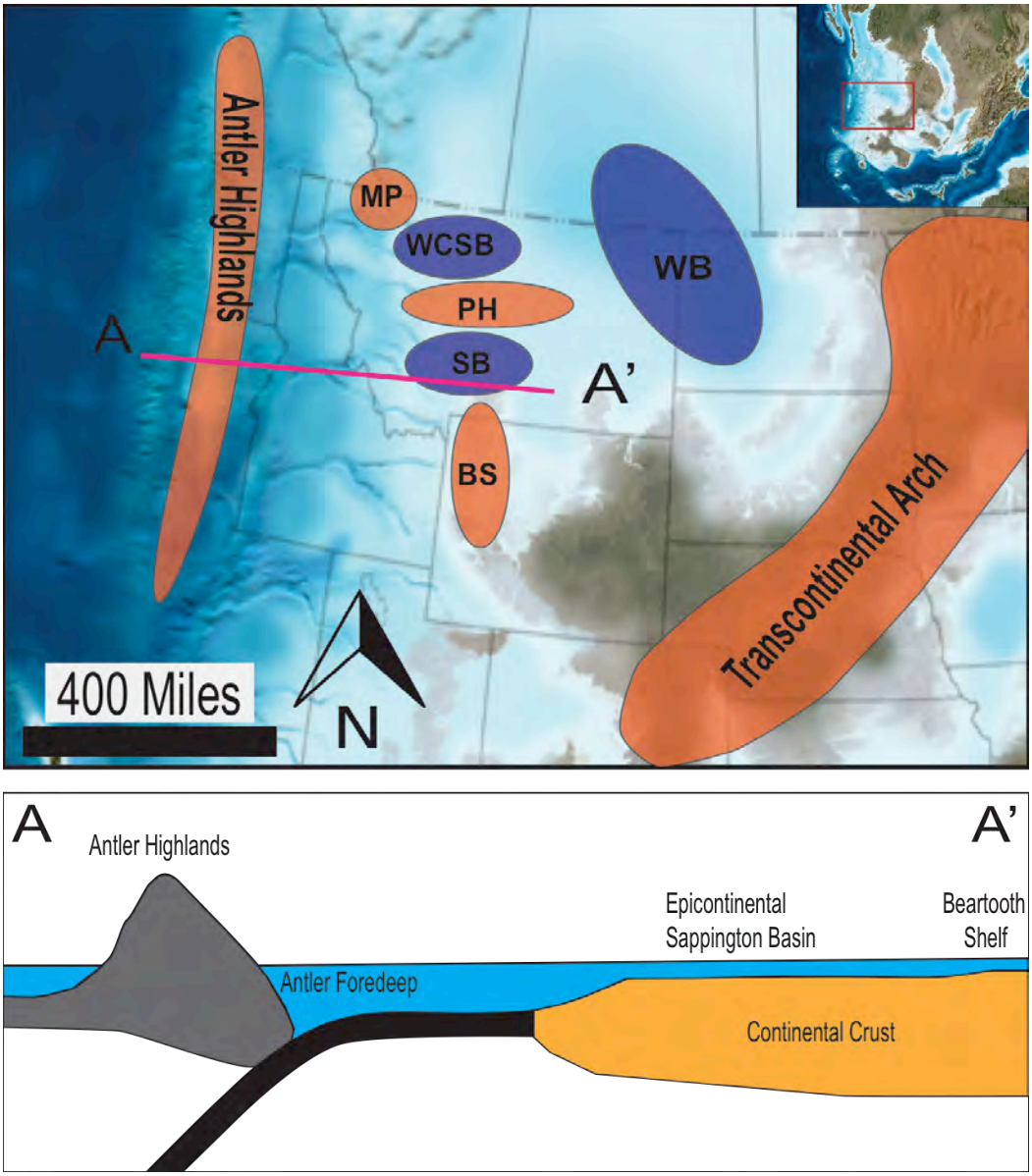


Figure 5: Paleotectonic reconstruction of the Devonian (c. 375 ma) according to Blakey (2013). Orange colors on the map indicate areas of increased topographic relief including the Antler highlands, the Montania platform (MP), the Pendroy high (PH), the Beartooth shelf (BS), and the Transcontinental arch (Adiguzel et al., 2012; Hartel et al., 2014). Relative topographic low areas are outlined in blue and include the Western Canadian Sedimentary basin (WCSB), the Sappington basin (SB), and the Williston basin (WB) (Gutschick et al., 1976; Adiguzel et al., 2012; Hartel et al., 2014). The cross section through the area shows the overall tectonic setting. The east-moving Antler highlands produced a foredeep to the west of the study area. The area of interest in located on continental crust, constituting an epicontinental basin setting.

including basal organic-rich black shale, a medial dolomitic siltstone and sandstone, and an upper organic-rich black shale (Angulo and Buatois, 2012).

Geologic Setting

Tectonic Setting

The area of interest was situated on continental crust, and was initially tectonically quiescent. The Antler allochthon situated to the west of the study area moved eastward, closed an ancient oceanic basin, and possibly reactivated Precambrian basement lineaments that may have controlled sedimentary routing during Late Devonian to Early Mississippian time (Dorobeck et al, 1991; Adiguzel et al., 2012) (Figures 5 and 6).

The structural geometry and subsequent basin fill of the Devonian-Mississippian western Montana basins are likely connected to the Precambrian assembly of Laurentia (Figure 6). Precambrian suture zones, and other lineaments create relative zones of weakness and strength which controlled the creation and propagation of future geomorphic features (Winston, 1986). Basement provinces are generally concurrent with isochore distribution of Devonian-Mississippian strata, indicating a possible link between basement terrains and tectonic movements that may have controlled sedimentary routing (Figure 6). Key identified emergent features include the Beartooth Shelf, Pendroy fault zone high, and Montania platform (Sonnenberg, 2011, Adiguzel et al., 2012) (Figures 5 and 6).

Figure 6: Precambrian Basement Configuration and Structural Features

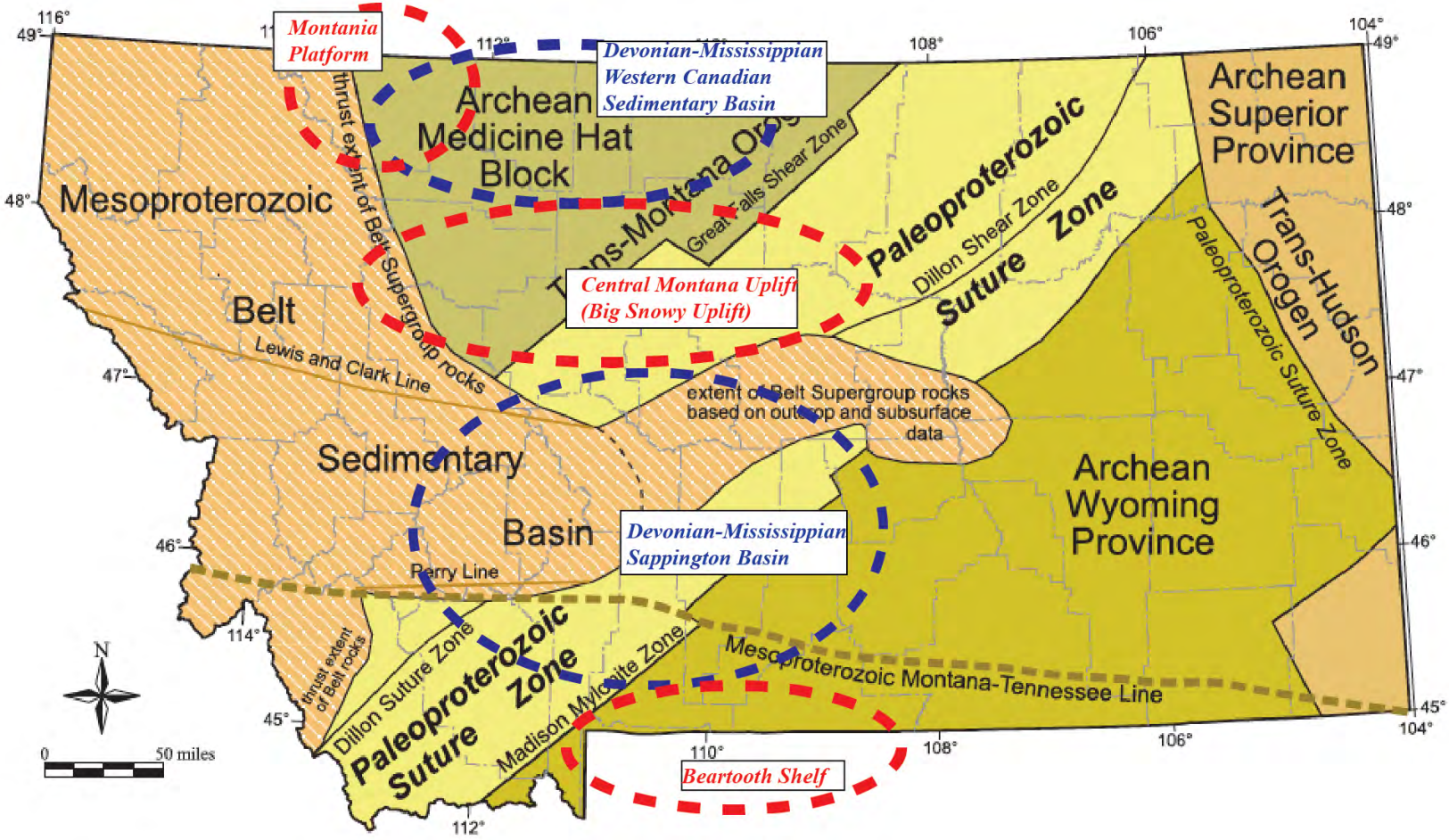


Figure 6: Precambrian Basement Configuration and Structural Features. Basement provinces and the sutures between them often correlate well with the location and movement of Phanerozoic sedimentary basins shown and labeled in dotted lines (Modifed from Vuke et al., 2007). Basement lineaments have been proposed to be reactivated, causing changes in paleotopography (Dorobeck et al., 1991).

Sedimentary Basin Types

A sedimentary basin is a relative topographic low capable of trapping and preserving sedimentary material over geologic periods of time (Ingersoll and Busby, 1995). Sedimentary basins in western Montana during the Devonian-Mississippian were dominated by marine influences, yet were also in communication with the intracontinental Williston basin (Dorobeck et al., 1991; Sloss, 1988). The western margin of North America was composed of epicontinental sedimentary basins (Sandberg and Poole, 1977) (Figure 6). However, during the late Devonian, the eastward-moving Antler allochthon may have brought foreland-type basin flexure to the epicontinental platform in western Montana (Adiguzel et al., 2012; Dorobeck et al., 1991; Giles and Dickinson, 1995).

The Acadian Unconformity

One of the first to recognize sedimentary rock packages as unconformity-bounded units was Sloss (1950). Sloss (1962) proposed that tectonic movements of the North American Craton controlled the arrangement of rock packages into unconformity-bound units. He partitioned the entirety of the sedimentary cover of North America into six rock packages defined by regional unconformities.

Within the Three Forks Formation is Sloss' (1963) Kaskaskia Sequence. This sequence began began in Early Devonian time, reaching maximum transgression during the Early Mississippian, and finally regressing during the Late Mississippian. However, Wheeler (1963) recognized an additional significant unconformable surface within the Kaskaskia sequence named the Acadian unconformity (Figure 4). This unconformity

marks a key surface within the study area both in lithostratigraphy and sequence stratigraphy.

CHAPTER 2 - DATA AND METHODS

Data

Outcrop and Core

Outcrops were selected primarily with the goal to create a dip-oriented cross section. The cross section orientation was chosen with knowledge gleaned from past literature pertaining to the Sappington basin morphology (Sonnenberg et al., 2011). Additional criteria acquired from previous literature in the high grading of outcrop localities included the quality of exposure, access availability, and completeness of section. Outcrop localities have all been reported in literature, and previous authors' observations were integrated into interpretation. However, at many outcrop localities higher resolution data was required for the overall goal of this project.

The Three Forks Formation is a fine-grained siliciclastic unit sandwiched between two carbonate units: the underlying Jefferson Formation and the overlying Madison Limestone Group. In comparison to the surrounding rock intervals, the Three Forks Formation is incompetent. Therefore it is uncommon to find complete, quality exposure of this interval. Rather, exposures are incomplete, consisting of either the upper or the lower portions of the Three Forks Formation.

Outcrop data was collected using a Brunton pocket transit compass to record bedding orientations, a 1.2 meter Jacob's staff to measure lithological thickness, a hand lens to identify lithologies and a geological field notebook. Measurements were taken in metric units, but later converted to standard units for integration into PETRA® software

for mapping purposes. Samples were collected at significant changes in lithology for thin section petrography and lithofacies analysis. At each outcrop locality, a complete vertical profile was measured and characterized, noting lithological attributes such as mineralogy, sedimentary structures, trace fossil assemblages, and carbonate framework grain type and abundance.

The core was described in a similar procedure as the outcrop, although samples were not collected for later thin section petrography. Appendix A shows a complete drafting of all outcrop and core locations including samples, rock attributes, and facies analysis. The following sections are a complete list and description of outcrop localities utilized for this study.

Moose Creek Field Site. The Moose Creek (MC) field site is located in the SE¼, SW¼, S4, T6S, R5E, in Gallatin County, Montana. Here, 24 meters of middle Three Forks Formation to Lodgepole Formation outcrop in a dramatic south-facing cliff (Gutschick and Rodriguez, 1990). This field site is the best exposure of the Three Forks Formation. This field site is accessed from Forest Service Road 6959 off Moose Creek Road in the Gallatin Canyon (Figure 7).

Sacajawea Peak Field Site. The Sacajawea Peak (SP) field site is located in the NW¼, SW¼, S22, T2N, R6E, in Gallatin County, Montana. Here 70 meters of the Three Forks Formation are well exposed on the crest of the Bridger Mountain Range (Gutschick et al., 1975). This field site is relatively easily accessed from the Fairy Lake Camp Ground. Although the actual measured section lies on an adjacent peak (Pomp Peak) to

Figure 7: Moose Creek Outcrop Overview

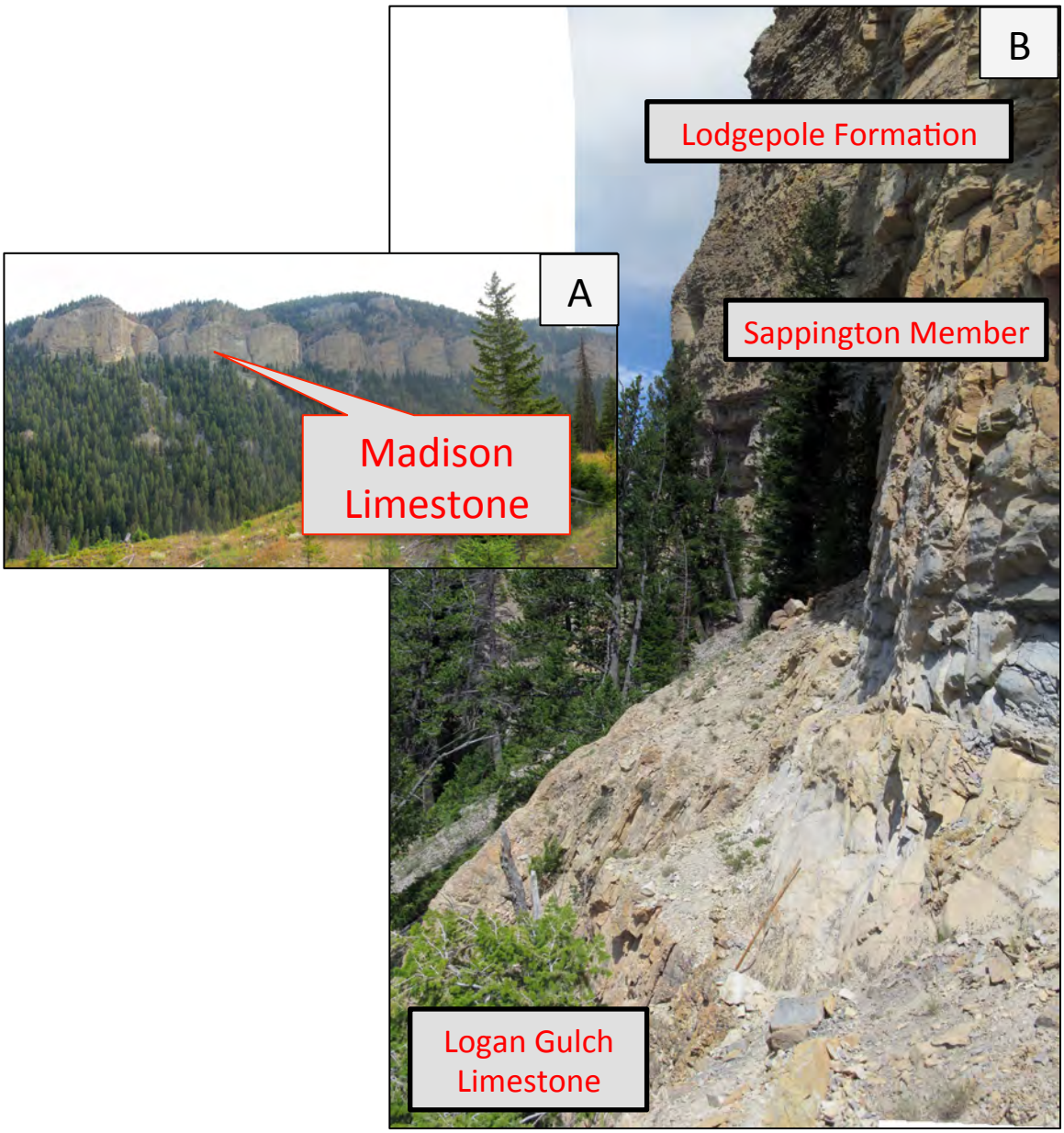


Figure 7: A) Moose Creek Outcrop Overview. Note the steep, cliff exposure. The Madison Group limestone forms the prominent ramparts, with the Three Forks Formation cropping out at the base of the sloped interval. B) Close up of Moose Creek outcrop. The Sappington Member shows sharp lithologic contacts at this location in particular. Note the 1.2 M. Jacob's Staff for scale and the undulatory contact between the Sappington and Logan Gulch members of the Three Forks Formation indicating a sequence boundary at this location.

Sacajawea Peak, the field site is named Sacajawea due to the trailhead leading to the outcrop locality named Sacajawea Peak (Figure 8).

Antelope Valley Field Site. The Antelope Valley (AV) field site is located in the SE¼, NW¼, S2, T1S, R2W, in Madison County, Montana. Here 42 meters of upper Three Forks Formation to basal Lodgepole Formation are exposed (Gutschick, 1975). The Lodgepole Formation forms a prominent east-west trending ridge with the Three Forks Formation exposed at the base. Although the field site is on BLM property, access to the field site is gained via travel through the KG Ranch property near Sappington, MT. Access *must* be granted by the ranch manager (Figure 9).

Logan Gulch Field Site. The Logan Gulch (LG) field site is located in the NE¼, SE¼, S25, T2N, R2E, in Gallatin County, Montana. Here, Jefferson Formation through Lodgepole Formation strata outcrop on the southeast limb of a northeast-southwest-trending syncline. This outcrop is the type section for the Three Forks Formation (Sandberg, 1962), and is currently the property of the F Double D Ranch. Access is gained via a gravel road to the west of the section that crosses the Gallatin River. Permission *must* be granted by the ranch manager.

Lone Mountain Field Site. The Lone Mountain (LM) field site is located in the SW¼, SE ¼, S5, T4N, R1W, in Broadwater County, Montana. Here 11 meters of upper Three Forks Formation (Sappington Member) to basal Lodgepole Formation outcrop on the eastern limb of a north-plunging anticline. The resistant Lodgepole Formation forms a prominent north-south trending ridge, allowing for partial exposure of the underlying

Figure 8: Sacajawea Peak Outcrop Overview

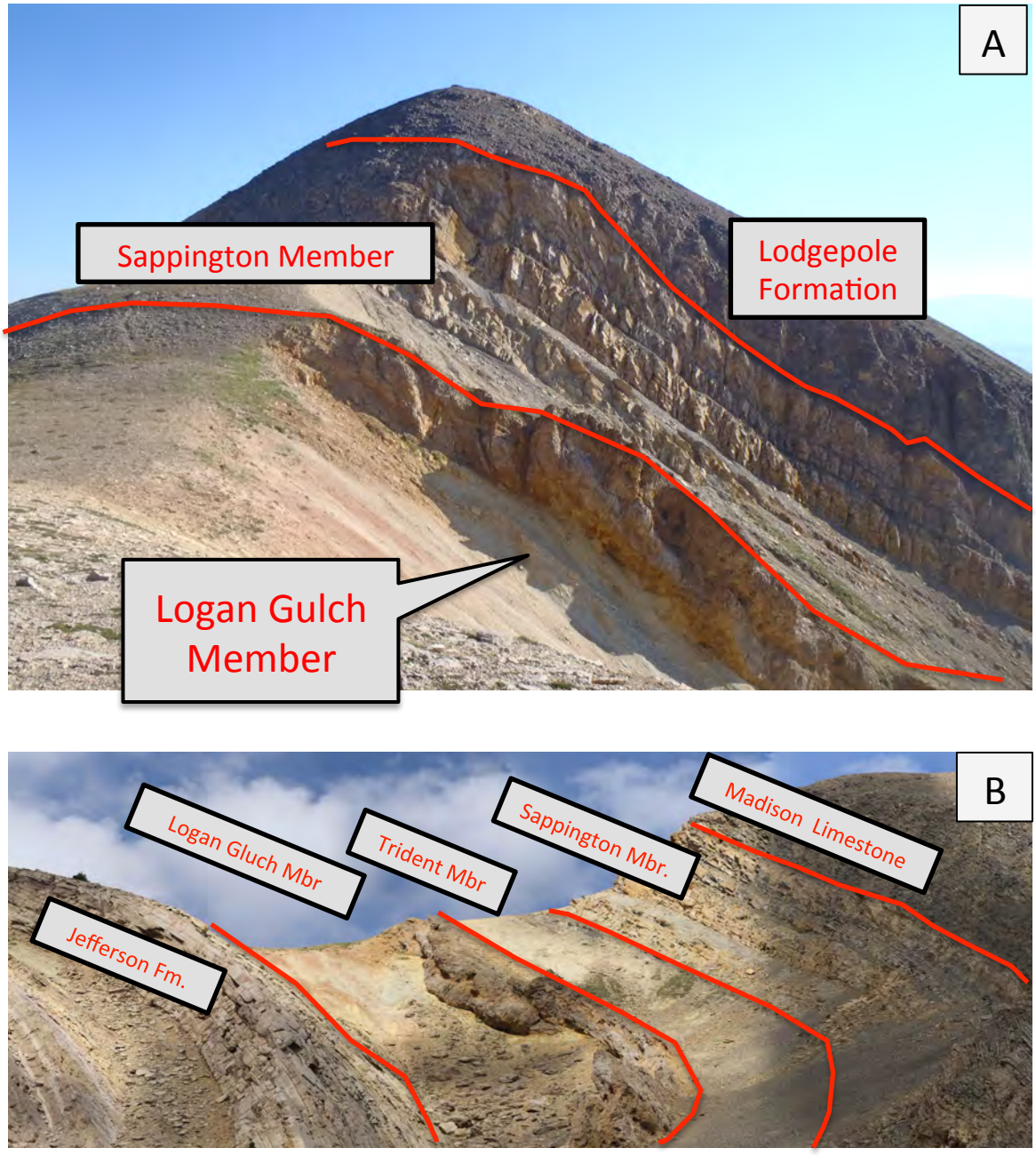


Figure 8: Sacajawea Peak Outcrop Overview. Note the dramatic thickening of this outcrop in comparison to that of Moose Creek. This is the largest, and most cited outcrop of the Sappington Member likely due to its great exposure, beautiful location, and relative ease of accessibility. Note the well-developed karstification of the Logan Gulch limestone, marking it as a good candidate a sequence boundary.

Figure 9: Antelope Valley Outcrop Overview

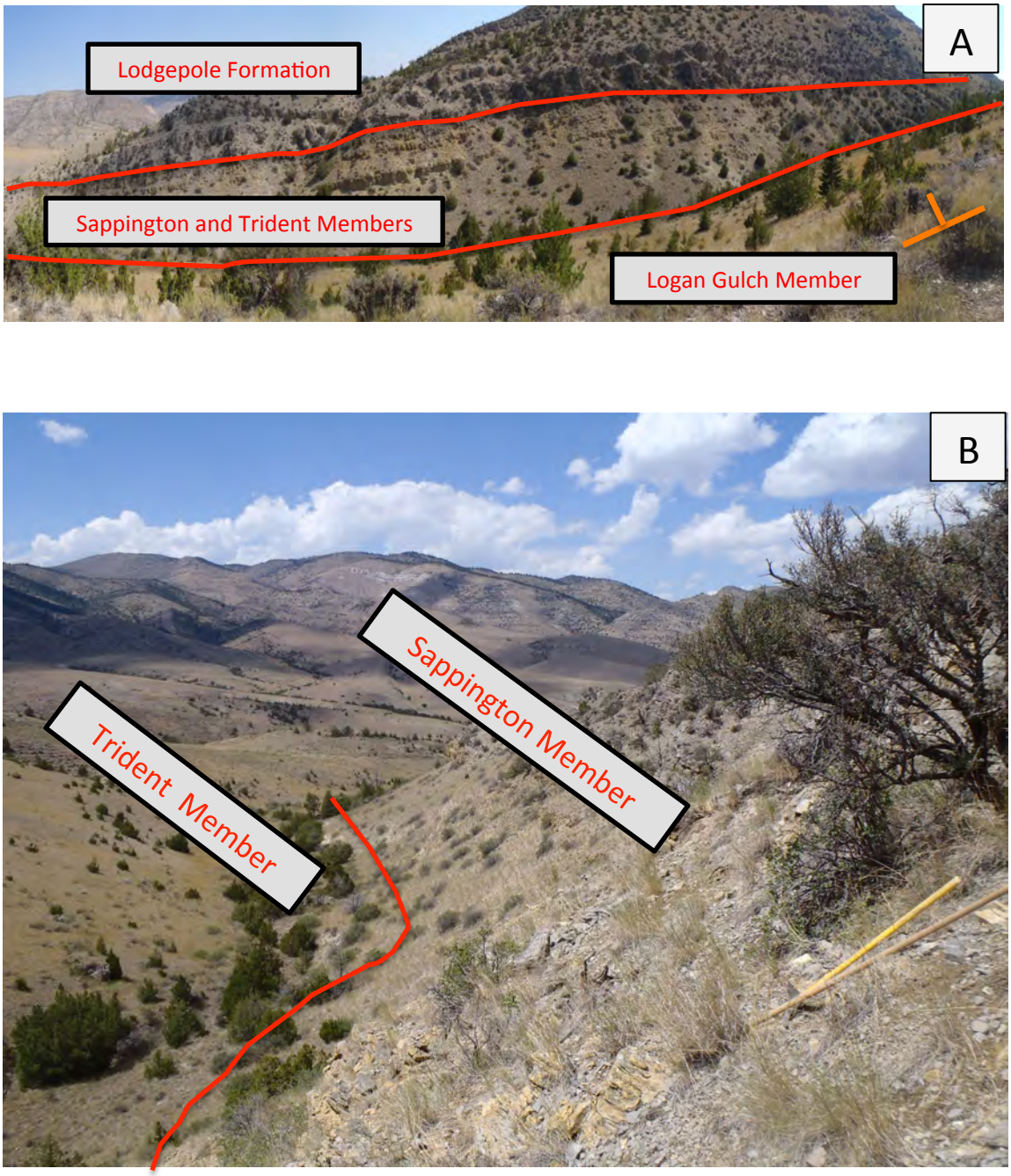


Figure 9: A) Antelope Valley Outcrop Overview. Photo is taken from atop the Logan Gulch Member looking down at a strike valley formed by the Sappington Member of the Three Forks Formation. Beds are dipping into the plane of view. B) Axial view of the Antelope Valley outcrop location showing the prominent strike valley formed by the slope-forming Three Forks Formation.

Three Forks Formation. This is a relatively small outcrop exposure, yet illustrates the variation in the upper Sappington Member, as well as the nature of the contact with the overlying Lodgepole Formation (Figure 10).

Simmes Ranch Core. The Simmes Ranch Well (API 25-101-24320) is located in S2, T36N, R3W in Toole County, Montana. Core was obtained from 3245 ft. (MD) to 3122 ft. (MD) measured from the Kelly Bushing at 3423 ft. elevation. The Simmes Ranch core has been measure in standard units for integration into PETRA software, and regional mapping (Appendix A).

Thin Sections

Hand samples were collected at significant lithological changes at outcrop localities, and made into thin sections for petrographic analysis. Thin sections were used for microfacies analysis of carbonate-dominated intervals, as well as for the interpretation of a paragenetic evolution. Fifty-two standard 30-micron-thick 24x37mm thin sections (½ stained with alizarin red) and 5 51x76 mm were made by Spectrum Petrographic (Appendix B).

Geophysical Well Logs

Geophysical well logs were utilized to correlate rock attributes of outcrops using known petrophysics-to-rock relationships (Slumberger, 1972). Geophysical curves are dominantly in raster form, the one exception being the Simmes Ranch well that is in digital form. Primary log curves utilized include gamma ray, bulk density, photoelectric factor, and shallow and deep resistivity. A list of 198 alpha wells—wells that have been

Figure 10: Lone Mountain Outcrop Overview

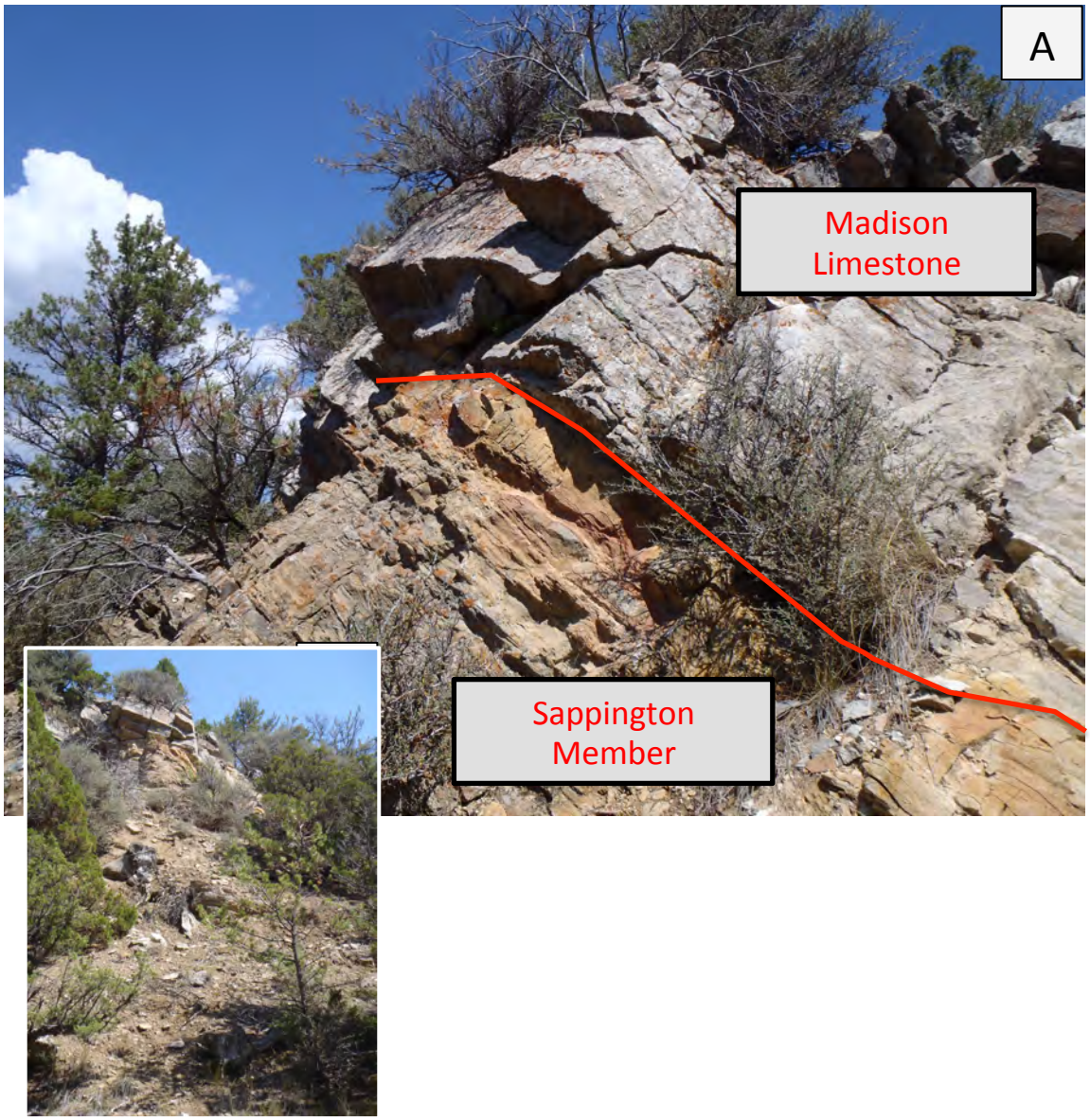


Figure 10: A) Lone Mountain Outcrop Overview. Here the upper black shale unit is absent and is likely erosional. The upper Sappington sandstone unit is much finer-grained, less resistant, and thinner than in updip localities. B) A secondary view of the Antelope Valley location showing the large amount of cover associated with this outcrop location requiring a large amount of trenching. The low resistance nature of this outcrop may be due to the fine-grained intervals so prominent in this area. Although not measured, below the Sappington Member at the Antelope Valley location lies dark grey to black shale of the Trident Member that forms a distinctive strike valley.

deemed suitable for correlation based on the quality of data—and stratigraphic picks are available in appendix C. Geophysical logs are available in standard units (feet), and will be mapped according to this system of measurements.

Methods

Lithofacies Analysis and Lithofacies Assemblages

Lithofacies analysis includes the aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; especially as differentiating the unit from adjacent or associated units (Bates and Jackson, 1987). Eighteen lithofacies were identified in outcrop, hand sample and thin section observation based on the following criteria: 1) mineralogy, 2) grain size, and 3) sedimentary structures. Mineralogy was primarily gleaned from standard thin section petrography, while grain size and sedimentary structures were gleaned from outcrop and hand sample.

Rocks encountered in the Sappington basin include siliciclastic and carbonate lithologies. Carbonate rocks were classified in hand sample and thin section by the criteria described by Dunham (1962), while siliciclastic rocks were classified by the Folk et al. (1970) classification scheme. After classification, lithofacies were designated a code based on their respective assemblage of sedimentary attributes. Carbonate facies were gleaned from the work of Machel and Hunter (1994), and Flügel (2004 p.674, 681-710), while siliciclastic lithofacies were derivative of Plint (2010).

Sedimentary structures assumedly reflect hydrodynamic conditions that operate invariantly through time on matter (Harms and Fahnestock, 1965; Simons et al., 1965).

Sedimentary structures in association with lithology constitute a lithofacies that are non unique to any environment of deposition. However, lithofacies interpreted to be closely related by similar depositional energy according to hydrodynamic indicators constitute a lithofacies association that indicates a depositional environment. Depositional environments have been interpreted on a depositional profile according energy regimes defined by water depths. Terminology of these energy regimes was applied according to Machel and Hunter (1994) and Plint (2004).

Tying Rock Data to Derived Rock Data

Tying rock data to derived rock data allows lithostratigraphic and sequence stratigraphic bodies to be mapped across a large area. In order to tie rock data to geophysical data and effectively map stratigraphic horizons, geophysical ties need to be grounded in outcrop. In order to achieve this, IHS geophysical raster logs were acquired and identified near outcrop localities and through cored intervals. Then, geophysical well log curves were correlated to key stratigraphic surfaces in core and nearby outcrop localities using knowledge of the petrophysical characteristics of specific lithologies (Schlumberger, 1970). After key stratigraphic intervals and surfaces were identified in outcrop and core and calibrated to geophysical data, they were then mapped throughout the project area using IHS PETRA® software.

Lithostratigraphy

The North American Stratigraphic Code states that lithostratigraphic units are mappable rock bodies distinguished by lithological attributes that generally adhere to the

law of original horizontality (North American Stratigraphic Code, 1983). Rock bodies were identified in outcrop according to the lithological attributes defined by lithofacies analysis and nomenclature of the USGS in the Sappington basin (Sandberg, 1965; Sandberg and Klapper, 1967). These rock bodies were then correlated throughout the study area using geophysical well logs.

Sequence Stratigraphy

Sequence stratigraphic interpretation follows the techniques outlined by Van Wagoner et al. (1990) and Catuneanu (2006). Outcrops are the most abundant in the Sappington basin, and are the ideal medium from which to construct a sequence stratigraphic framework. Discrete beds were assigned individual lithofacies. Vertical stacking of lithofacies were interpreted into shallowing-upward parasequences bounded by flooding surfaces (Van Wagoner et al, 1990). These parasequences were then grouped into systems tracts. Surfaces between systems tracts and parasequences indicate key surfaces within the project area. These surfaces were correlated between outcrops, and throughout the project area using geophysical well logs.

The most significant outcome of a sequence stratigraphic framework is the inference of contemporaneous surfaces, allowing the interpretation of time-equivalent depositional systems, and how they are distributed through space and time in western Montana (Appendix C). Additionally, identification of key sequence stratigraphic surfaces dictates the diagenetic evolution of discrete rock bodies (Morad, 2010), and provides a framework to interpret diagenesis.

Linking Diagenesis to Sequence Stratigraphy

Framing diagenesis within a sequence stratigraphic framework allows for a better understanding of diagenetic processes (Morad et al., 2010). Sequence stratigraphic interpretation discerns significant surfaces and rock packages in time and space. According to sequence stratigraphy, these surfaces characterize several forcing functions that exert a strong control during the eogenetic regime of diagenesis (Morad et al., 2012). Initial boundary conditions defined by sequence stratigraphy have been shown to exert a strong control on the later mesogenetic and telogenetic regimes as well (Morad et al, 2012). Therefore a paragenetic evolution has been interpreted for discrete rock bodies that are defined by key sequence stratigraphic surfaces.

CHAPTER 3 – SEDIMENTOLOGY

Lithofacies

Sedimentary processes impart attributes onto sediment that are interpreted by lithofacies analysis to reflect conditions during deposition. Lithofacies classification fundamentally relies on the intrinsic characteristics of sedimentary rocks including grain size, matrix to framework ratio, mineralogy, sedimentary structures, and ichnofossils. All outcrop and core that was described was divided into discrete lithofacies, and was assigned a rock type, description, and interpretation. For example, in lithofacies CGoi C stands for carbonate, G stands for the rock type (grainstone) in Dunham's classification, while i and o stand for characteristic features of that particular lithofacies (ooid and intraclast framework grains).

While siliciclastic lithofacies largely relied on outcrop scale of attributes similar to the fluvial scheme of Miall (1996), carbonate units required a thin-section petrographic scale for interpretation. This approach to facies characterization is called microfacies analysis, and has been well-outlined by Flügel (2004, p.53-70). This technique has been applied to Upper Devonian carbonate units throughout the world by Machael and Hunter (1994). While many of the lithofacies classification of Machael and Hunter (1994) are directly and appropriately applicable to that of western Montana, some lithologies are not captured by their lithofacies scheme. Thus, standard microfacies have been utilized from Flügel (2004, p.698) to account for

remaining observed lithofacies. Carbonate and siliciclastic lithofacies, and the samples that represent them are summarized in tables 1 and 2.

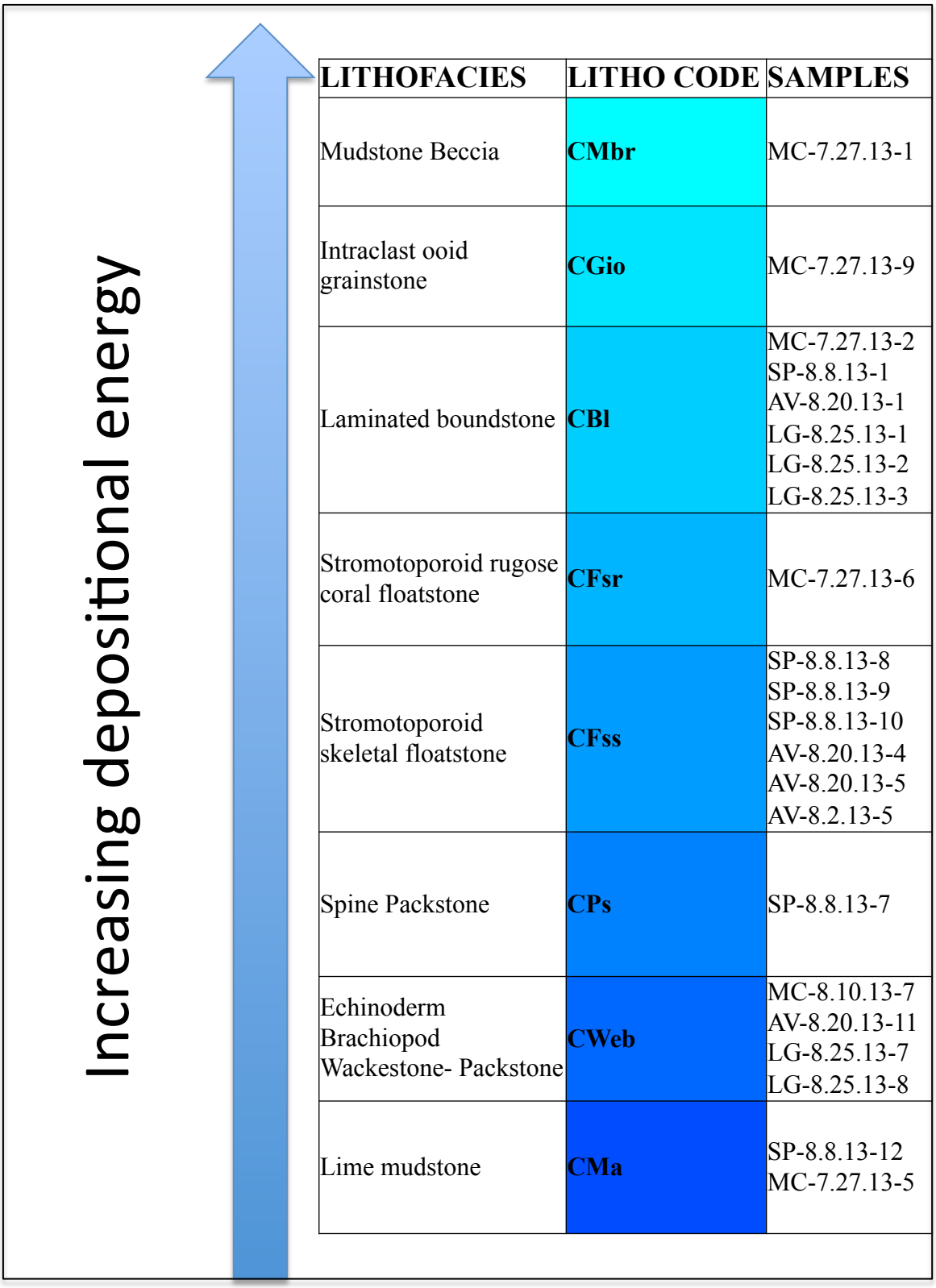
Carbonate Lithofacies

Lithofacies CMbr. This lithofacies is characterized as a breccia (br), ranging in grain size from sand to boulder. This lithofacies is observed within a mudstone/boundstone dominated interval where mudstone to boundstone clasts are likely derived—leading to the interpretation that clasts are autochthonous. It is interpreted that this lithofacies is formed from *in situ* dissolution, karstification, and subsequent collapse (Machel and Hunter, 1994). Clasts are suspended in a variously dolomitic to calcic matrix. Fracturing is pervasive throughout this lithofacies, although fractures have been healed by blocky calcite (Figure 11)

Lithofacies CGio. This lithofacies is characterized as an intraclast(i) ooid (o) grainstone (G). CGio is composed of micritized, rounded intraclasts (50%) and heavily micritized radial ooids (30%). Additional grains include very fine to fine-grained sand-sized, sub angular quartz grains (20%). Cement is calcite, and ranges from drusy to blocky spar. Fractured framework grains and parallel lamination indicates high-energy traction transport during deposition (Southard, J.B, and Boguchwal, L.A., 1990) (Figure 12)

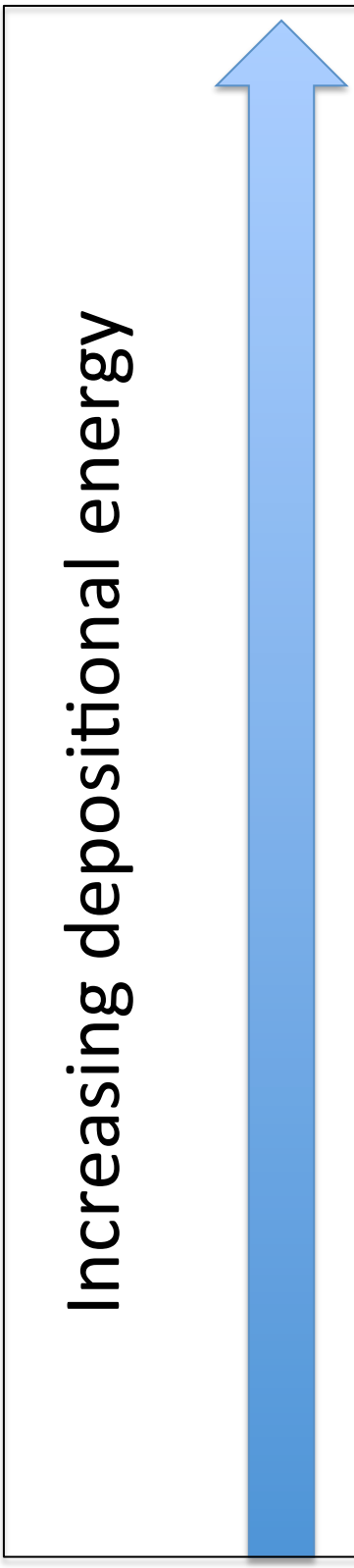
Lithofacies CBl. This lithofacies is characterized as a boundstone (B). Fine laminations (l) observed in outcrop and hand sample have been demonstrated to be in

Table 1:Carbonate Lithofacies



LITHOFACIES	LITHO CODE	SAMPLES
Mudstone Beccia	**CMbr**	MC-7.27.13-1
Intraclast ooid grainstone	**CGio**	MC-7.27.13-9
Laminated boundstone	**CBl**	MC-7.27.13-2 SP-8.8.13-1 AV-8.20.13-1 LG-8.25.13-1 LG-8.25.13-2 LG-8.25.13-3
Stromotoporoid rugose coral floatstone	**CFsr**	MC-7.27.13-6
Stromotoporoid skeletal floatstone	**CFss**	SP-8.8.13-8 SP-8.8.13-9 SP-8.8.13-10 AV-8.20.13-4 AV-8.20.13-5 AV-8.2.13-5
Spine Packstone	**CPs**	SP-8.8.13-7
Echinoderm Brachiopod Wackestone- Packstone	**CWeb**	MC-8.10.13-7 AV-8.20.13-11 LG-8.25.13-7 LG-8.25.13-8
Lime mudstone	**CMa**	SP-8.8.13-12 MC-7.27.13-5

Table 2: Siliciclastic Lithofacies



LITHOFACIES	LITHO CODE	SAMPLES
Low-angle crosbedded medium sandstone	**Sl**	MC-7.27.13-10
Ripple cross-laminated fine-medium sand	**Sr**	MC-8.10.13-5 SP-8.8.13-13 AV-7.29.13-7 AV-8.20.13-10
Swaley cross stratified, hummocky fine sandstone	**Ssw**	LG-8.25.13-12 LM-8.1.13-3 LM-8.14.13-1 LM-8.14.13-2 LM-8.14.13-5 MC-8.10.13-2 MC-8.10.13-3 AV-8.20.13-9 AV-8.20.13-8 AV-7.29.13-6 AV-7.29.13-8 MC-7.27.13-12 MC-8.10.13-3
Massive siltstone	**Fsm**	MC-7.27.13-8 MC-7.27.13-7 MC-8.10.13-6 SP-8.8.13-11 LM-3.1.13-2 LM-8.14.13-3 LM8.14.13-4 MC-7.27.13-11
Graded, organic-bearing siltstone	**Fsgo**	
Dolomitic, stromotoporoid-bearing siltstone	**Fsds**	MC-7.27.13-4 MC-7.27.13-3 MC-8.10.13-1
Dolomitic laminated siltstone	**Fsl**	MC-8.10.13-8 SP-8.8.13-2 SP-8.8.13-3 SP-8.8.13-4 LG-8.25.13-4 AV-8.2.13-6 AV-8.20.13-7 AV-7.29.13-2 AV-8.20.13-2 AV-8.20.13-1 LM-3.1.13-1
Laminated mudstone	**Fml**	LG-8.25.13-6 AV-8.2.13-3 AV-8.20.13-2
Massive claystone	**Fcm**	SP-8.8.13-5 LG-8.25.13-5 AV-8.2.13-7
Organic rich claystone	**Fmo**	SP-8.8.13-6 SP-8.8.13-7A SP-8.8.13-14 LG-8.25.13-11 LG-8.25.13-10 AV-8.2.13-4 AV-8.20.13-3 MC-8.10.13-4

Figure 11: Lithofacies CMbr—Mudstone Breccia

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Mudstone Beccia	**CMbr**	Tan to light grey fresh/light grey weathered. Pebble to boulder-sized breccia clasts are composed of finely-laminated dolomitic mudstone, creating a massive texture. Breccia clasts are suspended in a light tan, variously dolomitic to calcitic matrix. Fractures throughout are filled with blocky calcite cement.	Secondary dissolution during exposure to meteoric waters. Clasts in this particular lithology are derived from a laminated carbonate mudstone (Flugel, 2004; Morad, 2012).

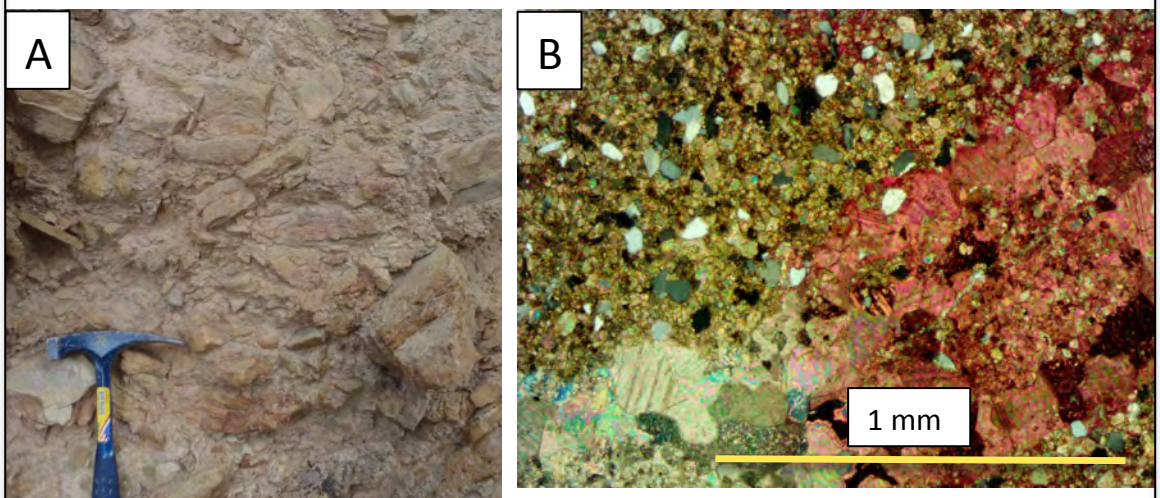


Figure 11 A and B: A) Lithofacies CMbr at Moose Creek. This facies is only observed in the Logan Gulch limestone. Brecciation does not seem to be vertically systematic from locality to locality, but is likely due to dissolution. Clasts are autochthonous pebble to boulder-sized lime mudstones. B) crossed nicols photomicrograph of MC-7.27.13-1 showing silty dolostone truncated by a calcite-filled fracture.

Figure 12: Lithofacies Cgio—Intraclast Ooid Grainstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Intraclast ooid grainstone	**CGio**	Light grey fresh, light grey weathered. Low angle cross bed sets dip at 5-10 degrees. Framework grains consist of dominantly rounded intraclasts (50%) and heavily micritized radial ooids (30%). Additional grains include very fine to fine-grained sand-sized, sub angular quartz grains (20%). Cement is calcite, and ranges from drusy to blocky spar.	Low angle crossbed sets indicate unidirectional flow causing lower upper flow regime traction transport (Flugel, 2004).

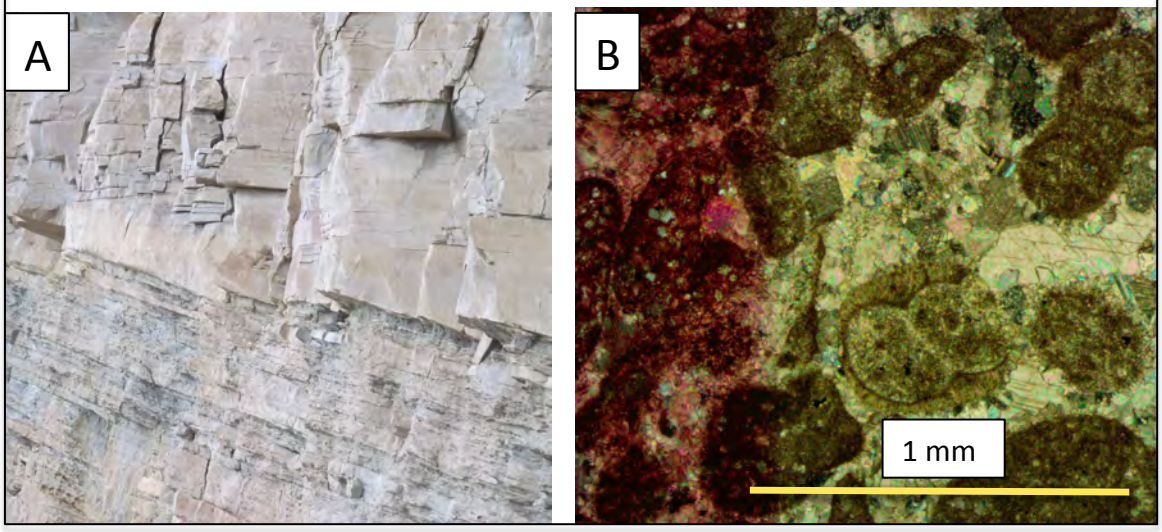


Figure 12 A and B: A) Lithofacies GCio at the Moose Creek outcrop. This is a thin interval of parallel-laminated oolitic limestone within a clastic succession. Due to the high energy deposits surrounding CGoi, high energy sedimentary structures (parallel lamination), and high-energy framework grains (radial ooids and highly fractured interclasts), this deposit is interpreted to be a shoal deposit within the foreshore environment. B) micritized intraclasts, ooids and grapestones are suspended in a sparry calcite matrix.

part microbial-induced laminations indicated by a clotted texture observed in thin section. Faint outlines of what appear to be peloids and shell fragments observed in thin section may also produce laminations (Flügel, 2004, p. 704-705). Microbial structures produce fenestral porosity that has largely been occluded by microcrystalline to blocky cement (Flügel, 2004, p. 374-375) (Figure 13).

Lithofacies CFsr. This lithofacies is characterized as a stromatoporoids (s) rugose coral (r) floatstone (F). Framework grains consist of (in place?) rugose corals (~30%), well-articulated crinoids and other echinoderms (30%), brachiopods (20%), bivalves (15%), and a small amount of silt sized quartz grains (~5%). Carbonate framework grains are commonly encrusted with stromatoporoids. Matrix is fine-grained calcite. Cement is microcrystalline calcite. Rugose corals and encrusting stromatoporoids are interpreted to produce a weak framework that is weakly winnowed by wave action evident from the large amount of fine-grained matrix material (Machel and Hunter, 1994) (Figure 14)

Lithofacies CFss. This lithofacies is characterized as a stromatoporoid (s) skeletal(s) floatstone (F). Framework grains consist of crinoid and other echinoderm fragments (40%), brachiopods (20%), bivalves (15%), intraclasts (10%), bryozoans (10-15%). and a small amount of very fine sand-sized quartz grains (~5-10%). Framework grains are variously silicified, and are heavily encrusted with stromatoporoids (creating 2-3 cm clasts) and are covered in a reddish material that is likely siderite. Framework grains are suspended in a fine-grained argillaceous calcite

Figure 13: Lithofacies CBl: Laminated Boundstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Laminated Boundstone	**CBl**	Dark grey fresh, dark grey weathered. Fine laminations. Faint outlines of peloids and possibly shell fragments are evident in laminations, but have been highly neomorphosed. Thrombolitic textures are locally dominant, creating a fenestral type porosity. Pores are filled with sparry calcite cement, and are locally silicified. Carbonate matrix is very fine-grained, and locally dolomitized. Bioturbation rare if at all evident.	Thrombolitic texture suggest that the dominant carbonate producer was cyanobacteria which may baffle other framework grains, both clastic and carbonate (Machel and Hunter, 1994).

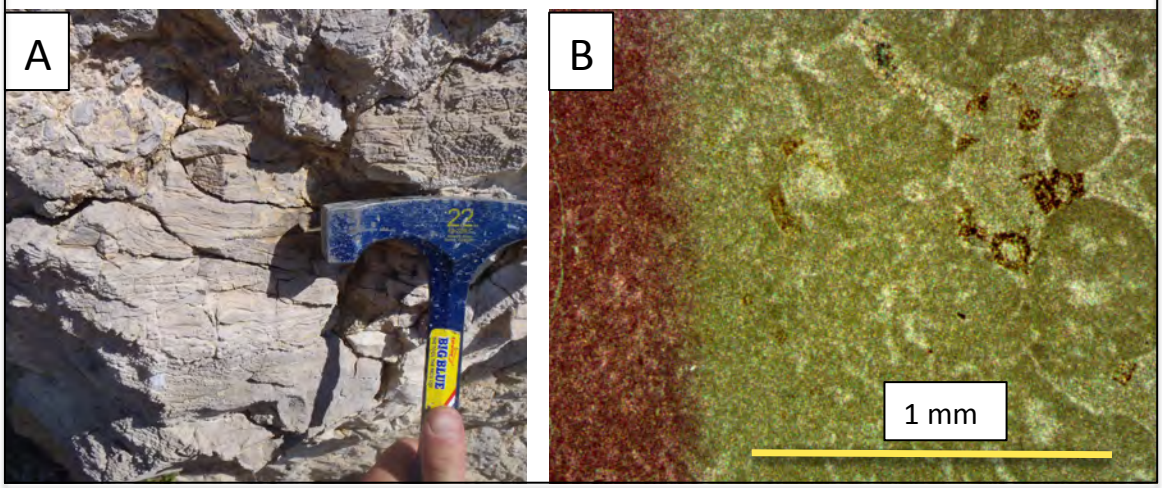


Figure 13 A and B: A) Lithofacies CBl at Antelope Valley. Note the wavy nature of many of the laminations. This may be in part microbally induced creating an interpreted fenestral porosity that has been since filled with sparry calcite cement. This lithofacies is characteristic of the Logan Gulch limestone interval that is very continuous throughout the Sappington basin. This is the lithofacies from which the clasts in CMbr are created. B) crossed nicols photomicrograph of facies CBt showing thrombolitic texture locally dominates facies CBt.

Figure 14: Lithofacies CFsr—Stromotoporoid Rugose Floatstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Stromotoporoid rugose coral floatstone	**CFsr**	Dark grey fresh, dark grey weathered. Framework grains consist of (in place?) rugose corals (40%), well-articulated crinoids and other echinoderms (30%), brachiopods (20%), bivalves (15%), and a small amount of very fine quartz grains (~5%). Allochemical framework grains are commonly encrusted with stromotoporoids. Matrix is fine-grained calcite. Cement is microcrystalline calcite.	In situ rugose corals with encrusting stromotoporoids produce a weak framework that is slighly winnowed by wave action. Other unknown fine-grained carbonate producers produce a large volume of carbonate material (Machel and Hunter, 1994).

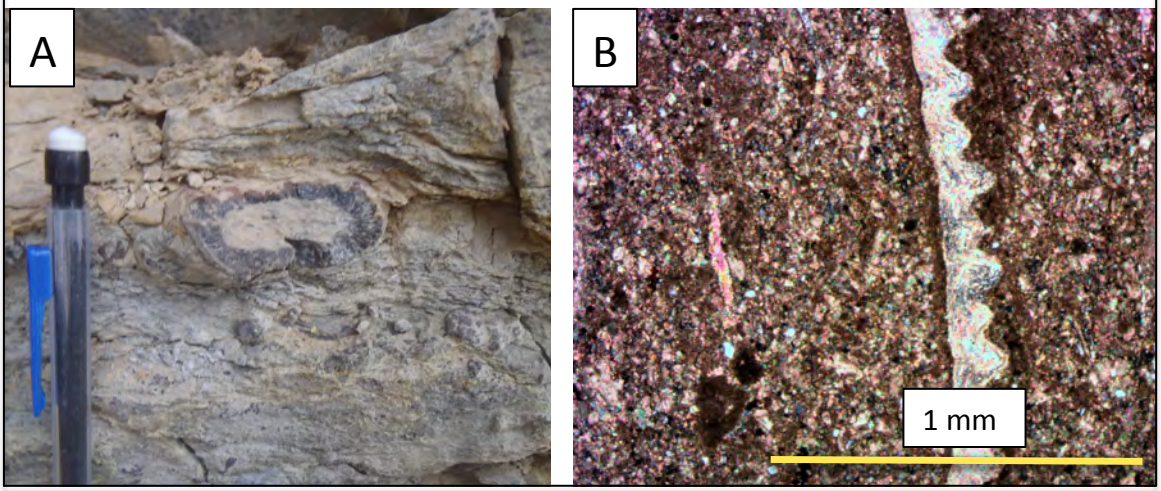


Figure 14 A and B: A) Lithofacies FSsr at Moose Creek. Well preserved solitary rugose corals are suspended in micritic cement. The high degree of preservation is interpreted to indicate relatively low energy conditions, and near *in situ* preservation of the sessile organisms. This facies is interpreted to be a deposited in relatively shallow water due to the abundance of corals, and hence deposition within the photic zone. B) crossed nicols photomicrograph of facies CFsr showing brachiopod shell that has been encrusted by a stromotoporoid suspended in a fine-grained calcite matrix.

matrix. Siliciclastic material may have been transported by aeolian or fluvial processes (Machel and Hunter, 1994) (Figure 15)

Lithofacies CPs. This lithofacies is characterized as a spine (s) packstone (P). Preferentially oriented oblate framework grains form laminations. Framework grains are dominantly elongate, tubular-shaped 2-3 mm brachiopod and echinoderm spines (60-70%), radial ooids (20%), crinoids (10%), and bivalves (~5%). Framework grains seem to be preferentially oriented, especially prolate-shaped grains. Matrix is fine-grained calcite. Cement is microcrystalline calcite. This lithofacies contains an anomalous assemblage of highly organized framework grains that likely indicate reworking and deposition during a storm event (Flügel, 2004, p. 605) (Figure 16).

Lithofacies CWeb. This lithofacies is characterized as an echinoderm (e) brachiopod (b) wackestone (W). Framework grains consist of well-articulated, yet sparse crinoids and other echinoderms (80%), brachiopods (20%), and bryozoans (20%). These framework grains are set in a fine-grained calcite matrix. Cement is microcrystalline calcite; blocky calcite fills in sheltered porosity created by shell fragments. Brachiopods and other framework grains may be in situ or reworked, having experienced abrasion during reworking. The abundance of fine-grained carbonate matrix produced by an unknown organism indicates a weak influence of wave action (Machel and Hunter, 1994) (Figure 17).

Lithofacies CMa. This lithofacies is characterized as an argillaceous (a) carbonate (C) mudstone (M). Framework grains are exceedingly rare. Clasts include

Figure 15: Lithofacies CFss: Stromotoporoid Skeletal Floatstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Stromotoporoid skeletal floatstone	**CFss**	Dark grey fresh, dark grey weathered. Framework grains consist of poorly-articulated, and highly diverse skeletal grains, including crinoid and other echinoderm fragments (40%), brachiopods (20%), bivalves (15%), intraclasts (10%), bryozoans (10-80%). and a small amount of very fine sand-sized quartz grains (~5-10%). Framework grains are variously silicified, and are heavily encrusted with stromotoporoids (Creating 1-2 mm clasts) and are covered in a reddish material that is likely siderite. Framework grains are suspended in a fine-grained argillaceous calcite matrix.	Stromotoporoids encrust previously deposited skeletal grains which are suspended in a fine-grained, argillaceous matrix. Siliciclastic material may have been transported by aeolian or fluvial processes (Machel and Hunter, 1994).

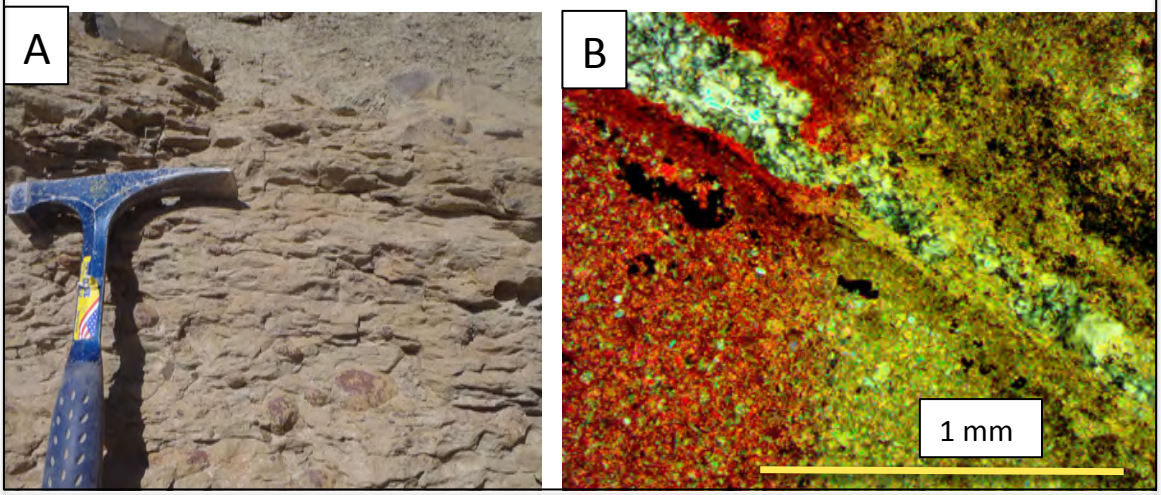


Figure 15 A, and B: A) Lithofacies CFss at Sacajawea Peak. This facies includes very conspicuous stromotoporoid-coated, silicified, well-articulated brachiopod tests suspended in a argillaceous, dominantly fine-grained calcite matrix. B)PL view of showing a chertified brachiopod shell that has been heavily encrusted.

Figure 16: Lithofacies CPs—Spine Packstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Spine Packstone	**CPs**	Dark grey fresh, dark grey weathered. Discreet laminations are formed by preferentially-oriented framework grains. Framework grains are dominantly elongate, tubular-shaped 2-3 mm brachiopid and echinoderm spines (50-60%), radial ooids (20%), crinoids (10%), and bivalves (~5%). Framework grains seem to preferentially oriented, especially prolate-shaped grains. Matrix is fine-grained calcite. Cement is microcrystalline calcite.	This lithofacies contains an anomalous assemblage of highly organized framework grains that likely indicate reworking and deposition during a storm event (Flügel, 2004, p. 605).

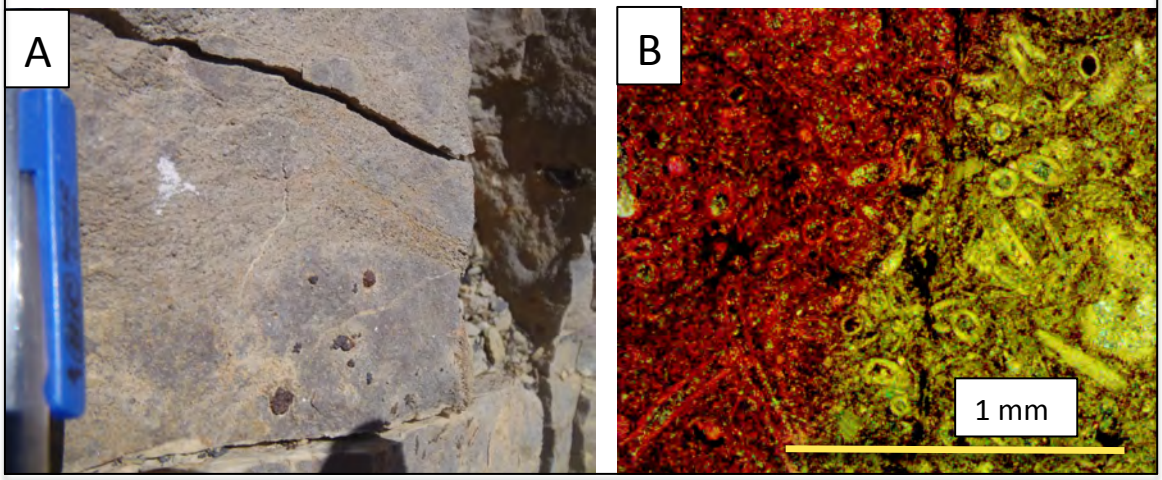


Figure 16 A and B: A) Lithofacies CPs at Sacajawea Peak. Note the overall fabric of the rock indicated by the alignment of framework grains that indicates hydrodynamic processes. B) XPL view of facies CPs displaying brachiopod and echinoderm spines.

Figure 17: Lithofacies CWeb—Echinoderm Brachiopod Wakestone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Echinoderm Brachiopod Wackestone-Packstone	**CWeb**	Dark grey fresh, dark grey weathered. Framework grains consist of well-articulated, yet sparse crinoids and other echinoderms (80%), Brachiopods (20%), and Bryozoa (20%). These framework grains are set in a fine-grained calcite matrix. Cement is microcrystalline calcite; blocky calcite fills in sheltered porosity created by shell fragments.	Echinoderms are fratured and deposited. Brachiopods are other framework grains may be in situ or reworked. Fine-grained carbonate matrix was produced by an unknown organism (Machel and Hunter, 1994).

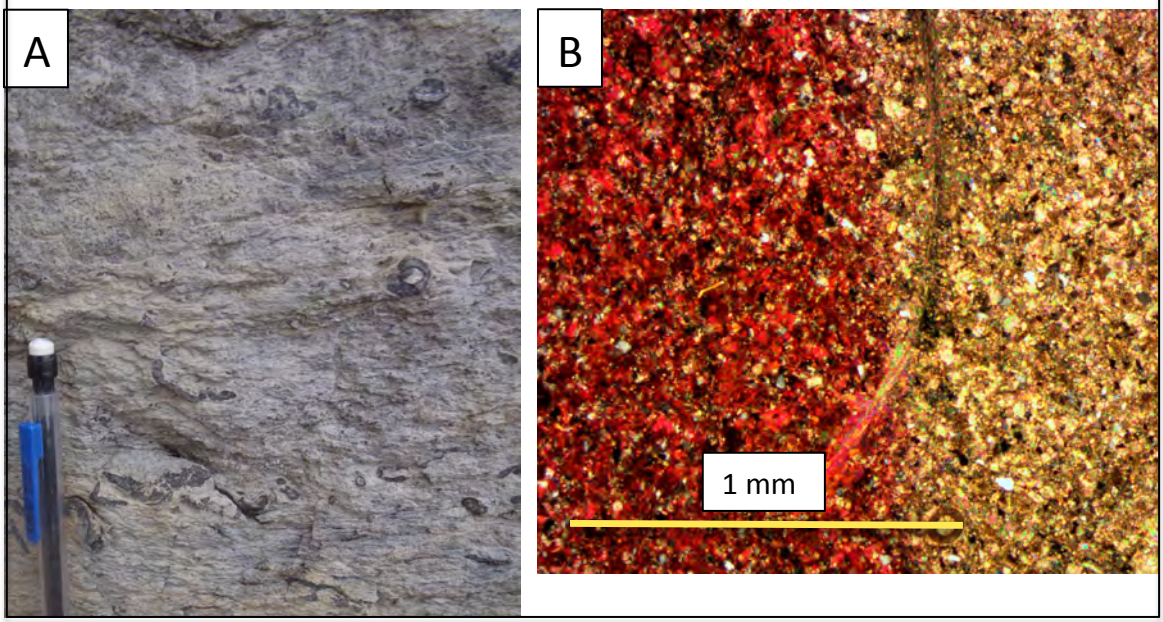


Figure 17 A, and B: A) Lithofacies CWeb at Moose Creek. Note the high preservation of fossils suspended in a argillaceous calcite matrix. B) Crossed nicols photomicrograph of facies CWeb showing a brachiopod framework grain suspended in a fine-grained, argillaceous calcareous matrix.

dominantly very fine sand to silt-sized quartz, and rare echinoderms and brachiopods. Bioturbation is pervasive, and often destroys any original depositional fabric. Matrix material dominates, and is microcrystalline to crystalline dolomite. Hemipelagic and pelagic deposition of fine-grained carbonate and siliciclastic sediment transported from more proximal localities during storms is interpreted to dominate deposition. Organisms rework sediment during times of nondeposition (Figure 18).

Siliciclastic Lithofacies

Lithofacies Sl. This lithofacies is characterized as a low-angle (l) crossbedded sandstone (S). This lithofacies is composed of quartz grains (~90+%), potassium feldspar and micas (2-3% each) and lithics (~5%). At Moose Creek, an increase in accessory and lithics is observed in this lithofacies. Grains are cemented with blocky calcite cement as well as calcite cement that is in the form of a rhombohedra. Low angle planar crossbedding is characteristic indicating high-energy traction transport (Southard, J.B, and Boguchwal, L.A., 1990). Two very dominant directions of bedform migration indicate bidirectional transport interpreted to be due to the swash action of waves (Plint, 2010) (Figure 19).

Lithofacies Sr. This lithofacies is characterized as a ripple cross-laminated fine-medium sandstone. Grains are composed of quartz (~95+%) and lithics (~5%). Accessory minerals include potassium feldspar, mica, and zircon. Multidirectional ripple cross-lamination is dominant. Bioturbation is rare, yet includes *Skolithos* and *Diplocraterion*. Rip and longshore currents entrain particles in lower flow regime

Figure 18: Lithofacies Cma—Lime Mudstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Lime mudstone	**CMa**	Dark grey fresh, dark grey weathered. Framework grains are exceedingly rare. Clasts include dominantly very fine sand to silt-sized quartz, and rare echinoderms and brachopods. Bioturbaution is pervasive, and often destroys any original depositional fabric. Matrix material dominates and is microcrystalline dolomite that has been neomorphosed to create a somewhat crystalline dolomite cement.	Hemipelagic and pelagic deposition from sediment derived updip is dominant. Reworking of seidment via bioturbation (Machel and Hunter, 1994).

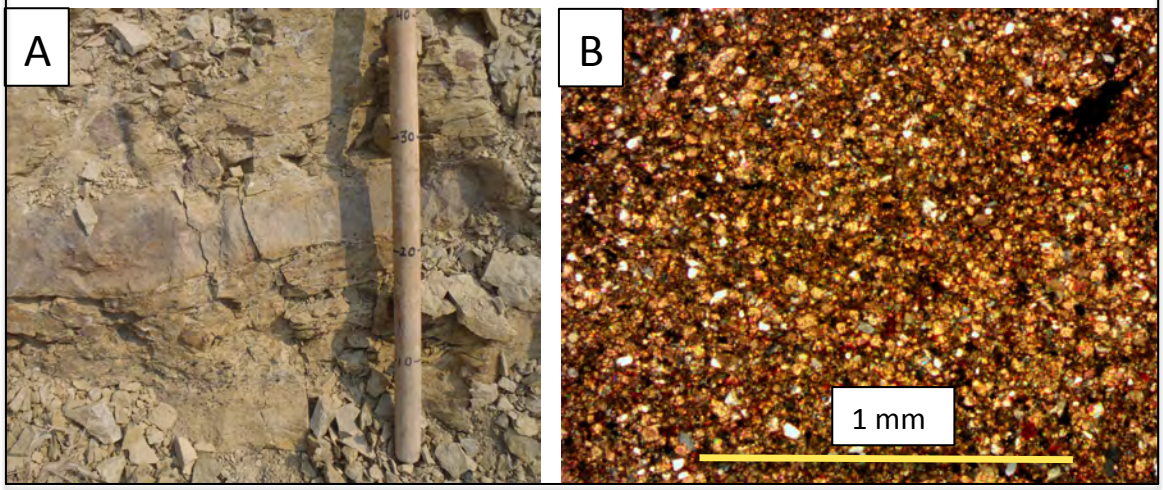


Figure 18 A and B: A) Lithofacies CMa at Antelope valley. This lithofacies is the very competent horizontal interval between the 20 an 30 cm mark on the Jacob's Staff. Note that this interval is between two tan intervals, that has a very low density of skeletal fragments. B) Crossed nicols photomicrograph of facies Cma showing a lack of framework grains, and dominance of argillaceous carbonate.

Figure 19: Lithofacies Sl—Low Angle Crossbedded Medium Sandstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Low-angle crosbedded medium sandstone	**Sl**	Tan fresh, tan weathered. Dominantly quartz grains (~95+ %) and lithics (~4%). Accessory minerals include micas, and zircon. In the Moose Creek Section, an increase in accessory and lithics is observed in this lithofacies. Low angle planar lamination is characteristic. Bioturbation is rare or absent.	Incoming waves overstep their orbitals, and break causing bidirectional, high energy traction transport of grains dominantly perpendicular to the shoreline (Plint, 2010). Lower upper flow regime entrainment of particles produces upper parallel-laminated crossbedded sandstone.

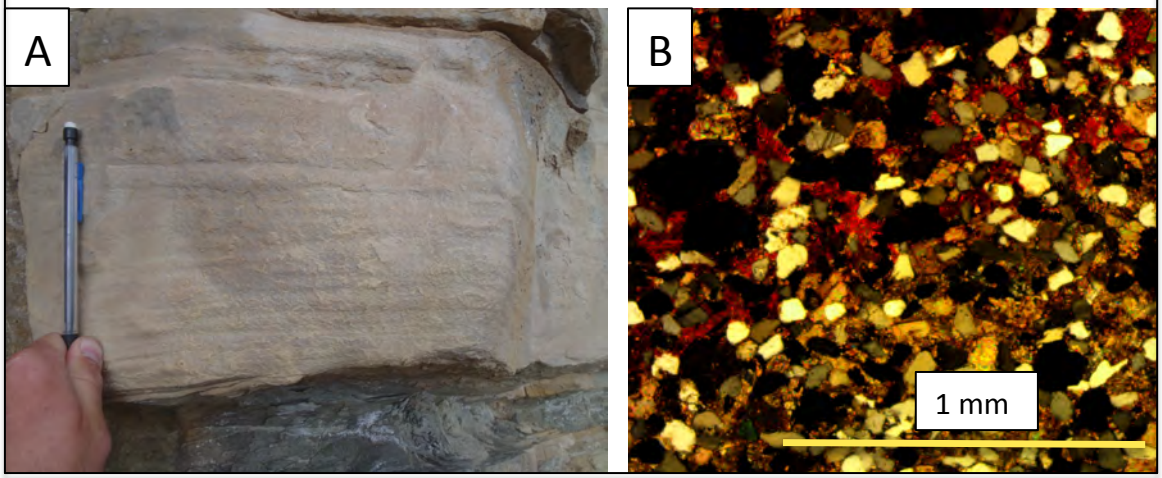


Figure 19 A and B) Lithofacies Sl at Moose Creek. This is the interpreted highest-energy siliciclastic lithofacies observed in outcrop and is only existent at the most up dip location (Moose Creek). B) Photomicrograph showing fine to medium-grained sub angular quartz grains that are cemented in sparry calcite. This this section has been half stained with alizerian red to differentiate between calcite and dolomite cement.

movement, producing ripple cross-lamination in multiple directions. Traction transport in unidirectional flow causes flow separation, and migration of ripples. Reactivation surfaces are common, and record erosion and times on non-deposition (Harms et al., 1975; Allen, 1992) (Figure 20).

Lithofacies Ssw. This lithofacies is characterized as a swaley (sw) and hummocky cross-stratified fine sandstone (s). This lithofacies is dominantly composed of well-sorted, sub angular to angular fine sand-sized quartz grains (~98%). Accessory minerals are rare, but include mica and potassium feldspar (~2%). Framework grains are cemented by sparry calcite cement with a small degree of dolomitization. Sedimentary structures include dominantly swaley cross stratification, and rare hummocky cross stratification. Trace fossils include *Teichichnus* (most common), *Diplocraterion, and Skolithos* genera. Traction transport and minor suspension settling are dominant processes. These sedimentary structures are interpreted to be the movement from both oscillatory and unidirectional currents resulting in combined-flow currents produced during storm events. Increased influence of combined flow favors hummocky cross stratification, while unidirectional flow favors swaley cross stratification (Harms et al., 1975; Leckie and Walker, 1982). Burrowing within unit is rare, but burrows on the base and top of beds are common (Figure 21).

Lithofacies Fsm. This lithofacies is characterized as a massive (m) siltstone (Fs=fine-grained, s=silt). Dominantly composed of silt-sized angular quartz grains

Figure 20: Lithofacies Sr—Ripple Cross-Laminated fine-Medium Sandstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Ripple cross-laminated fine-medium sandstone	**Sr**	Tan fresh, tan weathered. Dominantly quartz grains (~95+%) and lithics (~5%). Accessory minerals include mica, and zircon. Multidirectional ripple cross-lamination is dominant, yet planar/tabular cross bedding is observed. Bioturbation is rare, yet includes *Skolithos* and *Diplocirierion*.	Rip and longshore currents entrain particles in lower flow regime movement, producing multidirectional trough cross bedding. Dominantly traction transport in unidirectional flow causes flow separation, and migration of unidirectional ripples. Reactivation surfaces are common. Reactivation surfaces record erosion and times on non-deposition. (Harms et al., 1975; Allen, 1992).

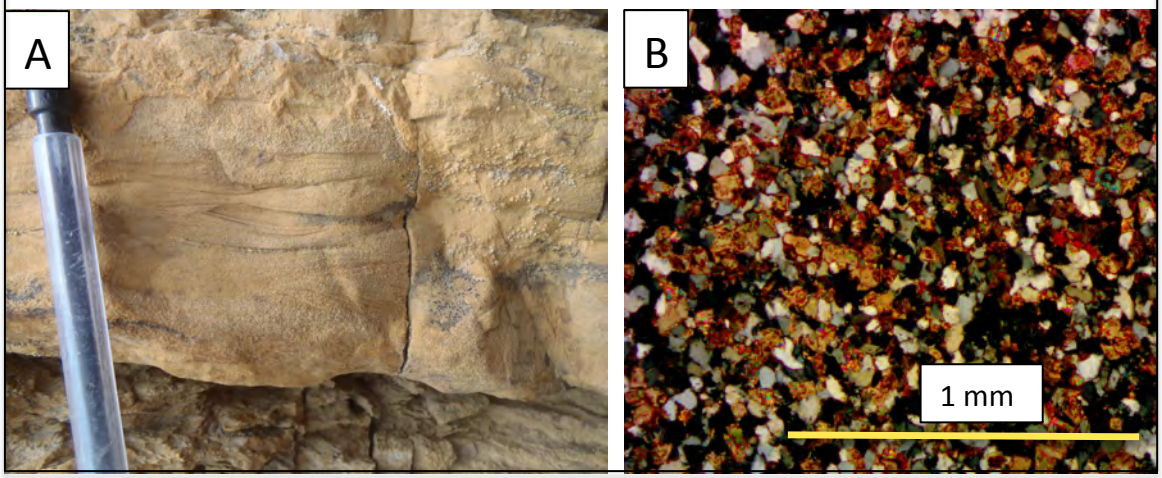


Figure 20 A, and B: A) Lithofacies Sr at Sacajawea Peak outcrop. Multidirectional trough crossbedding reflects transport sediment transport in several directions. This particular lithology is present at all outcrop localities. B) crossed nicols photomicrograph showing fine-grained, angular to sub-angular quartz grains cemented in a sparry calcite.

Figure 21: Lithofacies Ssw—Swaley cross-stratified fine Sandstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Swaley cross stratified, hummocky fine sandstone	**Ssw**	Tan fresh, tan weathered. Dominantly well-sorted, sub angular to angular fine sand-sized quartz grains (~98%). Accessory minerals are rare, but include mica. Framework grains are cemented with dominantly sparry calcite cement with a small degree of dolomitization. Sedimentary structures include dominantly swaley cross stratification, and rare microhummocky cross stratification. Trace fossils include *Teichichnus* (most common), *Diplocraterion , and Skolithos* genera.	Traction transport and minor suspension settling are dominant processes. Influence from both oscillatory and unidirectional currents resulting in strongly combined-flow currents. Increased influence of combined flow favors hummocky cross stratification, while unidirectional flow favors swaley cross stratification (Harms et al., 1975; Leckie and Walker, 1982). Burrowing within unit is rare, but burrows on the base/top of beds are common.

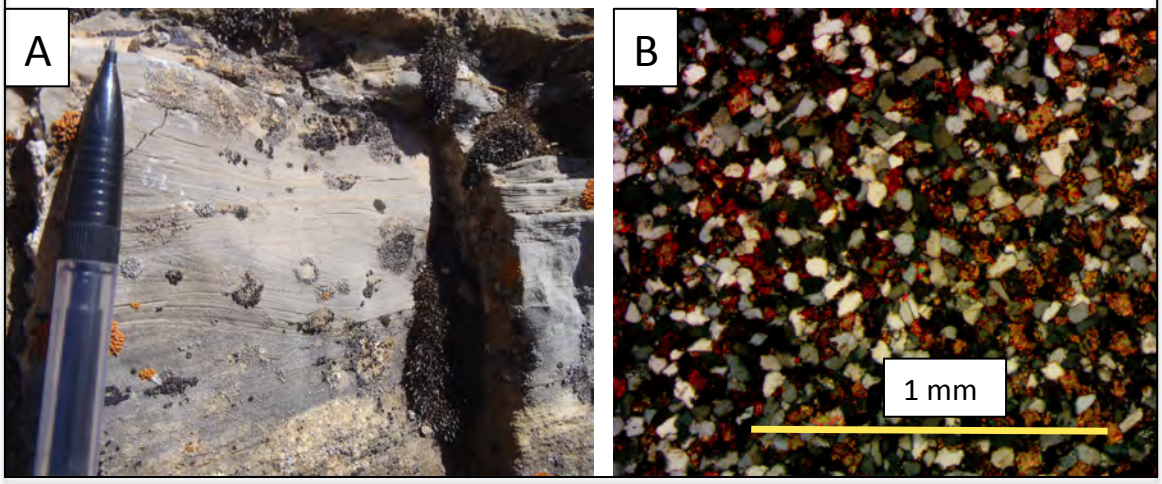


Figure 21 A and B: A) Lithofacies Ssw at Lone Mountain showing microhummocky cross stratification characteristic of this facies. B) crossed nicols photomicrograph showing fine to very fine-grained sub angular quartz grains cemented in sparry calcite.

(~100%). Framework grains are cemented by calcite cement with a small amount of dolomite cement. A high degree of bioturbation causes a massive texture. Bioturbation is dominantly horizontal, yet include vertical traces as well. Some horizontal traces are crescent-shaped, calcite-filled, and weather out preferentially in outcrop. These traces are interpreted to be *Phycosiphon,* and are very pervasive. Vertical traces are rare, yet include *Dipliocriterian to Skolithos* genera. Bioturbation has reworked and destroyed any original fabric (Figure 22).

Lithofacies Fsgo. This lithofacies is characterized as a graded (g), organic-bearing (o) siltstone (Fs). Framework grains are angular quartz grains (~100%). Beds are normally- graded with organic matter preserved preferentially at the base of graded units. Lithofacies FSgo is interpreted to be the result of slumps or small scale sediment gravity flows. Suspension settling of plankton in a dysoxic basin, and subsequent mining of organic matter by organisms is interpreted to occur during quiescent times (Figure 23).

Lithofacies Fsds. This lithofacies is characterized as a dolomitic (d), stromatoporoid-bearing (s) siltstone (Fs). This lithofacies is composed of silt-sized quartz clasts (>90%) and 1-2 cm reddish-brown stromatoporoids-encrusted bivalves. Red laminations throughout rock are common, and are interpreted to indicate bioturbation. Ripple cross lamination is rare. Suspension settling during storm events is interpreted to be the dominant sedimentary process, and is modified by reworking via traction transport during storm events (Figure 24).

Figure 22: Lithofacies Fsm—Massive Siltstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Massive siltstone	**Fsm**	Tan fresh, Tan weathered. Dominantly silt-sized angular quartz grains (~100%). Framework grains are cemented with dominantly calcite cement, with a small amount of dolomite cement locally important. Highly degree of bioturbation causes a massive texture. Bioturbations are dominantly horizontal, yet include vertical traces as well. Some horizontal traces are crescent-shaped, calcite-filled, and weather out preferentially in outcrop. Horizontal bioturbation is dominantly *Phycosiphon* and is pervasive. Vertical traces are rare, yet include *Dipliocriterian to Skolithos* genera.	Bioturbation has reworked and destroyed any original fabric.

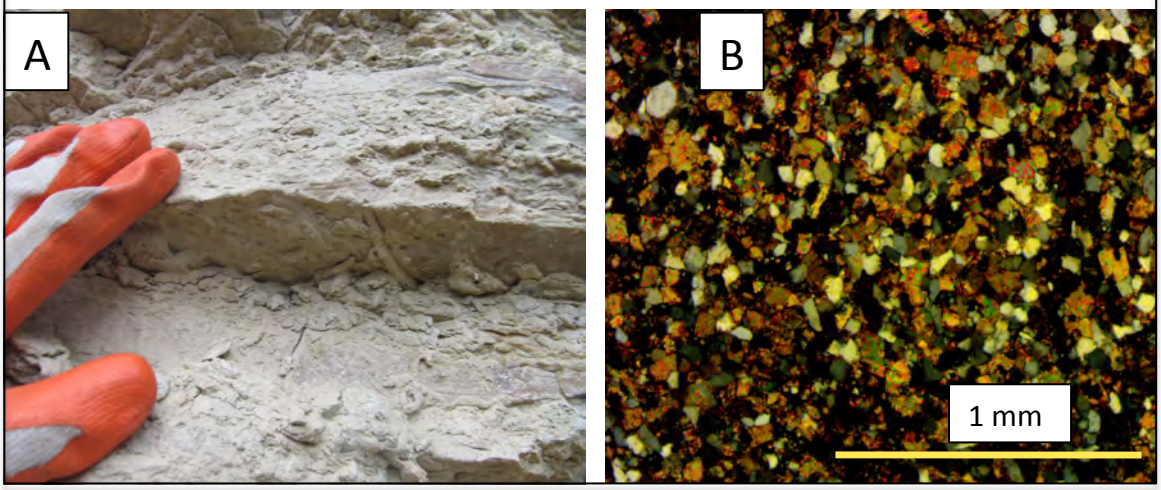


Figure 22 A and B: A) Lithofacies Fsm at Sacajawea Peak outcrop. This lithofacies is highly bioturbated and very difficult to interpret from outcrop. In many places this a large degree of both horizontal and vertical bioturation leading to a mottled texture, and subsequent destruction of original fabric. B) crossed nicols photomicrograph showing very fine to silt-sized, sub angular quartz grains cemented in sparry calcite.

Figure 23: Lithofacies Fsgo—Graded, Organic-bearing Siltstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Graded, organic-bearing siltstone	**Fsgo**	Dark-light grey fresh and weathered. Framework grains are angular quartz grains. Beds are normally- graded with organic matter preserved preferentially at the base of graded units.	Slumps or small scale sediment gravity flows. Suspension settling of plankton in a dysoxic basin, and subsequent mining of organic matter by organisms occurs during quiescent times.

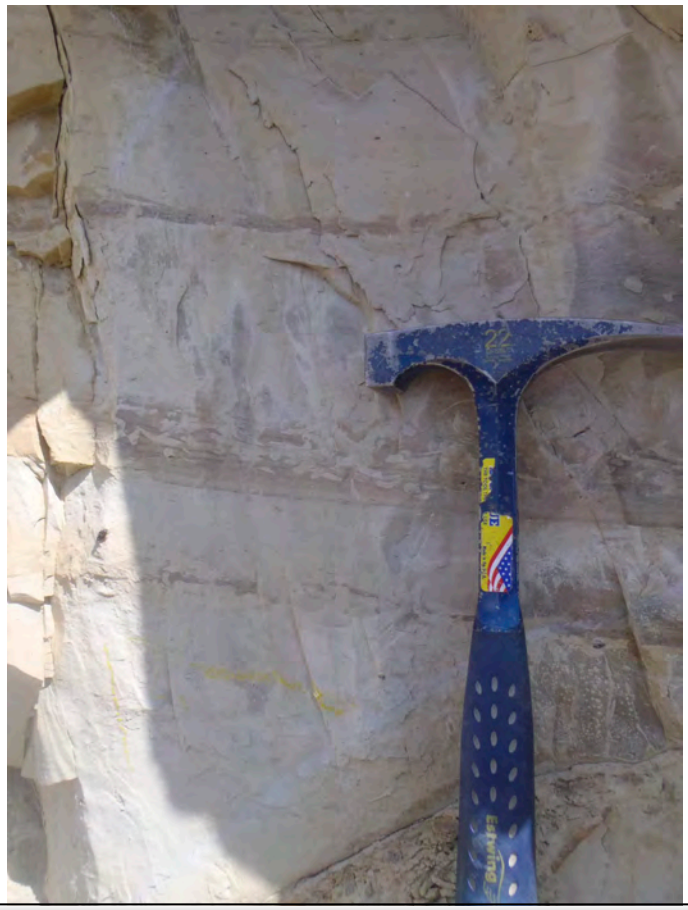


Figure 23: Lithofacies Fsgo at Moose Creek Outcrop. This lithofacies is unique to the Moose Creek location, and is interpreted to be discreet slumping events creating graded beds with preserved organic material at the base of each bed. Organisms are interpreted to then mine the beds post deposition.

Figure 24: Lithofacies Fsds: Dolomitic Stromotoporoid-bearing Siltstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Dolomitic, stromotoporoid-bearing siltstone	**Fsds**	White/light tan, white/light tan/ red weathered. Silt-sized quartz clasts dominate (>90%). Extremely well-sorted. Red concentrations throughout are stromatoporoid encrusted allochems. Red laminations throughout rock are common. 2-3 mm ripple cross lamination is evident but rare.	Suspension fall out is dominant, and modified by reworking via traction transport. Bioturbation moderate to extreme.

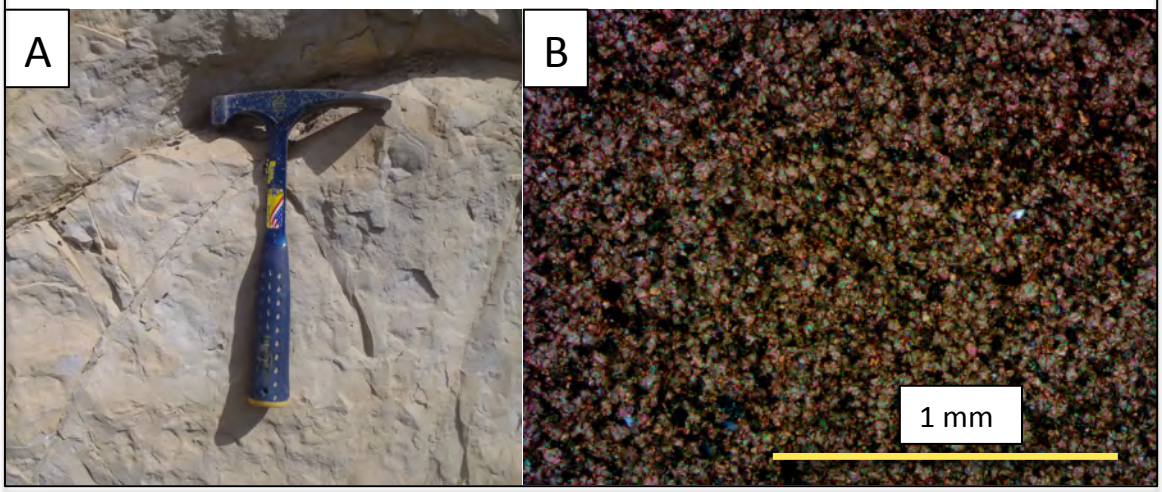


Figure 24 A and B: A) Lithofacies Fsds at Moose Creek outcrop. This facies is unique to the Moose Creek. This lithofacies is an extremely well-sorted dolomitic siltstone that is generally massive, and contains a host of reddish blemishes that may be due to alternate weathering from bioturbation. It seems as though the reddish alteration increases around fractures that may indicate they were conduits for fluid flows. B) Basal contact of facies Fsds (whitish siltstone) with facies CMbr is undulatory with a magnitude of nearly 3 meters. b) crossed nicols photomicrograph showing silt-sized quartz grains cemented in microcrystalline dolomite.

Lithofacies Fsl. This lithofacies is characterized as a dolomitic laminated (l) siltstone (Fs). Silt-sized quartz grains are cemented with dolomite. Lamination dominates, yet very thin bedding may be common (up to 2 cm.). 1-3 mm ripple cross lamination is locally evident, yet cryptic. Bioturbation is concentrated at bed boundaries. This lithofacies is interpreted to be the result of hemipelagic sedimentation that has been modified by low energy, traction transport (Kneller, 1996) (Figure 25).

Lithofacies Fml. This lithofacies is characterized as a laminated (l) mudstone (F=fine-grained, m=mud). Wavy laminations of clay and silt-sized material are cemented with carbonate. This lithofacies is interpreted to be the result of hemipelagic deposition of sediment derived from more proximal areas produced by catastrophic storms. Quiescent times are characterized by suspension settling from wind-derived sediment, and bioturbation (Figure 26).

Lithofacies Fmo. This lithofacies is characterized as an organic (o) mudstone (Fm). Clay-sized particles dominate, with a minor amount of silt-sized particles that are cemented with calcite. Fmo is fissile and massive. Black organic material is abundant throughout. This lithofacies is interpreted to be deposited in highly anoxic to dysoxic conditions due to eutrophication of the water column (Caplan et al., 1996) (Figure 27).

Figure 25: Lithofacies Fsl Dolomitic Laminated Siltstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Dolomitic laminated siltstone	**Fsl**	Light grey fresh, tan weathered. Dominantly silt-sized quartz grains are cemented with dolomite. Lamination is dominant, yet very thin bedding may be common (up to 2 cm.). 1-3 mm ripple cross lamination is locally evident, yet cryptic. Bioturbation is concentrated at bed boundaries.	Hemipelagic sedimentation dominates, and is modified by low energy, traction transport depletive flow (Kneller, 1996).

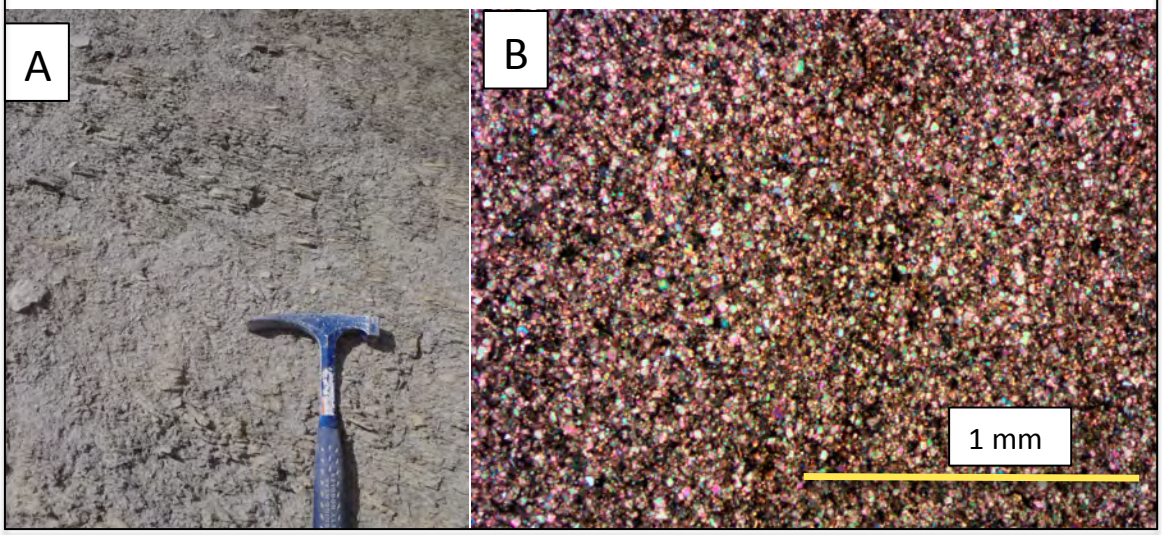


Figure 25 A and B: A) Lithofacies Fsl at Sacajawea Peak outcrop. This lithofacies is very difficult to distinguish in outcrop, but is less bioturbated than facies Fsm. What is interpreted to be varying amounts of cement throughout areas of this facies causes a variations in weathering profiles. B) Crossed nicols photomicrograph showing silt-sized quartz grains cemented by microcrystalline dolomite.

Figure 26: Lithofacies FML—Laminated Mudstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Laminated mudstone	**Fml**	Green fresh, greenish-grey weathered. Wavy laminations of clay and silt-sized material dominate; cemented with carbonate.	Hemipelagic deposition of sediment derived from updip areas produced by catastrophic movements punctuates suspension settling from wind-derived sediment.

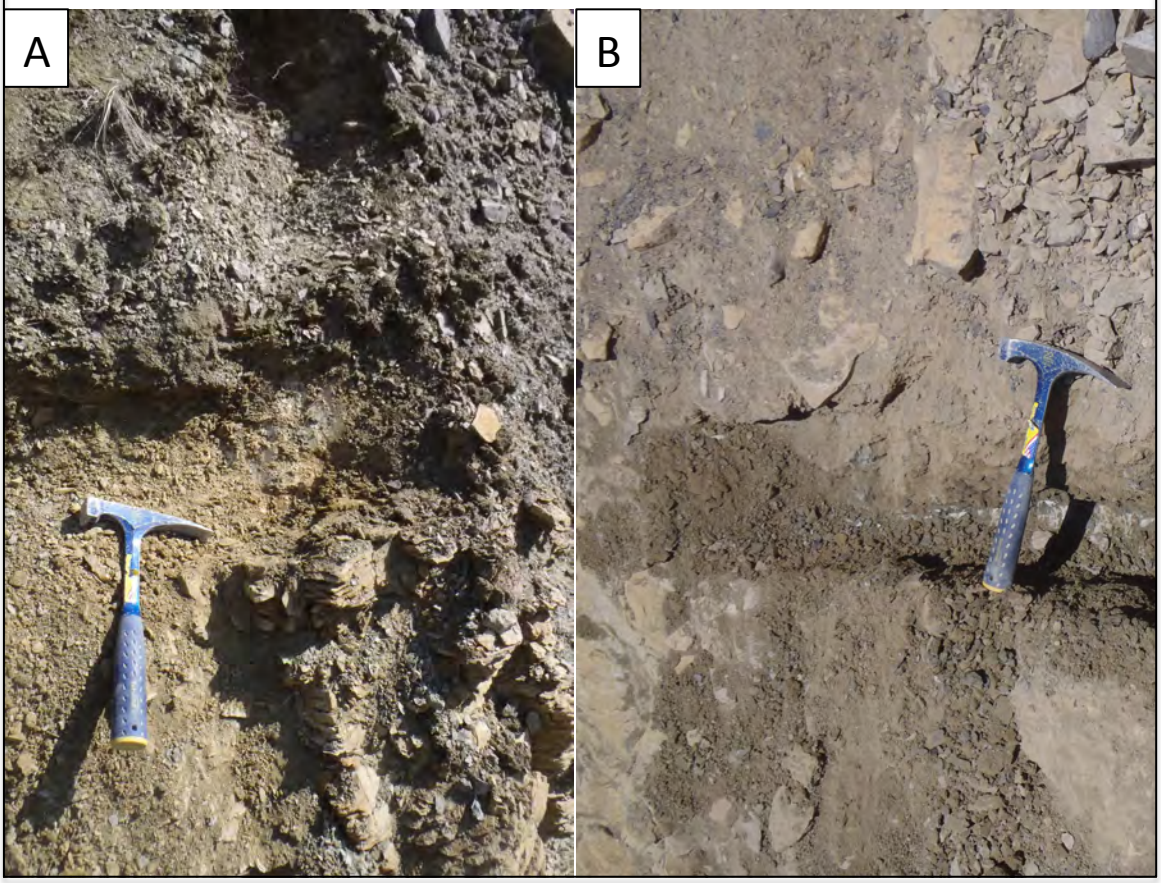


Figure 26 A and B: A) Lithofacies Fml at Antelope Valley outcrop and B) Facies Fml at Sacajawea Peak outcrop. This facies is a moderately sorted mudstone. This lithology is poorly consolidated especially at Sacajawea Peak, and internal lamination or stratification was not observed.

Figure 27: Lithofacies Fmo—Organic-rich Mudstone

LITHOFACIES	LITHO CODE	DESCRIPTION	INTERPRETATION
Organic rich mudstone	**Fmo**	Black fresh/black weathered. Clay-sized particles dominate, with a minor amount of silt-sized particles which are cemented with calcite. Rock is fissile, and massive. Black organic material is abundant throughout.	Highly anoxic to dysoxic conditions due to eutrophication of the water column, suspension settling and preservation of organic matter (Caplan et al., 1996)

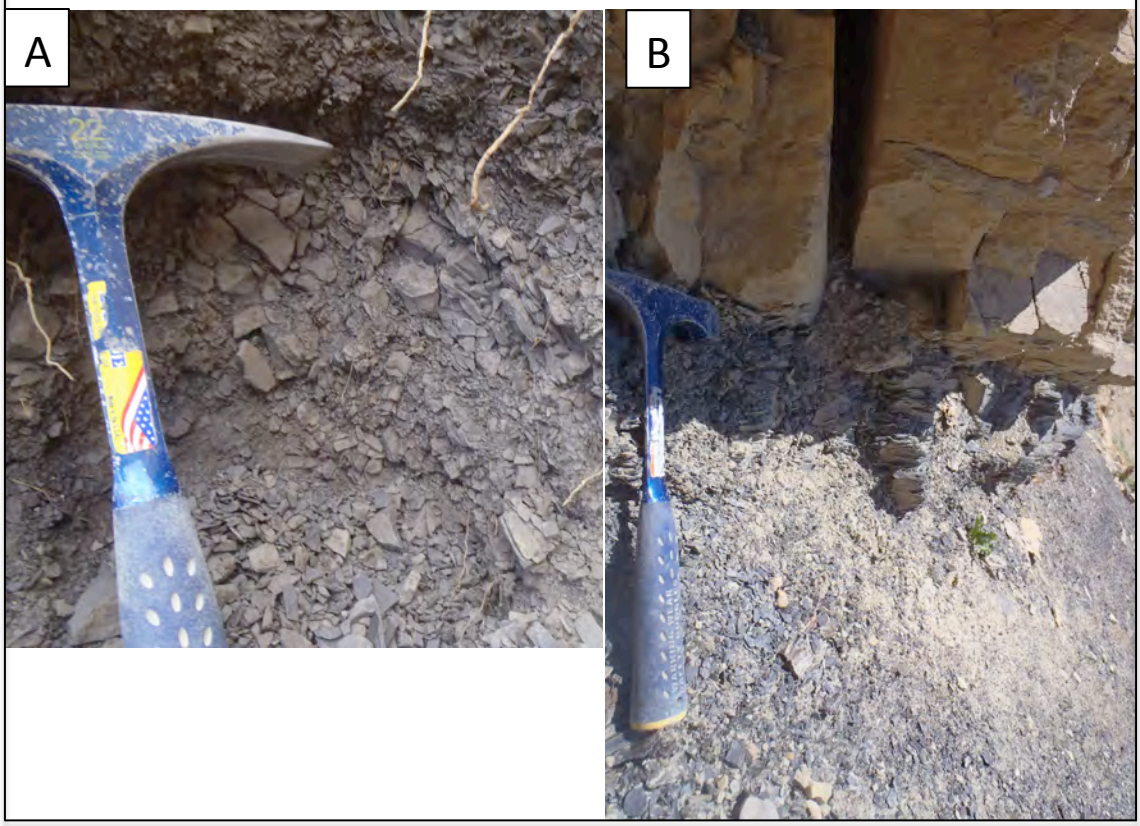


Figure 27 A and B: A/B) Lithofacies Fmo at two various intervals at the Sacajawea Peak Outcrop where it is best developed. This interval is petroliferous as evident from a petroliferous smell. This lithology is interpreted to have been originally widespread, yet has likely been eroded at several outcrop localities.

Lithofacies Assemblages and Depositional Environments

General Statement

Lithofacies with attributes indicating hydrodynamically similar conditions during deposition are grouped into lithofacies assemblages. Lithofacies assemblages indicate depositional processes defining a depositional environment and location within a basin (Flügel, 2004, p. 674). Individual lithofacies may or may not be unique to a particular lithofacies assemblage. Carbonate lithofacies assemblages include C1, C2, and C3, and carbonate lithofacies assemblages include S1, S2, S3 and S4. Carbonate depositional environments include the foreshore, upper shoreface, lower shoreface, and offshore environments. Carbonate depositional environments include the intertidal, ooid shoal, patch reef, mid ramp and outer ramp (Appendix D) (Machel and Hunter, 1994). The following is a description of lithofacies assemblages and the depositional environments that they represent.

C1: Inner Ramp: Intertidal/Ooid Shoal/Patch Reef

Lithofacies assemblage C1 includes lithofacies CMbr, CGoi, CBl, CFsr and CFss. Depositional environments are located in the inner ramp, and include intertidal, ooid shoal, and patch reef (Burchett and Wright, 1992) (Appendix D). The intertidal depositional environment is a low energy environment characterized by daily incursion of the sea that produces fine laminations and microbial buildups (Burchette and Wright, 1992; Machel and Hunter, 1990). Ooid shoals environments are characterized by high-energy wave agitation and longshore currents, forming sheet-

like bodies (Burchette and Wright, 1992; Flügel, 2004 p. 719). Patch reef environments occur within the photic zone with moderate wave agitation. During times of seaward migration of the shoreline, meteoric incursion into the area may produce brecciation in previously cemented carbonate rocks (Machel and Hunter, 1994).

C2: Middle Ramp

Lithofacies assemblage C2 includes lithofacies CPs, CWeb and CMa, and represents the middle ramp depositional environment (Appendix D). Organisms and reworked framework grains are suspended in a relatively larger amount of micritic material. Ooids may be present, representing a possible offshore shoal deposit (Machel and Hunter, 1994). This depositional environment is dominated by storm reworking, although fair weather phases may be dominated by hemipelagic sediment setting, and burrowing of organisms (Burchette and Wright, 1992).

C3: Outer Ramp

Lithofacies assemblage C3 includes lithofacies CMa, and represents the outer ramp depositional environment (Appendix D). Sedimentary processes include constant pelagic to hemipelagic sedimentation punctuated by suspension settling of sediment plumes after catastrophic events (Machel and Hunter, 1994).

S1: Foreshore

Lithofacies assemblage S1 includes lithofacies Sl and represents the foreshore depositional environment. The foreshore is defined as the region between high and

low tide, or intertidal zone (Van Wagoner, 1990) (Appendix D). Sedimentary processes dominating this region include the swash and backwash of wave action generating medium-sand sized low angle cross-lamination that dip gently basinward (Walker and Plint, 1992)(Appendix D).

S2: Upper Shoreface

Lithofacies assemblage S2 includes lithofacies Sr and Ssw, and represents the upper shoreface environment (Appendix D). The upper shoreface is defined in its upper limit as mean low tide and its lower limit as the time-averaged surface where wave action reworks sediment (fair weather wave base) (Howell and Flint, 2003; Reading and Collinson, 1996, Clifton, 2006). The upper shoreface is characterized by unidirectional currents that produce ripple cross lamination and swaley cross stratification (Walker and Plint, 1992).

S3: Lower Shoreface

Lithofacies assemblage S3 includes lithofacies Fsm, Fsgo, Fsds, Fsl, and represents the lower shoreface environment. This depositional environment's upper limit is defined as the fair weather wave base, and its lower limit as the storm weather wave base. Characteristic of this depositional environment are swaley/ hummocky cross stratification, and the presence or even dominance of muddy intervals. Fundamentally, this depositional environment is dominated by a lowering of wave base during large magnitude storm events that rework sediment (Howell and Flint,

2003; Van Wagoner and Kamola, 1995). Storm events produced combined oscillatory and unidirectional currents that produce swaley and hummocky cross stratification.

S4: Offshore

Lithofacies assemblage S4 includes lithofacies Fml and Fmo, and represents he offshore depositional environment. This region is defined as outboard of storm weather wave base, and is thus never agitated by wave reworking. Bioturbation is common, and is most often horizontal. Sedimentary processes are dominated by suspension settling of sediment plumes after catastrophic events (Plint, 2010).

CHAPTER 4 – STRATIGRAPHY

General Statement

This thesis presents a sequence stratigraphic framework based on a number of rock attributes and derived attributes found in outcrop, core, and geophysical logs. In conjunction with newly acquired data, interpretations represent the culmination and integration of previously established lithostratigraphy, biostratigraphy, and interpreted regional unconformities. The units correlate regionally to productive reservoirs in the Alberta basin to the north and the Williston basin to the east.

Two types of data are utilized in correlating rock attributes: physical rock data (outcrop and core) and derived rock data (geophysical well logs). Physical rock data is dominantly encountered in the southern portion of the study area, while one cored interval is located in the north of the study area. Geophysical well logs are encountered throughout the project area, but are concentrated in the northern study area, and are more numerous than outcrop. This data distribution skews mapping resolution towards the northern project area. Because outcrop allows for the highest resolution to interpret stratigraphy, observations and interpretations gleaned from outcrop have been correlated to derived rock data, and regionally mapped. Key outcrop to geophysical well log surfaces and rock bodies are shown in figure 28.

Figure 28: Lithostratigraphy Type Log

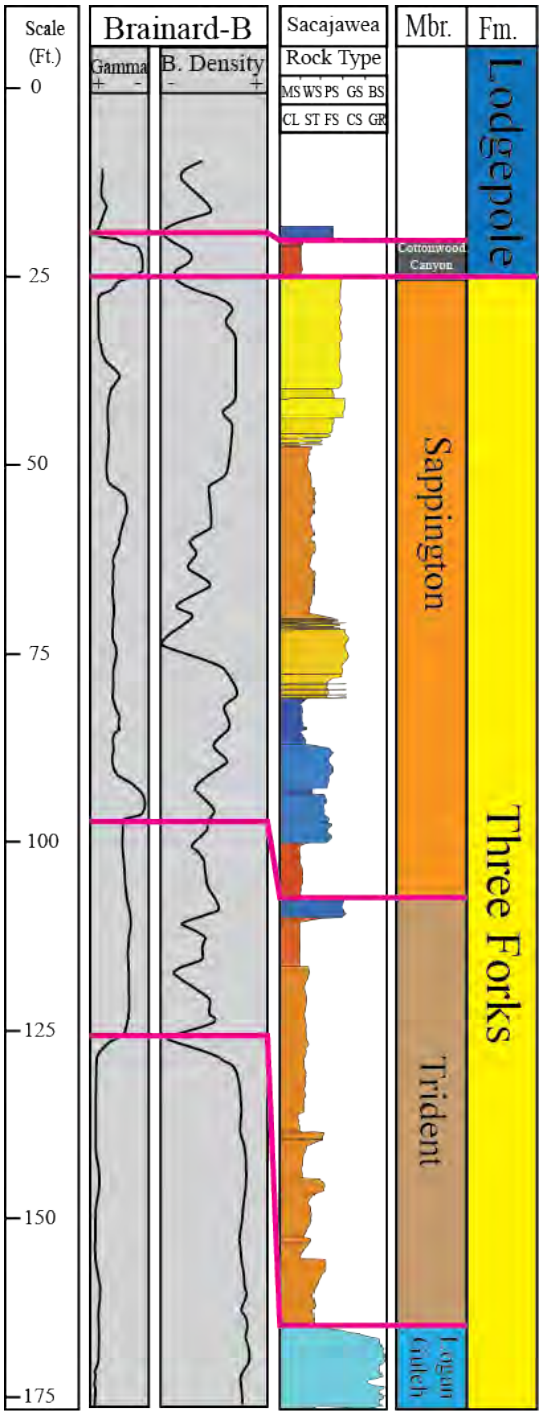
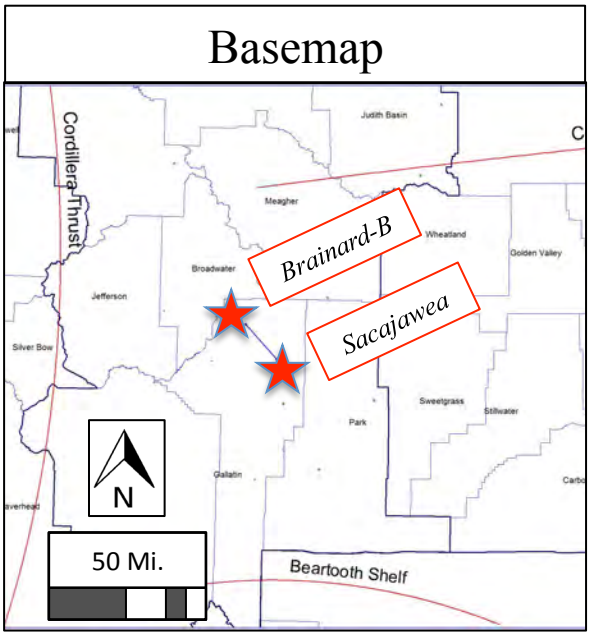


Figure 28: Lithostratigraphy Type Log. Lithofacies identified in outcrop are correlated to geoplhysical logs and mapped throughout the project area. Natural gamma (Gamma) and bulk density (B. Density) curves were two primary geophysical logs used for mapping. Key lithostratigraphic intervals utilized for mapping were there Cottonwood Canyon Member of the Lodgepole Formation and the basal beds of the Sappington Member of the Three Forks Formation. These two lithostratigraphic intervals are composed of fine-grained, organic rich material (lithofacies Fmo), and are associated with high natural gamma ray readings, making them ideal horizons for correlation.



Lithostratigraphy

The North American Stratigraphic Code states that lithostratigraphic units are mappable rock bodies distinguished by lithological attributes that generally adhere to the law of original horizontality (North American Stratigraphic Code, 1983). While well suited for its original intention as a pragmatic approach to field mapping and delineation of economically significant rock bodies, significant pitfalls are obvious in the methods inherent in lithostratigraphy. Most notably lithostratigraphic units are often placed within geochronologic ages (i.e. the Cambrain Flathead Sandstone), lithostratigraphy only takes into account one aspect of sedimentary architecture—materially recorded time (or rock)—and discounts the importance of surfaces. By not stressing surface, lithostratigraphy produces a plethora of nomenclature across different regions that can often be confusing This study will subscribe to the nomenclature prescribed by Sandberg (1965). In the lithostratigraphy section, only observations are made; there are no references to specific basins, tectonic events, or movements of relative sea level. Rather, such discussions are reserved for the sequence stratigraphy section of this chapter.

Three Forks Formation

Sandberg (1965) divides the Three Forks Formation into three formal members: 1) the basal, Upper Devonian Logan Gulch Member 2) the medial Upper Devonian Trident Member, and 3) the Upper Devonian-Lower Mississippian Sappington Member (Figure 4) (Sandberg, 1965; Johnson et al., 2010). The Three Forks Formation of is distributed across western Montana and thickens in two distinct areas (Figures 29-34).

Figure 29: Logan Gulch Member Isochore

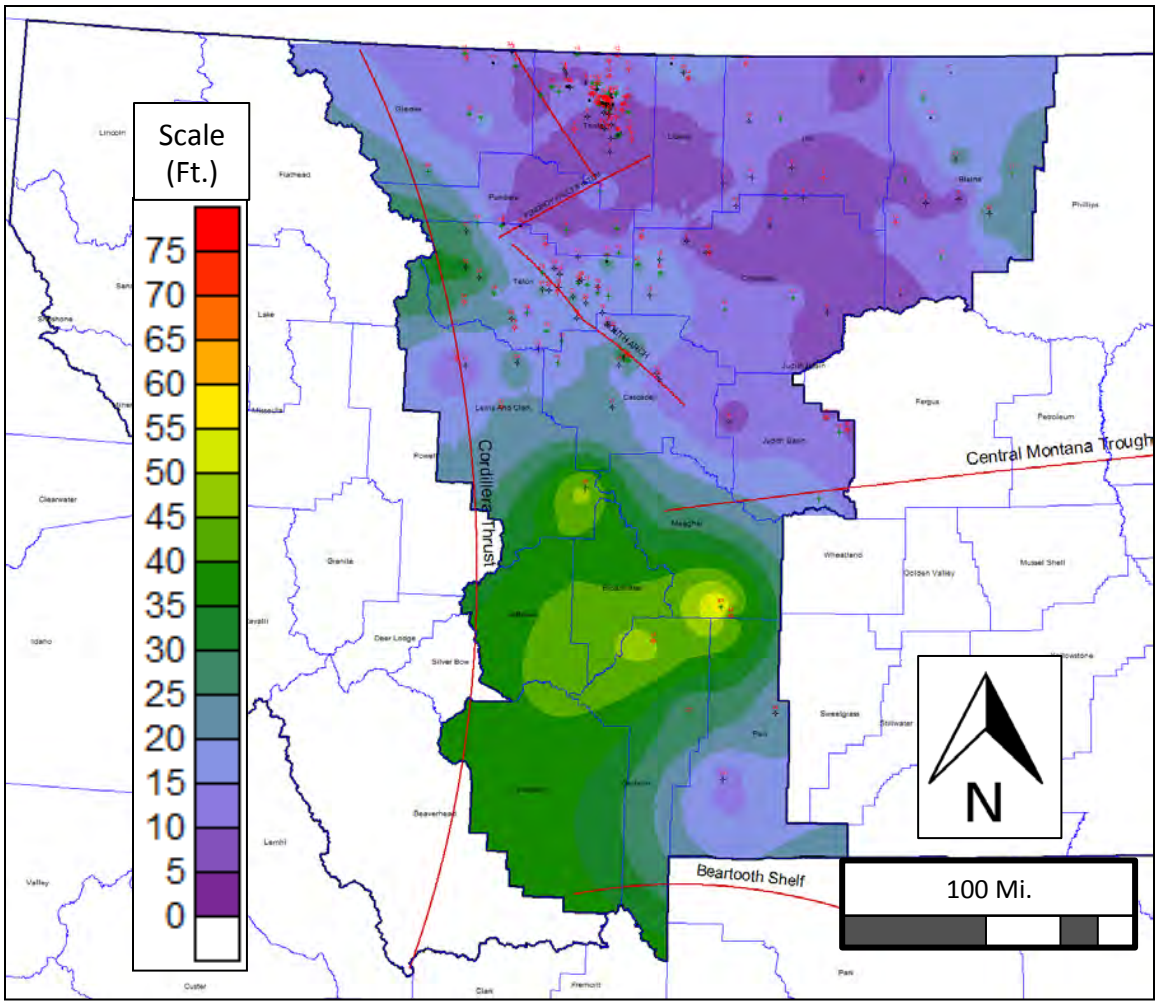


Figure 29: Logan Gulch Member Isochore. This Logan Gulch Member is particularly widespread, and relatively uniform in comparison to the other mapped intervals, with a minor isochore thickness observed in southwest Montana.

Figure 30: Trident Member Isochore

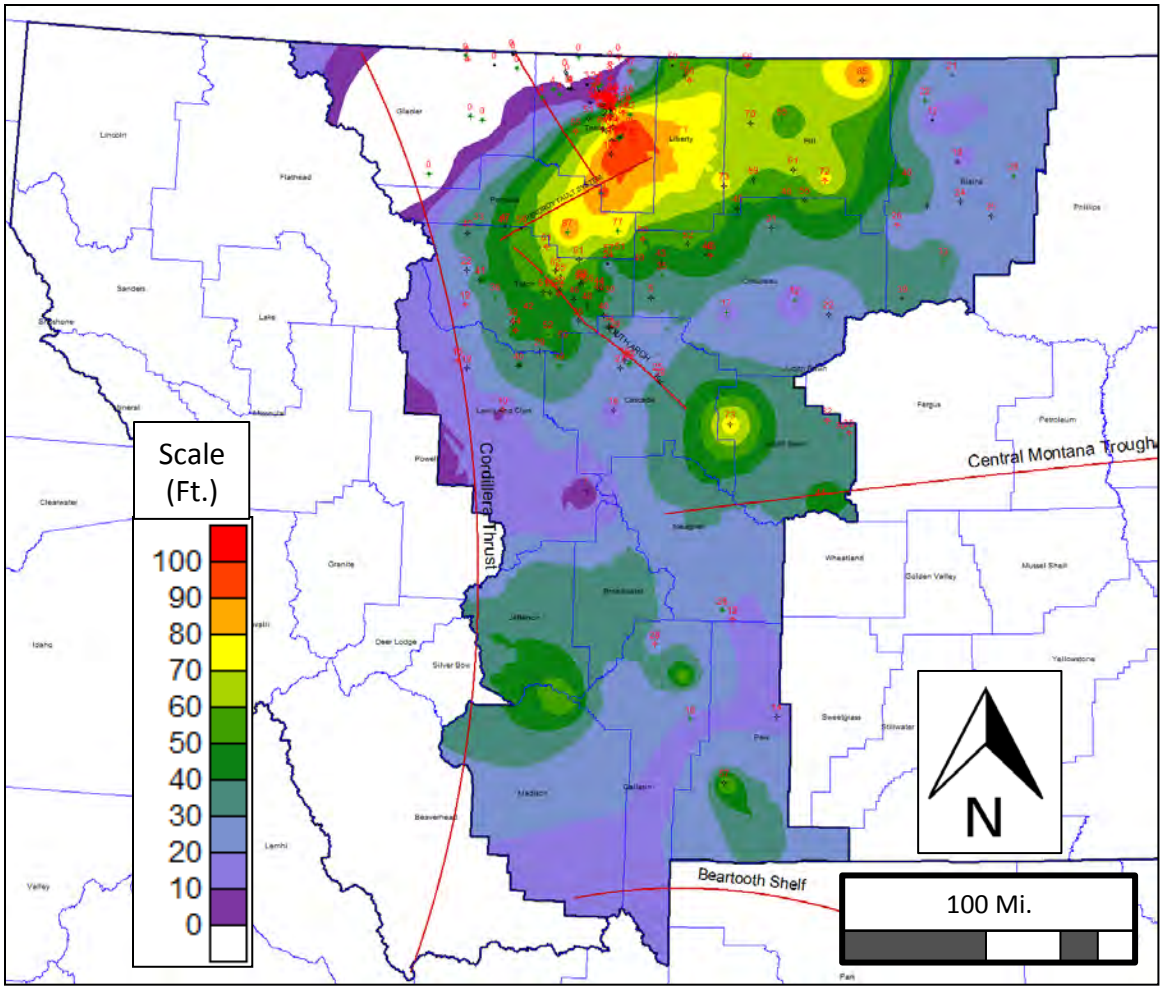


Figure 30: Trident Member Isochore. Overall the modern day distribution of the Trident Member is thickest in Toole County, with a minor isochore thickness in southwest Montana.

Figure 31: Sappington Member Lower Shale Tongue Isochore

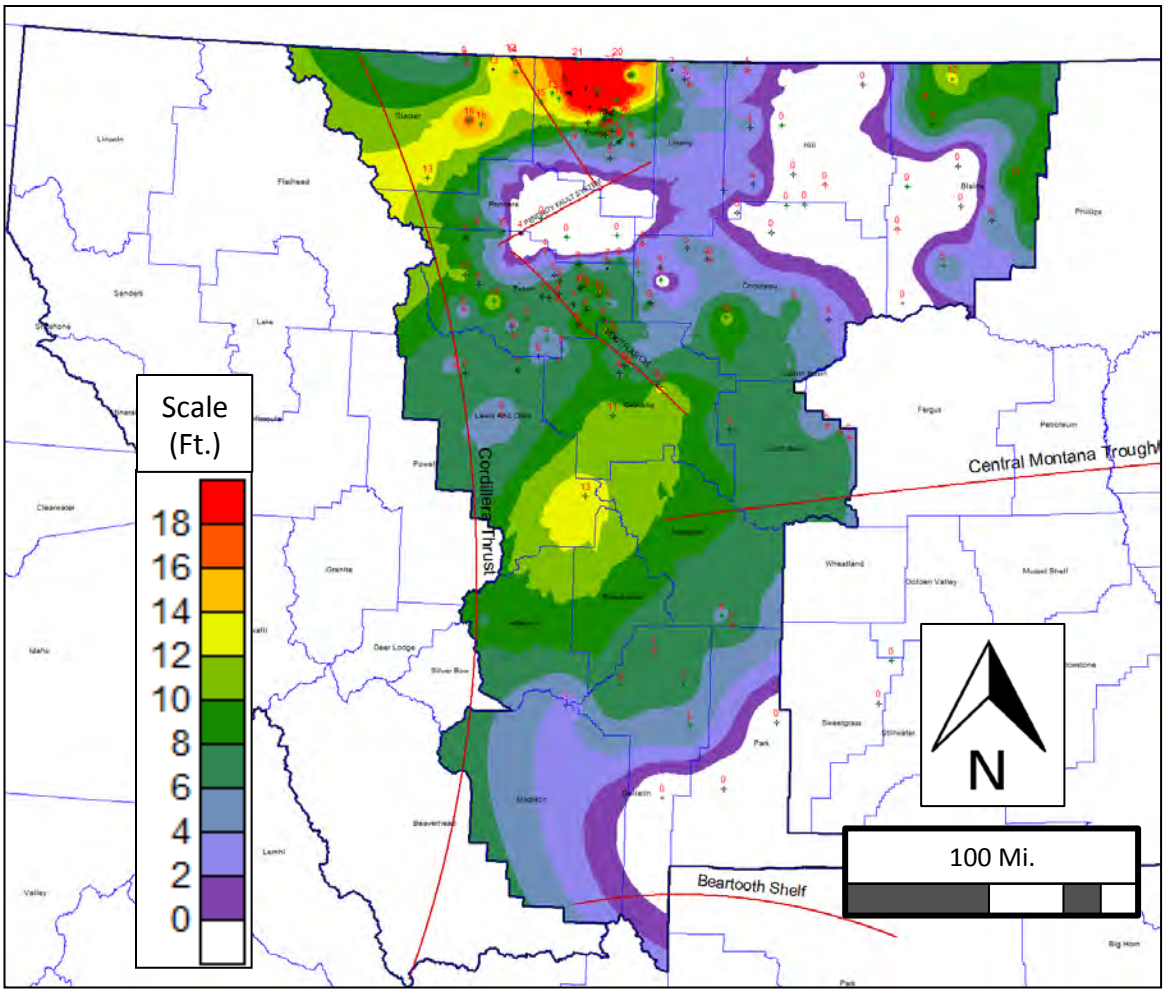


Figure 31: Sappington Member Isochore. This member was relatively easily mapped throughout the study area due to its unique petrophysical character. Isochore trends indicate the largest thickness up to 20 feet in northern Toole County, with sporadic distribution throughout the remaining study area.

Figure 32: Sappington Member Isochore

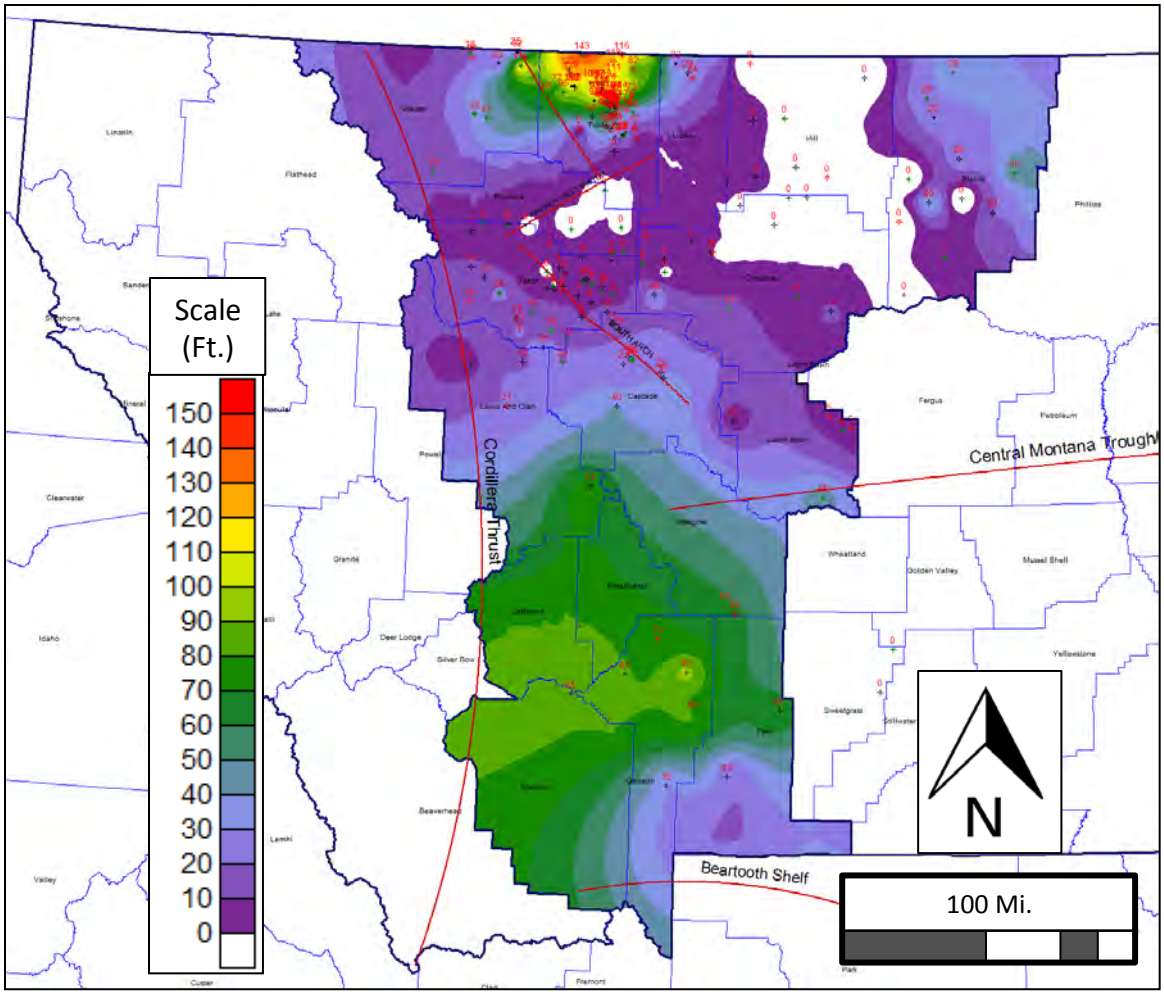


Figure 32: Sappington Member Isochore. Overall the modern day distribution of the Sappington Member is thickest in northern Toole County, with a minor isochore thickness in southwest Montana.

Figure 33: Cottonwood Canyon Member Isochore

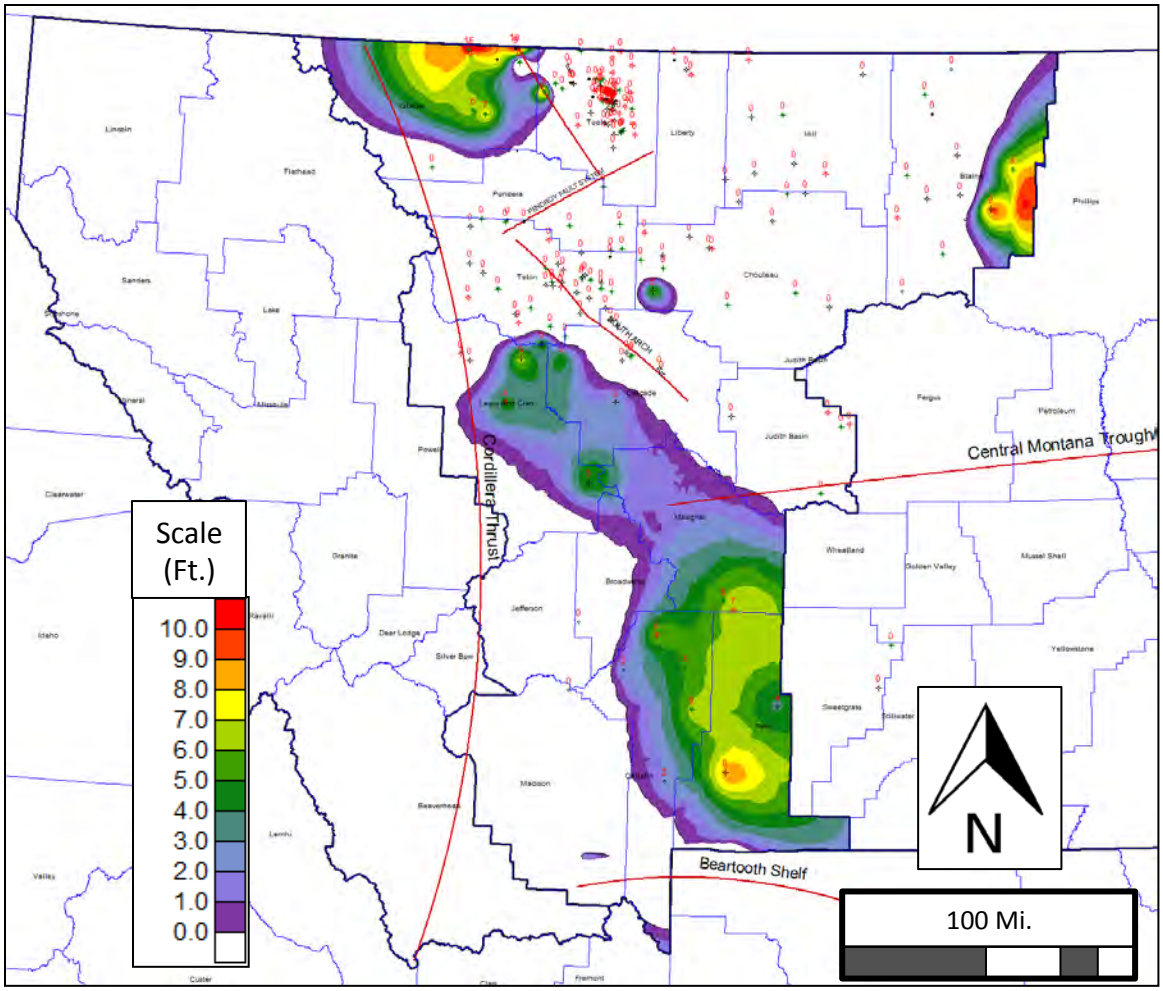


Figure 33: Cottonwood Canyon Member Isochore. Three isochore thickness trends are observed, with the thickest area in northern Toole and Glacier County.

Figure 34: Three Forks Formation Isochore

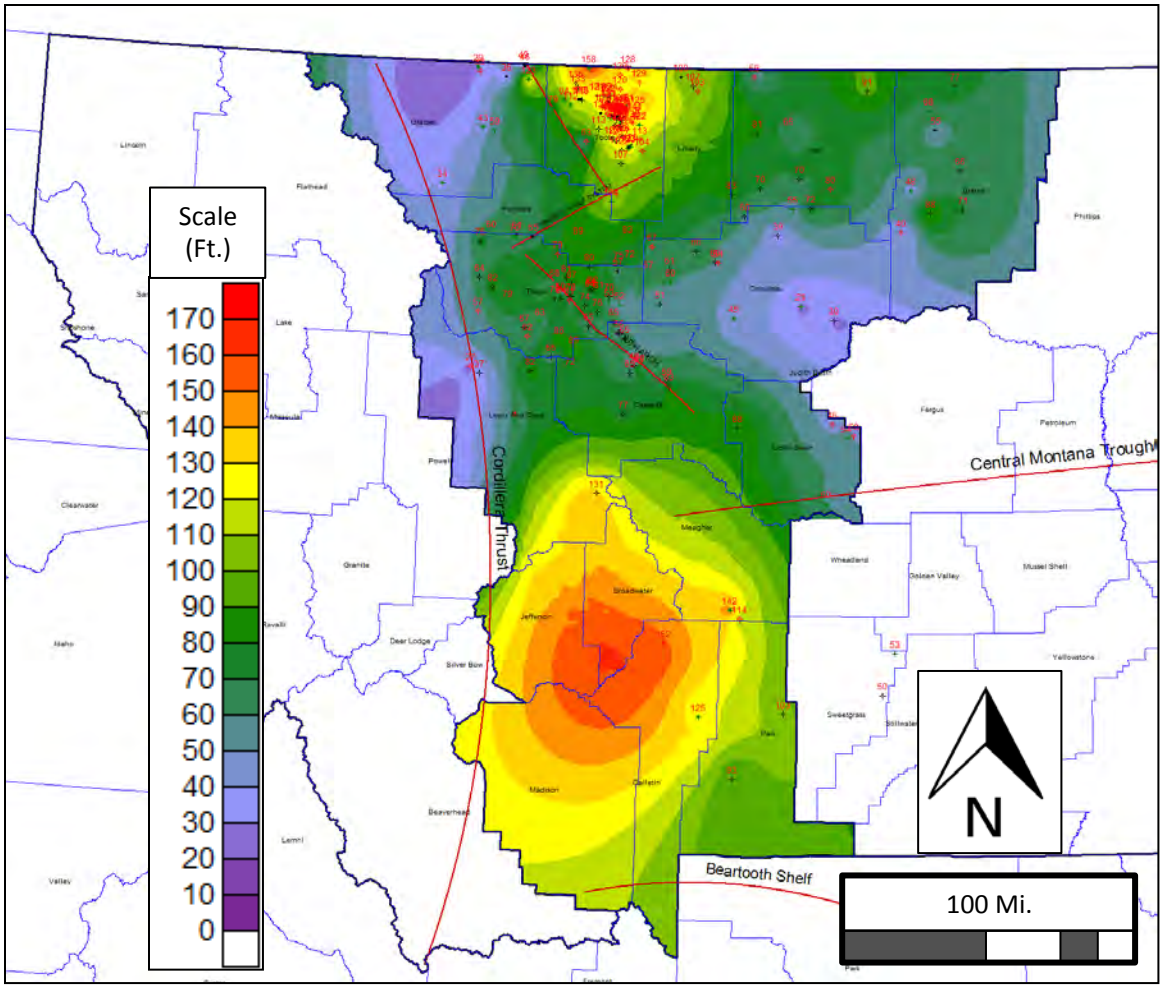


Figure 34: Three Forks Formation Isochore. This isochore map includes the Logan Gulch, Trident, and Sappington members. Overall, the Three Forks Formation isochore distribution shows two iscochore thickness trends– one in the area of Gallatin, Madison, Jefferson, and Broadwater counties, and the other in Northern Toole County likely extending into Canada. This isochore pattern is consistent with the work of previous authors Macqueen and Sandberg (1970).

Isochore maps indicate an isochore thickness up to 170 feet centered in the counties of Broadwater, Jefferson, Gallatin, and Madison (Figure 34). To the north of this thick, the Three Forks Formation begins to thin (~20 feet or less) in Choteau County. In the furthest northern reaches of the study area, the Three Forks Formation thickens dramatically to nearly 160 feet in northern Toole County. The interval remains conspicuously thin to the west (Glacier County).

Logan Gulch Member The Logan Gulch Member is the most aerially extensive member of the Three Forks Formation, and is composed of interbedded argillaceous limestone and shale that are locally brecciated (Figure 29 and Appendix E). The top of the Logan Gulch Member is highly brecciated likely owing to dissolution of anhydrite lenses or collapsed karsts (Adiguzel et al., 2012). A shale unit that is not incorporated into this study underlies this upper limestone unit in the Sappington basin, but is apparently absent in the northern project area. The Logan Gulch Member is underlain by the massive, dense, dark gray dolomite of the Jefferson/Palliser Formations. These two units were primarily distinguished using the PE curve in subsurface mapping.

In some areas of the northern study area, an informal unit known as the Potlatch Anhydrite underlies or intertongues with the Logan Gulch Member (Sandberg and Hammond, 1958). For this study the Potlatch Anhydrite will be treated as a separate stratigraphic unit similar to that of a member of the Three Forks Formation, although not formally recognized as so (Figure 4).

Trident Member. The Trident Member at its Logan Gulch type section is a greenish-gray to light-olive gray calcareous, fossiliferous shale and dark orange, yellowish gray dolomitic limestone and silty dolomite (Appendix E and Figure 30) (Sandberg, 1965). The member thickens overall in a westward direction. In the study area, the Trident Member shows a northeast-southwest-trending isochore thickness trend across southwest Toole County, extending through Teton, Pondera, Liberty, and Hill counties. The Trident Member attains a maximum thickness of 100 feet in southern Toole, and western Liberty County, and thins towards Glacier County where it is nonexistent. Over the southern study area, the Trident Member is largely isopachous with thicknesses generally averaging around 20 feet.

Sappington Member. The Sappington Member is the focus of this study, and will receive an increased amount of attention. The Sappington Member records the Devonian-Mississippian transition evident from several studies of conodont zonation (Figure 4) (Johnson, 2010). Although Gutschick (1963) identifies nine discrete, informal lithological horizons, this study groups the strata into five discrete horizons for mapping purposes. These lithological horizons include 1) basal black shale tongue (Figure 31) 2) carbonate tongue 3) lower siltstone tongue 4) medial shale tongue and 5) upper siltstone tongue. Although some workers include the black shale above the upper siltstone tongue as part of the Sappington Member, it is actually the basal member of the Lodgepole Formation, and is named the Cottonwood Canyon Member (Sandberg and Klapper, 1967).

Within the study area the Sappington Member of the Three Forks Formation is comprised of three areas of increased thickness that are separated by areas of thin or

absent Sappington Member (Figure 32). Areas comprising thick packages of the Sappington Formation include 1) Gallatin, Madison, Broadwater, and Jefferson counties where thicknesses range from 60 to 90 feet, 2) Blaine County where thickness range from 10 to 50 feet, and 3) northern Toole County where the Sappington Member reaches its maximum thickness of nearly 140 feet (Figures 32 and 33).

The Sappington Member is comprised of several drastically varying lithologies with regional distribution. Specifically, the lowermost black shale tongue of the Sappington Formation may be extensively mapped (Figures 28 and 32) due to its petrophysical signature—an anonymously high gamma ray reading in geophysical well logs. The basal black shale tongue is present over much of the study area with thicknesses ranging from 0 to 18 feet. Its greatest thickness is observed in northern Toole County; it is absent in eastern Pondera County, and much of Hill, Choteau, and Blaine counties.

Lodgepole Formation

Cottonwood Canyon Member. The Cottonwood Canyon Member of the Lodgepole Formation is a thin siliciclastic unit at the base of the Lodgepole Formation. Two tongues comprise this unit: an older, silty lower tongue present in eastern Montana, and an organic-rich black shale present in western Montana and Wyoming. Although the tongues interfinger in localities, only the latter is present in the study area, and is lithologically comprised of an organic-rich, fissile mudstone with phosphate, coprolite, and conodont fossils common (Sandberg and Gilbert, 1967).

The Cottonwood Canyon Member is present in three localities: 1) an arcuate-shaped thick centered in Park County attaining a maximum thickness of 8 feet, 2) northern Glacier County where thicknesses reach 12 feet, and 3) eastern Blain County where the Cottonwood Canyon Member is 10 feet thick (Figure 33).

Sequence Stratigraphy

General Statement

Sequence stratigraphy involves the identification and correlation of chronostratigraphically-significant surfaces. This study utilizes rock data obtained from outcrop, core, and wireline logs to identify and correlate these surfaces. Since its inception (Vail et al, 1977), sequence stratigraphy has become a standard technique for organizing stratigraphic data to better enable the correlation of time-equivalent strata. This study largely adheres to the sequence stratigraphic methods and models derived by Sarg (1988), Van Wagoner et al. (1990) and Catuneanu (2006).

Lithofacies analysis and outcrop-scale attributes of 5 stratigraphic sections from the Sappington basin of southwest Montana are utilized to construct a sequence stratigraphic framework. Beds of lithofacies were grouped into shallowing-upward parasequences that are bound by flooding surfaces—a surface across which a significant increase in water depth is recorded by an abrupt shift in depositional environments (Van Wagoner et al., 1990, p.10-13). The collective stacking of parasequences creates aggradational, progradational, or retrogradational stacking patterns in relationship to the coast line, and are a reflection of the change in base level during deposition. These

stacked parasequence are called systems tracts and are bound by a number of key stratigraphic surfaces that are regionally correlatable (Appendix E, Figures 35 and 36).

The interval of rock under study is composed of both siliciclastic *and* carbonate packages of rock which require different models for interpretation. However, common reference points may be utilized to achieve a unified interpretation. These common reference points are energy surfaces dictated by water depth and include the intertidal zone, fair weather wave base and storm weather wave base. Appendix D displays depositional environments manifested by lithofacies assemblages according to these energy surfaces. Through the use of this lateral facies definition, vertical succession of lithofacies, parasequences, and parasequence sets, a sequence stratigraphic framework may be constructed in a unified model.

Parasequence Types

Four parasequence types are recognized within the Devonian-Mississippian interval of western Montana. Although they are comprised of different vertical stacks of lithofacies, all cycles display a progressively shoaling-upward pattern whereby more proximal lithofacies stack on top of more basinal facies, implying a basinward movement of base level (progradation). Each cycle is bound by a surface representing a rapid increase in water depth manifested by a relatively more distal facies overlying a more proximal facies. These surfaces are known as flooding surfaces, which bound parasequences (Figure 37).

Figure 35: Sequences One and Two Sequence Boundary

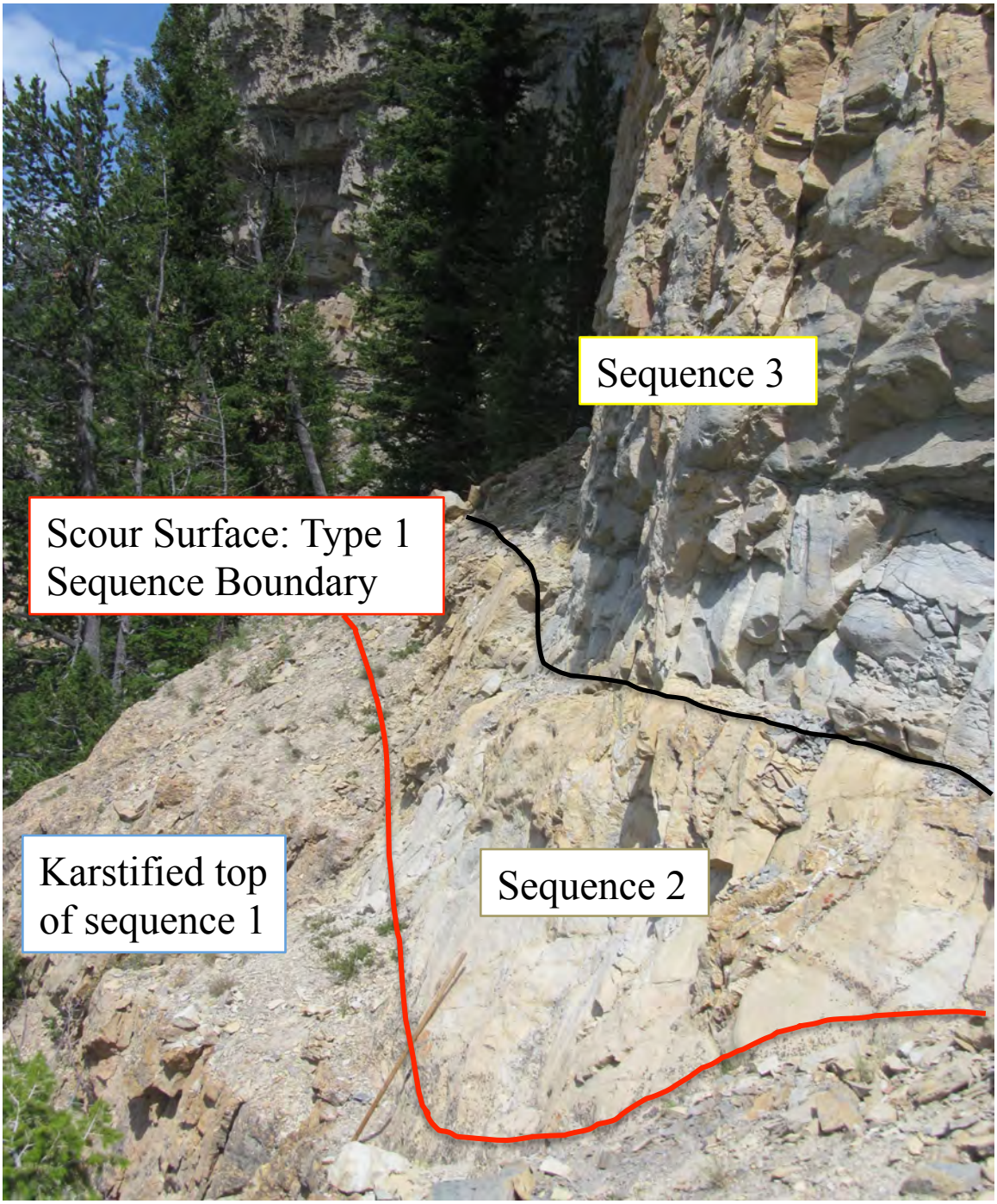


Figure 35: Sequences One and Two Sequence Boundary. Here, the contact between the Logan Gulch Member and the Trident Member is undulatory with nearly 4 meters of relief (see 1.2 m. Jacob's Staff for scale) indicating erosion. Additionally, the Logan Gulch Member is highly karstified, indicating subaerial exposure and meteoric weathering.

Figure 36: Sequences Three and Four Sequence Boundary

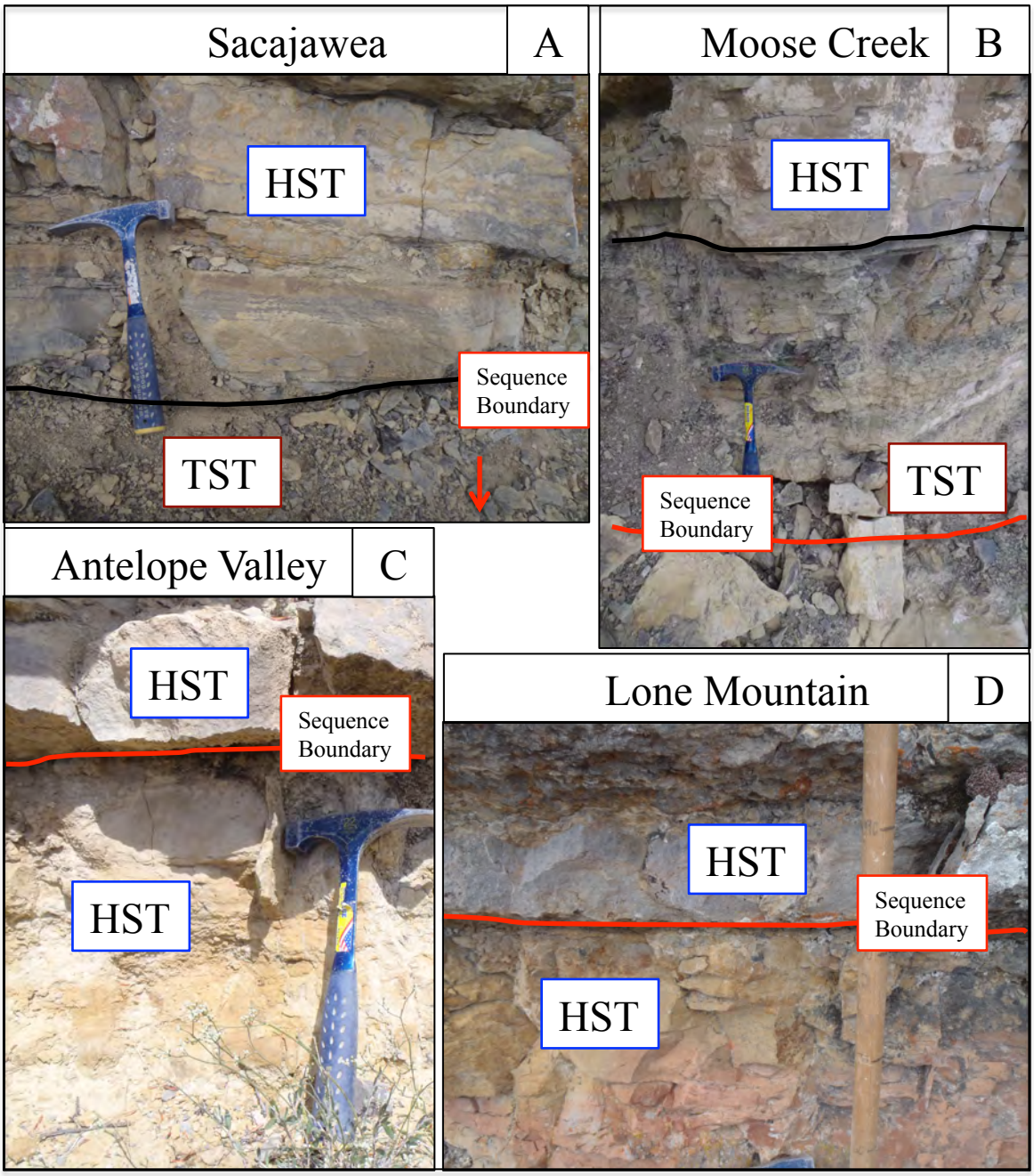


Figure 36: Sequences Three and Four Sequence Boundary. This sequence boundary separates sequences three and four. A) Sacajawea Peak locality showing a characteristic organic-rich TST deposit above a highstand deposit (sequence boundary not included in photo). B) Sequence boundary at Moose Creek locality separating a HST from a TST manifested by interbedded organic-rich black shale and burrow-mottled calcareous siltstone. C/D) Sequence boundary at Antelope Valley and Lone Mountain separating two HST deposits, although manifested by varying lithologies. A TST deposit is not manifested at this locality due to erosion or non deposition.

Siliciclastic Shoreface Parasequences. Terrigenous siliciclastic rocks dominate the shallow marine Devonian-Mississippian system in western Montana, and therefore siliciclastic shoreface cycles are the most commonly observed parasequence. Overall siliciclastic shoreface cycles are manifested by an increase in grain size and hydrodynamic energy up section indicated by sedimentary structures (Appendix A). These cycles are composed of quartz sandstone, quartz siltstone, and terrigenous siliciclastic mudstone. Within each cycle, upper shoreface lithofacies are stacked on top of lower shoreface lithofacies, indicating a basinward movement of depositional environments.

At the Moose Creek outcrop, facies Fcm (massive claystone) is overlain by facies Fsm (massive siltstone) which is in turn overlain by facies Ssw (swaley and hummocky cross stratified fine sandstone). This vertical succession of rocks indicates a basinward shift depositional environments, or progradation. Finally, this succession of rock is capped by an abrupt deepening surface—or flooding surface—as indicated by a decrease in grain size and hydrodynamic energy manifested by facies Fsm (massive siltstone) overlying Ssw (swaley and hummocky cross stratified fine sandstone) (Figure 37).

Intertidal Carbonate Parasequences. Only one partial intertidal carbonate cycle is recognized and is comprised of lithofacies CMbr (mudstone breccia) and CBl (laminated boundstone). The association of these two lithofacies is interpreted to represent the top of a shallowing-upward cycle, due to its intertidal/subaerial depositional environment indicated by this lithofacies assemblage (Machel and Hunter, 1994). This cycle is uniquely observed at the top of the Logan Gulch Member of the Three Forks Formation.

Figure 37: Identified Parasequence Types

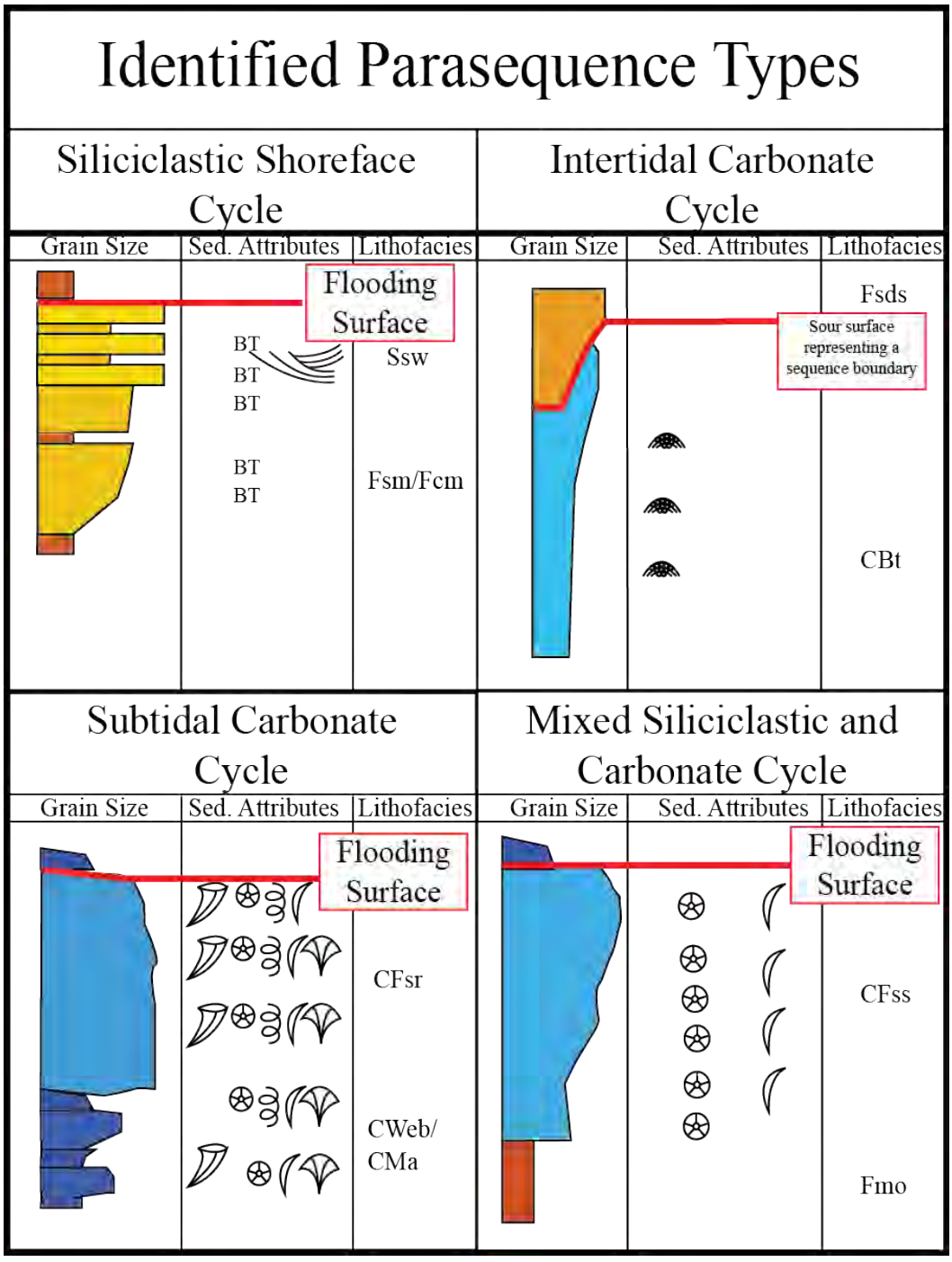


Figure 37: Identified Cycle Types. Cycles are also known as paraseqeuences in sequence stratigraphic terminology. Parasequence are defined as shallowing upward successions of lithofacies bound on their top and base by flooding surfaces. Flooding surfaces are manifested in outcrop by a relatively deeper facies overlying a relatively shallower lithofacies, signifying an abrupt increase in water depth.

Brecciation within and a scour surface on top of this unit are attributed to subaerial exposure, and the creation of an unconformity. This subaerial interpretation indicates that this intertidal carbonate cycle is bounded on its cycle top by a sequence boundary (Figure 37).

Subtidal Carbonate Parasequences. The most common carbonate cycles observed in the Three Forks Formation are subtidal carbonates. Typically lithofacies CMa (argillaceous lime mudstone) or CWeb (echinoderm brachiopod wakestone) are overlain by lithofacies CFss (stromatoporoids skeletal floatstone) or CFsr (stromatoporoids rugose coral floatstone). This succession of lithofacies suggests the subtidal carbonate cycles were deposited at or below fair weather wave base, and in the case of lithofacies CMa, below storm weather wave base. Subtidal carbonate cycles generally indicate deeper water depths than do the other identified cycles. Subtidal carbonate cycles are consequently associated with lower highstand systems tracts, and are basally bound by a maximum flooding surfaces (Figure 37).

Mixed Carbonate and Siliciclastic Parasequences. Mixed carbonate and siliciclastic parasequences are commonly observed in the Three Forks Formation, and are associated with a very specific location of a sequence stratigraphic framework. These cycles typically include lithofacies Fmo (organic rich claystone), Fcm (massive claystone) or Fml (laminated mudstone) that are overlain by sub storm weather wavebase lithofacies of CWa or CWeb. The fine-grained terrigenous siliciclastic intervals are often associated with organic material, and are considered a condensed section—a horizon

starved by siliciclastic flux characteristically containing increased amounts of organic material—characteristically occurring above a sequence boundary at the base of a transgressive systems tract (Creaney and Passey, 1993). Mixed carbonate and siliciclastic parasequences are commonly overlain by subtidal carbonate parasequences (Figure 37).

Basin Type and Attitude

During Devonian-Mississippian time, the Sappington basin was a northwest-facing epicratonic basin (Macqueen and Sandberg, 1970; Sandberg, 1988, Allen and Allen, 2005) (Figure 5). Epicratonic sedimentary basins are relative topographically low areas upon continental crust capable of storing sedimentary material for geologically significant periods of time.

An important implication for epicontinental basins and the application of sequence stratigraphy is the concept of accommodation. This concept characterizes the amount of space available for sediment deposition, and is a composite function of relative sea level and subsidence (Jervy, 1988). Epicontinental basins are often associated with low subsidence rates (Allen and Armitage, 2012), generally producing low accommodation settings. The consequence of interpreting a sequence stratigraphic framework in a low accommodation setting is a relatively low-resolution image of the geologic past due to significant amounts of time represented as surfaces; a large portion of the rock record has either not been deposited, or has been eroded. However, low accommodation settings do imply well-pronounced unconformable surfaces represented by soil horizons, basal lags and/or scour surfaces.

Sequence Stratigraphic Framework

The Devonian-Mississippian transition in western Montana is composed of four sequences: two complete sequences and two partial sequences delineated by three sequence boundaries. Central to the sequence stratigraphic framework is the inclusion of a second-order sequence boundary (Vail et al., 1977) known as the Acadian Unconformity (Wheeler, 1963). This regional unconformity separates Sloss's (1963) Kaskaskia cratonic sequence into the Kaskaskia I and Kaskaskia II cratonic sequences.

Sequence One. In outcrop, only the upper portion of sequence one has been described and included in this study. The sequence boundary between sequences one and two is evident at all outcrop localities. Characteristics of this sequence boundary include the following: 1) brecciation interpreted to be from karst collapse immediately below the identified boundary indicating subaerial exposure and meteoric weathering, and 2) a scoured surface with up to two meters of relief in the most proximal outcrop locality (Figure 38). Taken together, these two criteria sufficiently indicate prolonged subaerial exposure and meteoric weathering styles (Sarg, 1988; Flugel, 2004).

The top of sequence one is composed of lithofacies CMbr (mudstone breccia) and CBl (laminated boundstone), creating a intertidal carbonate cycle (Appendix E). The brecciated sections of this carbonate unit do not systematically thicken laterally or vertically. In short, there seems to be no discernable pattern associated with brecciation. However, consistent with the interpretation that brecciation is associated with meteoric weathering, lithofacies CMbr is thus likely a solution collapse breccia, and its clasts are composed of the rock surrounding it (CBt) (Catuneanu, 2006, p.285). Although not

Figure 38: Sequence One Isochore

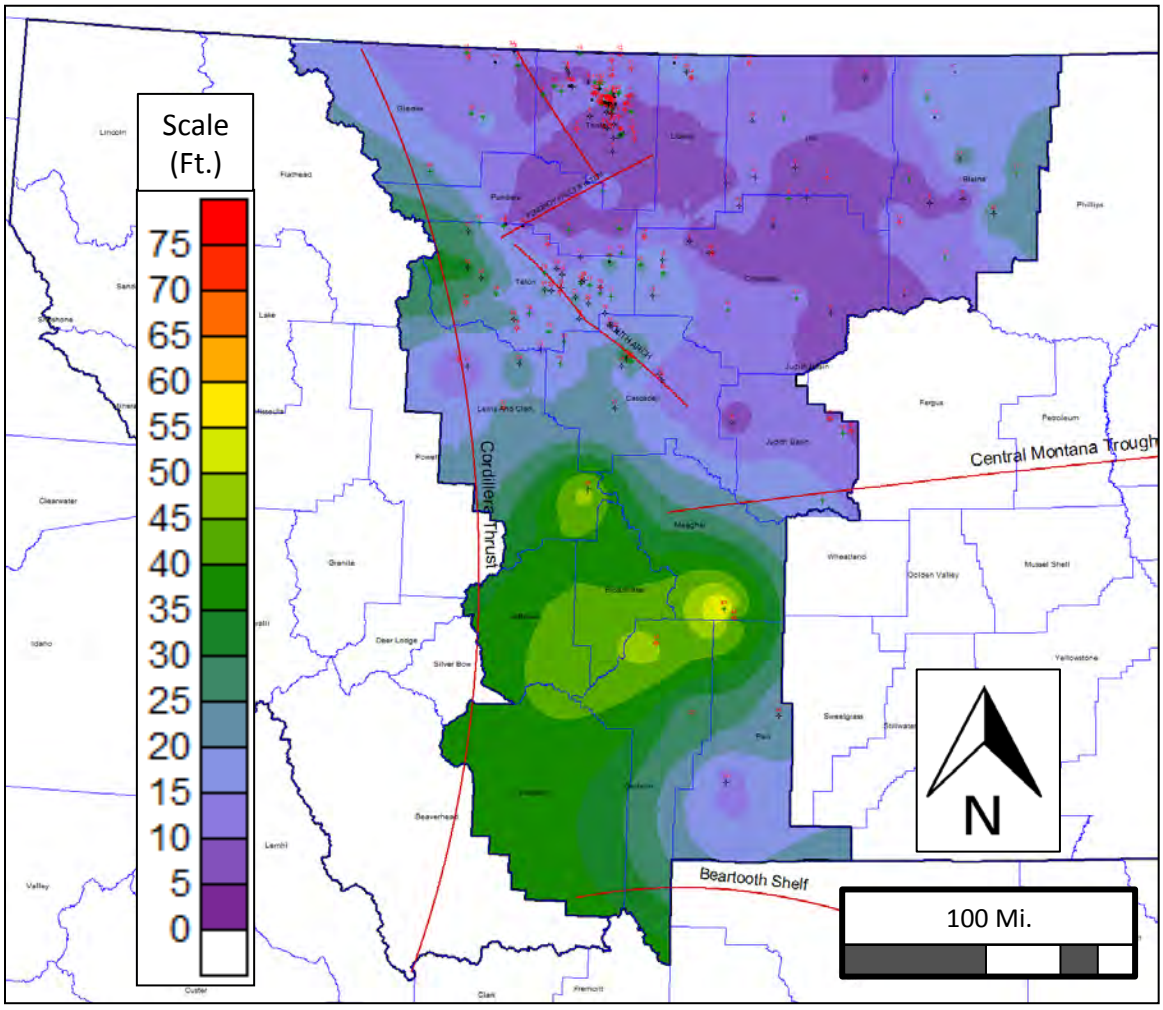


Figure 38: Sequence One Isochore. Sequence one is the most continuous interval in the study area, and shows a gradual thickening towards the south of the area. Lithofacies comprising this sequence include CMbr , CBl, and a shale unit that was not measured in outcrop. Due to the dominantly carbonate lithofacies, and isopachus distribution, this sequence is interpreted to represent a tectonically quiescent intertidal carbonate factory.

measured in outcrop, the base of sequence one is the top of the Jefferson Formation which will be used for mapping purposes.

This sequence is present throughout the entire study area. Thicknesses gently change from 10-50 feet thick across 100s of square kilometers (Figure 38). Coupling the observed carbonate/evaporite lithology with a broad, slightly undulating distribution, it is interpreted that this interval of rock represented a broad shallow sea across western Laurentia. Slight changes in relative sea level may have produced evaporite basins and broad cyanobacteria-dominated intertidal depositional environments.

Sequence Two. Evident from outcrop studies, sequence two is composed of the massive and laminated siltstone of the Trident Member of the Three Forks Formation. The nature of the basal contact with the Logan Gulch Member has been previously discussed—and is a scoured surface with a karstification directly below the erosional contact. The upper bounding surface of sequence two is a second order sequence boundary known as the Acadian unconformity (Wheeler, 1963).

The Acadian unconformity is a regionally unconformable surface evident in many localities throughout the North American craton, including examples within, as well as adjacent to the area of interest (Wheeler, 1963). Locally, the basal black shale of sequence two overlies an irregular surface with a relief of nearly 1 foot (Gutschick et al., 1972). Directly underlying this sequence boundary is highly weathered rock material including the development of a distinct paleosol at Milligan Canyon (Gutschick et al., 1967). Additionally, studies of conodont biostratigraphy indicate several missing biozones across this surface (Kaufmann, 2006; Johnson et al, 2010).

The fine-grained nature of this sequence and difficulty in observing sedimentary structures makes interpretation of this sequence difficult. For example, the Sacajawea outcrop location demonstrates a cryptic shallowing upward siliciclastic parasequences as evident by a systematic increase in grain size. However, the stacking trajectory of this parasequences set (progradational, aggradational, or retrogradational) is nebulous, making a systems tact designation difficult. This sequence is tenuously interpreted a TST/HST deposit. Although not explicitly observed in outcrop, a TST is interpreted due to the necessity of raising relative sea level after the subaerial exposure of the Acadian unconformity. This flooding of the craton was likely followed by progradation into the Sappington basin during a HST.

Sequence two is thickest around the Kevin-Sunburst Dome area, and thins dramatically to a zero edge westward, and to 5-10 feet in the Sappington basin (Figure 39). It is difficult to infer a sedimentary basin configuration during the deposition of sequence two due to the large amount of eroded rock. However, a NE-SW-trending isochore thickness trend near the modern geographical position of the Pendroy fault zone leads to the following interpretation: the modern location of the Pendroy fault zone may be a reactivation of an older basement zone of weakness that may produced increased accommodation, and hence deposition and preservation of strata. The area west of the modern position of the Pendroy fault zone may have been a paleo-high—a platform known as Montania (Hartel et al., 2012)—and may not have experienced deposition as indicated by a lack of preservation of strata. Alternatively, the zero isochore area west of

Figure 39: Sequence Two Isochore

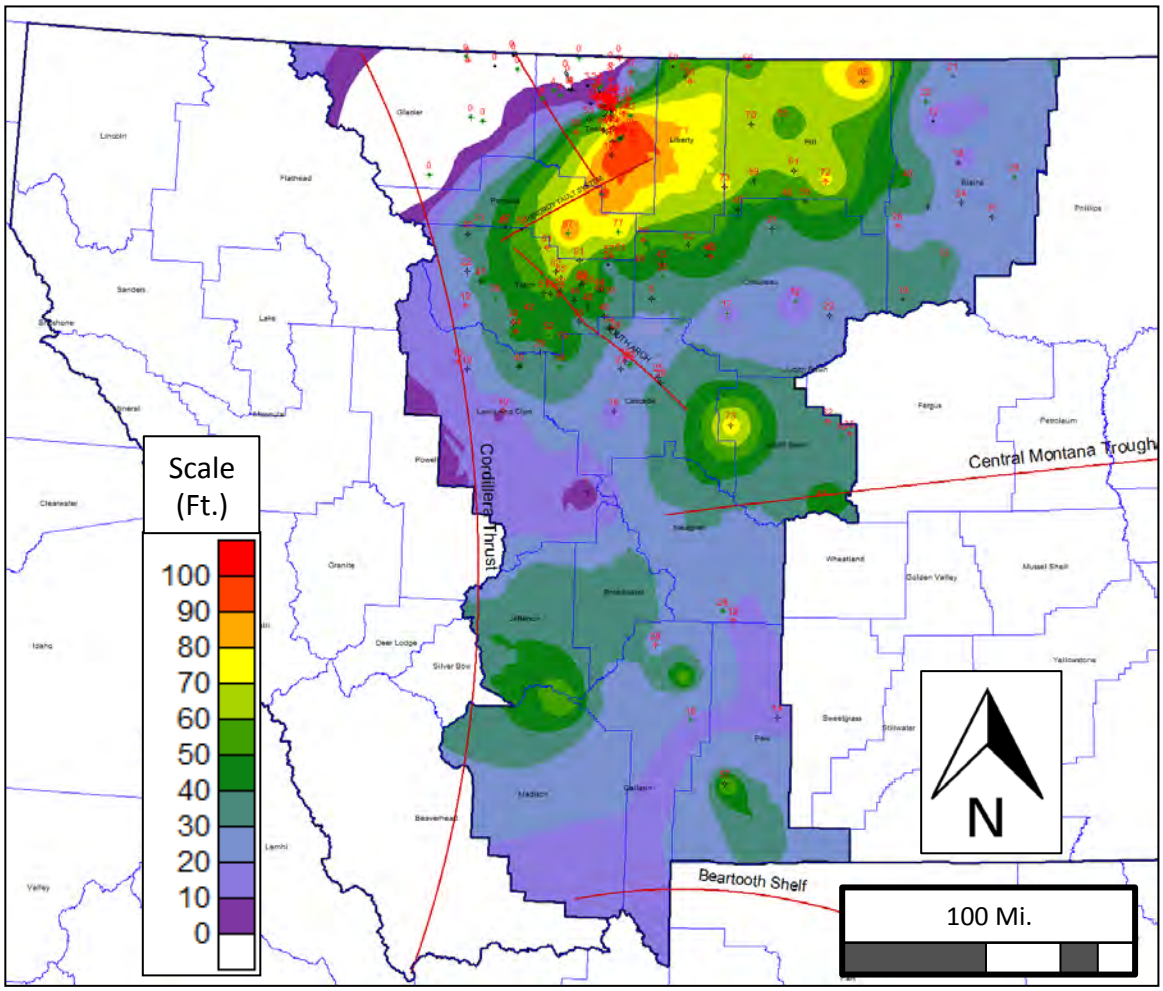


Figure 39: Sequence 2 Isochore. During the time of deposition of sequence two, tectonic movement in the north of the study area began to be significant in sedimentary routing. Specifically, a northeast-southwest trending isochore thickness indicates increased accommodation, while an area lacking sequence two deposits may indicate an emergent paleo high, referred to in this study as Montania.

the modern Pendroy fault zone may have been uplifted subsequent to deposition, inducing erosion (Figure 39).

The Sappington basin to the south seems to have been comparatively tectonically quiescent. The relatively isopachous distribution of sequence two in the Sappington basin indicates overall uniform erosion (Figure 39). In other words, tectonic movement likely did not affect this area; regional eustatic sea level regression was likely the main factor contributing to the creation of the Acadian unconformity in the Sappington basin, whereas the WCSB's isochore distribution indicates a tectonic overprint inferred from stark changes in the distribution of strata.

Sequence Three. Sequence three is composed of a mixed carbonate/siliciclastic parasequence overlain by carbonate parasequences, which are in turn overlain by siliciclastic shoreface parasequences. Sequence three is comprised of a retrograding transgressive systems tract (TST) overlain by a highstand systems tract (HST) delineated by a maximum flooding surface (MFS), which is in turn overlain by a falling stage systems tract (FSST) (Figure 40). The transgressive systems tract is manifested by a thin veneer of organic-rich fissile to massive shale (lithofacies Fmo). This lithofacies has been demonstrated to correlate to horizons associated with landward movement of base level (Creaney and Passey, 1993). Conceptually, during a transgressive systems tract, sediment is stored proximally, decreasing siliciclastic dilution of organic-rich material resulting in high concentrations of organic matter (Bohacs et al., 2005).

Following deposition of the organic-rich TST, a HST and FSST aggraded/prograded into the Sappington basin. Smith and Bustin (2001) have interpreted

Figure 40: Sequences Three and Four Stratigraphic Model

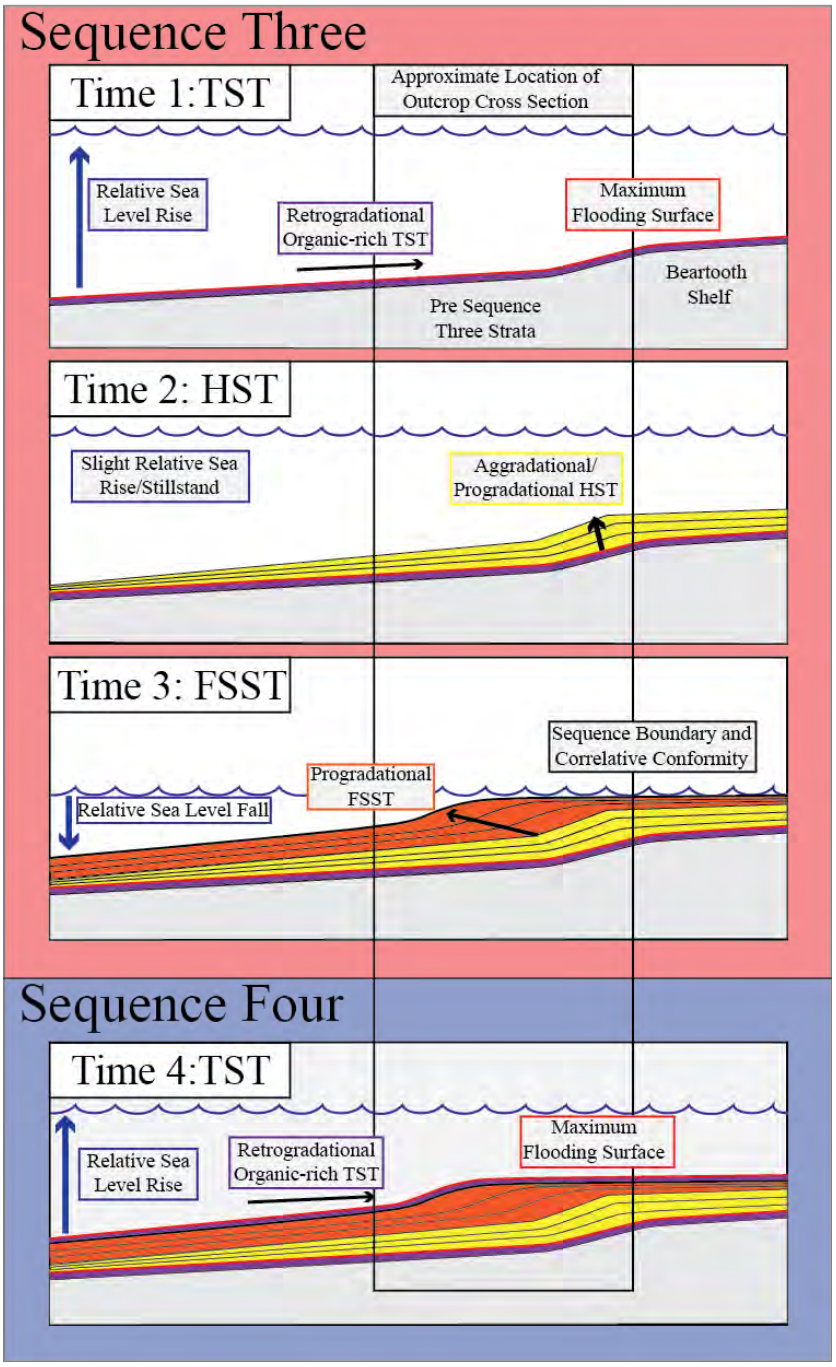


Figure 40: Sequences Three and Four Stratigraphic Model. Sequence three is composed of a retrograding TST, an aggradational/progradational HST, and a prograding FSST. Sequence four is composed of a retrograding TST. Sequence three and four are separated by a sequence boundary that is manifested by missing conodont zonations (Johnson et al, 2010) and a change from an aggradational/progradational stacking pattern of subtidal carbonate depositional environments to a progradational stacking pattern of foreshore/upper shoreface siliciclastic depositional environments.

this entire interval as a lowstand systems tract (LST) utilizing the concept of rapid relative sea level fall following a relatively prolonged TST that does not allow the deposition or preservation of a HST. However, in order to achieve such a progression, it would require extremely shallow water lithofacies unconformably overlying much deeper deposits. As the depositional environments are defined in this study (Appendix E), this relationship is not observed in outcrop.

The HST strata is interpreted from 1) the dominance of mid to outer ramp carbonate depositional environments, and 2) an aggradational/progradational geometry (Catuneau, 2006, p. 171-178) that has been demonstrated in outcrop study (Figure 40, Appendix E). Relative sea level during HST deposition is at its highest point in a sequence, decreases siliciclastic delivery to the basin, and enables the proliferation of carbonate depositional environments (Southgate et al., 1993). A dominantly aggradational depositional geometry is interpreted to be the result of a carbonate-dominated catch-up highstand systems tract (Figure 40) (Sarg, 1988).

Following HST deposition, relative sea level began to fall, initiating a falling stage systems tract (Catuneau, 2006, p. 178-196) (Figure 36). The FSST is interpreted from a strongly progradational geometry of siliciclastic deposits (Southgate et al., 1993) and a lack of strata in the direction of source terrains. Siliciclastic parasequences systematically increase in energy up section to where the FSST is capped by a sequence boundary. This trend indicates a lowering of relative sea level that is associated with an observed progradational stacking pattern.

Additionally, regional mapping indicates a lack of preservation in the direction of provenance (towards the transcontinental arch). This is proposed to be a subaerial exposure surface that propagated during base level fall, creating a sequence boundary. Subaerial exposure during this time increased weathering and rejuvenated source terrains, providing siliciclastic sediment that was transported into the Sappington basin.

Sequence three's distribution is mapped as to two litho bodies: a TST and a composite HST/FSST (Figures 41 and 42). The HST and FFST of sequence three are mapped conjunctively due to the difficulty in separating these systems tracts on geophysical well logs. The transgressive systems tract should be distributed more continuously across the basin than other systems tracts, as it is a minimum energy deposit (Galloway, 1989). Thus, areas not containing a transgressive systems tract are interpreted to be relative paleo-high areas, as they would have been areas of lower water depth, and higher energy where erosion would have been the dominant process.

Paleo-highs are interpreted for three areas during the deposition of sequence three TST based on isochore distribution. These areas include east and west of the Sweetgrass arch, and the Beartooth shelf where sequence three TST is absent (Figure 41). This is apparently a tectonically active time during the development and partitioning of western Laurentia, as there are the three identified paleo-highs, as well as the development of two discrete sedimentary basins: the Sappington basin, and the WCSB. These features may have resulted from the reactivation of basement lineaments due to the compressional stress induced from the east-moving Antler allochthon. As demonstrated with isochore

Figure 41: Sequence Three Transgressive Systems Tract Isochore

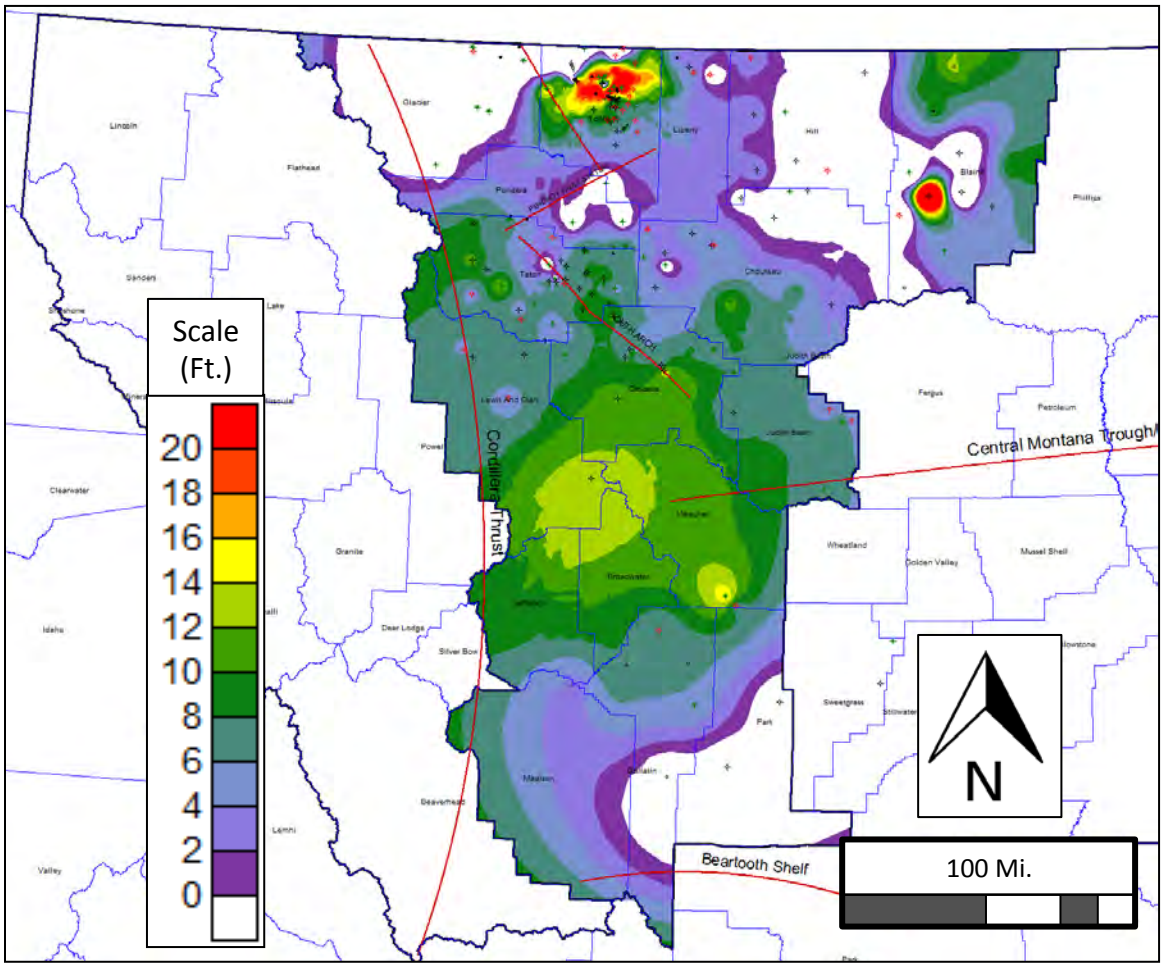


Figure 41: Seqeunce three Transgressive Systems Tract Isochore. A TST deposits should be the most continuous throughout a sedimentary basin, and where absent should indicate a paleo high. Thus, 4 paleo highs are interpreted during the deposition of this interval: 1)the Beartooth shelf, 2) Montania, 3) the modern location of the Pendroy fault zone, and 3) an unnamed are east of the Sweetgrass Arch that separates the WCSB from the Williston basin. By this time, tectonic movement continues to control sediment distribution, and the emergent area near the modern Pendroy fault zone has begun to partition the WCSB from the Sappington basin.

distribution of sequence two, the WCSB was already in a state of increased accommodation, a trend that continued throughout the TST of sequence three (Figure 41).

The HST/FSST of sequence three indicates increased accommodation, and subsequence deposition in the fully-established Sappington basin. Isochore distributions show a thickening to the west, and thinning east and south onto the paleo-high of the Beartooth shelf (Figure 42). Additionally, a lack of sequence three HST/FSST deposits in an east-west trend around the Pendroy fault zone indicates a paleo-high in the area—a trend manifested during the sequence three TST. Alternatively, this may be the result of post sequence three uplift and erosion.

Continued accommodation is interpreted in the WCSB during the HST/FSST of sequence three by a continued isochore thickness trend that increases northward into Alberta (Figures 42). Additionally, the area west of the WCSB begins to create accommodation as evident by a thin deposit of sequence three HST/FSST deposits. However photoelectric effect and bulk density geophysical logs indicate that lithologies in the more westward portions of the WCSB are composed of carbonates. Thus, it may be possible that the previously-mentioned Montania platform acted as an isolated carbonate platform, shedding allochthonous carbonate eastward into the WCSB.

Sequence Four. Only the basal portion of sequence four is measured and characterized in outcrop study. The basal portion of this sequence is composed of a mixed carbonate siliciclastic parasequence that grades into subtidal carbonate parasequences of the Lodgepole Formation. The siliciclastic portion of the mixed carbonate/siliciclastic parasequence is composed of lithofacies Fmo (organic rich

Figure 42: Sequence Three Highstand and Falling Stage Systems Tracts Isochore

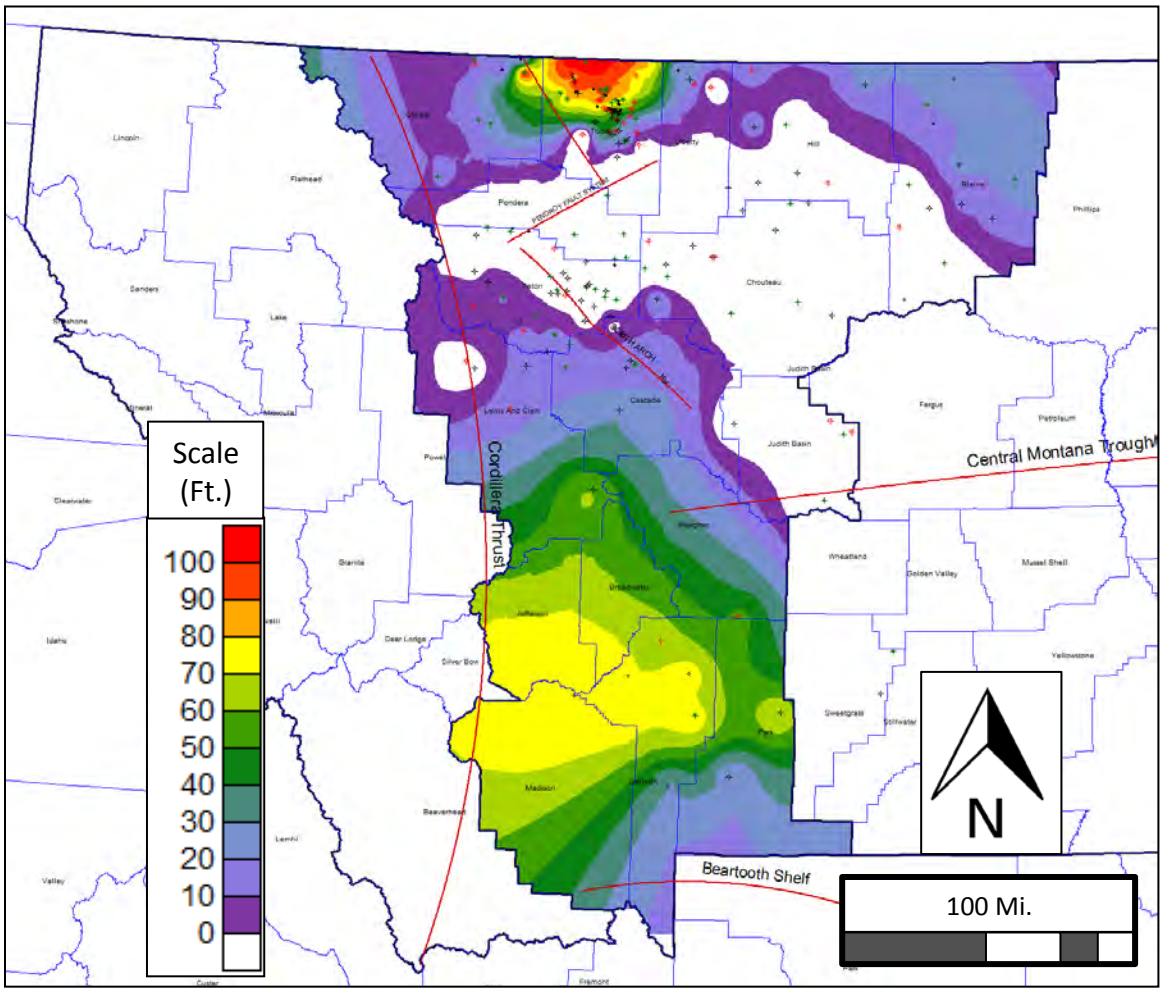


Figure 42: Sequence three Highstand and Falling Stage Systems Tracts Isochore. By this time, the Sappington basin and the WCSB are fully partitioned by an interpreted paleo high near the modern Pendroy fault zone into two distinct basins that are defined by the two areas of isochore thickness trends. The Beartooth shelf continues to be a positive feature evident from thinner sediment distribution.

mudstone), Fml (laminated mudstone) and Fsm (massive siltstone) that are overlain by CWeb (echinoderm brachiopod wakestone).

At the Lone Mountain outcrop location, the mixed carbonate/siliciclastic parasequence is not preserved in the sedimentary architecture as a result from either non deposition or erosion (Figure 36). Although the contact with the underlying sequence is very sharp, there does not seem to be any attributes suggesting an erosional contact such as a scoured surface or an erosional lag. Therefore it may be possible that this cycle was simply not at this locality.

In all cases, the siliciclastic portion of this parasequence (whether preserved or not) is overlain by open marine lithofacies Cweb (echinoderm brachiopod wakestone). Overall, the shallower lithofacies overlain by relatively deeper facies suggests a landward movement of base level. Although not measured in this study, continued open marine carbonate lithofacies may indicate a HST following the interpreted TST (Johnson et al., 1985; Johnson et. al, 2010).

An abrupt facies shift is observed from the underlying sandstone interval to the overlying fine-grained, organic-rich interval. This contact is interpreted to be a sequence boundary/correlative conformity due to its stacking pattern, missing conodont biozones, and interpreted changes in relative sea level (Figures, 4 and 40).

The only mapped portion of sequence four is the TST deposit and shows two areas of increase isochore thickness separated by an area thin or absent TST in an east-west pattern near the Pendroy fault zone (Figure 43). An east-west isochore thickness in the north of the area may indicate an incipient seaway connecting the WCSB to the

Figure 43: Sequence Four Transgressive Systems Tract Isochore

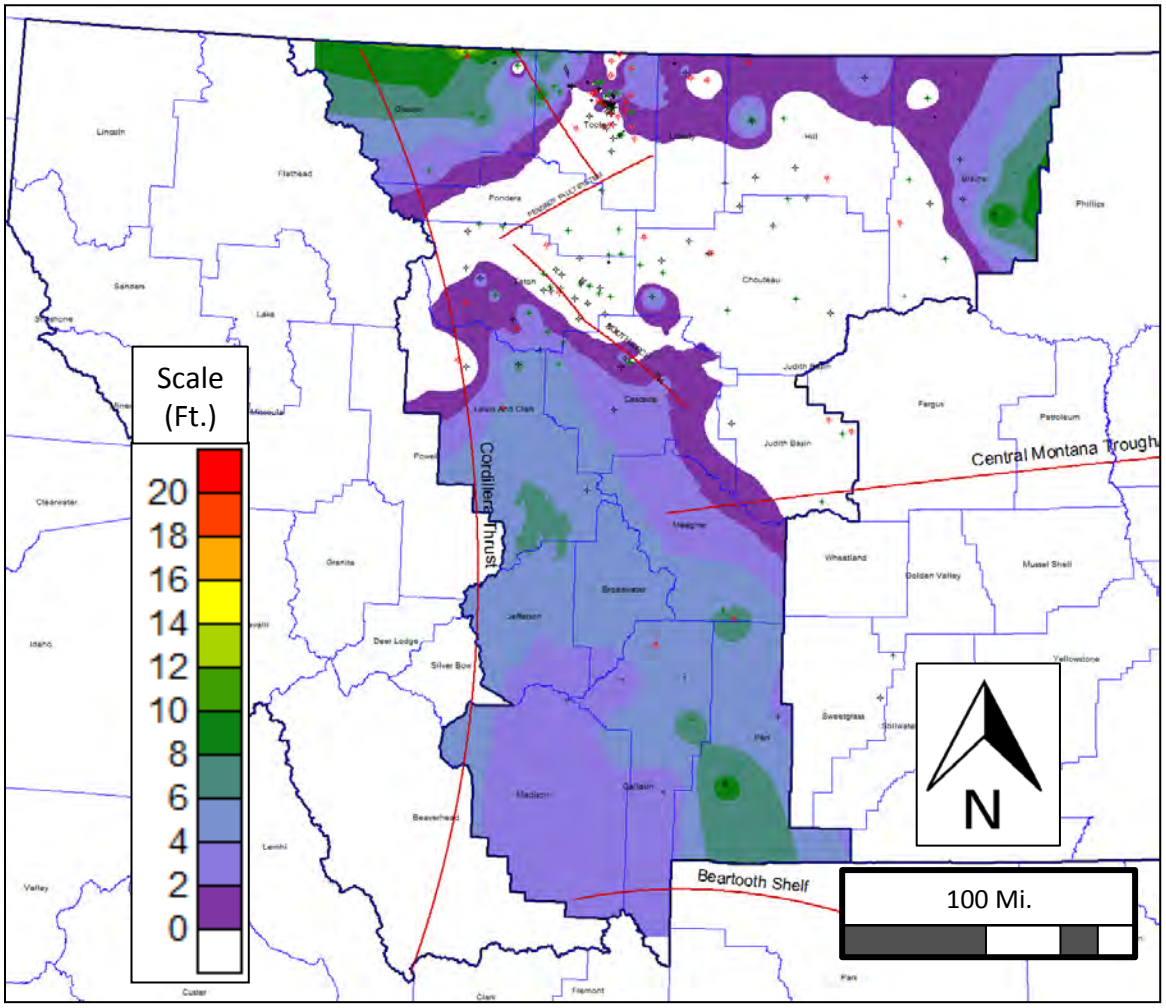


Figure 43: Sequence Four Transgressive Systems Tract Isochore. Similar to the TST deposit in sequence three, this TST distribution should represent the most continuous strata within the basin, absence of which should indicate paleo highs. Accordingly, the area near the modern Pendroy fault zone appears to continue to act as a paleotopographic high that partitions the WCSB from the Sappington basin. Additionally, it appears that a seaway between the eastern Williston Basin and the WCSB has begun to form.

Williston basin. Its patchy nature may indicate small paleo-highs within the area. The Sappington basin displays relatively isopachous distribution of TST deposits ranging from 4-8 feet. However, at the Lone Mountain outcrop, a TST deposit is absent (Appendix A and E). The lack of TST deposits is attributed to a shift in basin polarity as a result of forebuldge development from the eastward movement of the Antler Allochthon (Adiguzel et al., 2012).

Summary

Lithostratigraphy and Sequence Stratigraphy

Sequence stratigraphic boundaries are often concurrent with lithostratigraphic boundaries due to the broad extent, and low accommodation nature of the Devonian-Mississippian sedimentary basins of western Montana. Within the Sappington basin, often one lithofacies represents an entire systems tract—for example the thin veneer of organic rich shale associated with the TST of sequences three and four. Thus it becomes clear that the definition of sequence stratigraphic surfaces and lithostratigraphic surfaces are often concurrent in this scenario (Figure 44).

Where the sequence stratigraphic interpretation reigns superior to that of lithostratigraphy is its ability to correlate a single surface through varying lithologies that is chronologically significant. For example, while the Cottonwood Canyon Member represents a transgressive systems tract, other packages of rock—such as an interbedded shale and siltstone at Moose Creek—represent the same sequence stratigraphic event, yet are of a different lithological nature. Moreover, although in some areas—such as Lone

Figure 44: Stratigraphy Summary

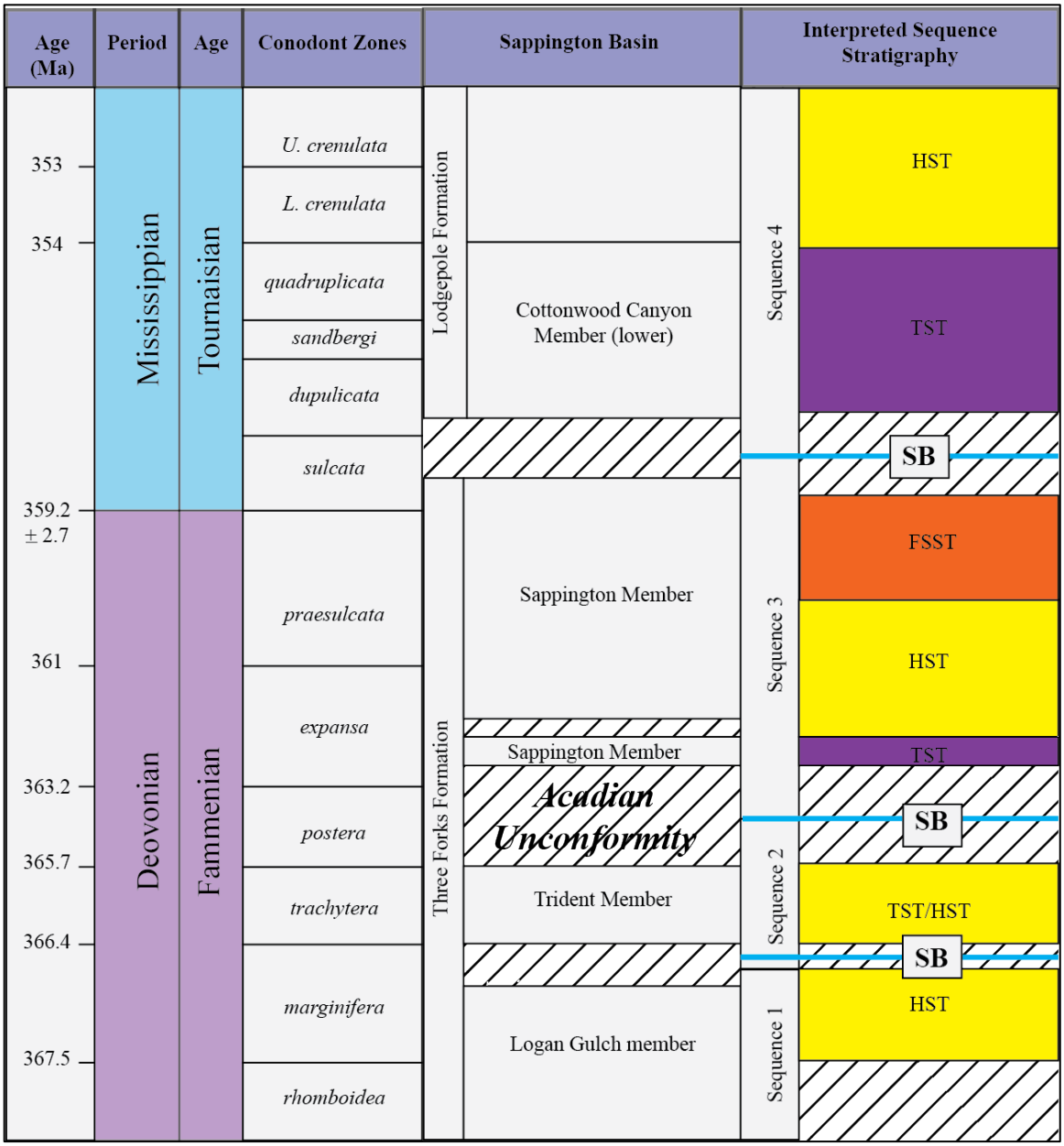


Figure 44: Stratigraphy Summary. Lithostratigraphic and sequence stratigraphic rock bodies are often concurrent. The sequence stratigraphic framework is composed of two complete sequences and two partial sequences. Key to this project is sequence three that is composed of a basal sequence boundary that is the Acadian Unconformity, a TST, a HST, a FSST, and an upper sequence boundary.

Mountain—the Cottonwood Canyon Member was not deposited, or has been eroded, sequence stratigraphic concepts allow for the definition of a chronostratigraphically-significant surface in the absence of the Cottonwood Canyon Member (Appendix A and E).

The definition of such surfaces allows grouping of genetically related packages that are bound by unconformable surfaces (Catuneanu et al., 2009). These surfaces and the stacking patterns of strata they contain systematically dictate the diagenetic evolution of rocks--a theme that will be discussed in the following chapter (Morad et al., 2012).

Basin Evolution

The interval under study is composed of four sequences. Sequence one is dominated by a tectonically quiescent, intertidal depositional environment. Relative sea level lowered causing meteoric weathering including karstification, erosional scouring, and propagation of a sequence boundary. Due to the incomplete nature of sequence two, it is difficult to interpret its systems tracts, but has been interpreted to be a mixed TST and HST deposit.

Following deposition of sequence two, base level fell to a maximum, subaerially exposing the entirety of western Montana, and creating the Acadian unconformity. This significant sequence boundary is manifested by multiple attributes throughout the region (Gutschick, 1975).

Overlying the Acadian unconformity is a thin veneer of organic-rich sediment representing the TST of sequence three. During this time, paleo-highs developed around the current location of the Pendroy fault zone, as well as around the Beartooth shelf. It is

likely that deep-seated basement lineaments were reactivated and uplifted by the compressional force of the eastward-moving Antler allochthon (Dorobeck et al, 1991). Patchy preservation of the sequence three TST in an east-west fashion suggests an incipient paleo-high, which will be very pronounced in the HST/FSST of sequence three. This paleo-high separates the WCSB from the Sappington basin.

Sequence three is separated from sequence four by a sequence boundary interpreted from missing conodont zonations and depositional geometry. During the deposition of sequence four TST, the area near the Pendroy fault zone continued to be a paleo-high as evident from thin isochore distribution. The rest of the study area remained relatively quiescent besides the west side of the Sappington basin that may have experienced a switch in basin polarity from forebuldge movement of the Antler allochthon (Adiguzel et al., 2012). On top of sequence four TST are carbonates of the Lodgepole Formation. Although beyond the scope of this study, these deposits have been interpreted as a HST (Johnson, 2010).

The stratigraphic architecture of epicratonic basins in western Laurentia during Devonian-Mississippian time is interpreted to be controlled by regional eustatic changes in sea level overprinted by tectonic movement. Third order sequences (Vail et al., 1977) are superimposed upon a long term regression-transgression cycle. Long term regression is interpreted to have rejuvenated siliciclastic source terrains and created the Acadian unconformity. Long-term transgression is interpreted to have lead to a return to carbonate deposition typical of the Laurentian Paleozoic. Vertical tectonic movement imposed constraints on sediment routing and preservation as evident by isochore distribution of

rock bodies. These vertical movements are attributed to the reactivation of basement lineaments from the compressional stresses imposed by the Antler allochthon (Dorobeck et al, 1991).

CHAPTER 5 – LINKING DIAGENESIS TO SEQUENCE STRATIGRAPHY

Diagenesis in a Sequence Stratigraphic Framework

Sequence stratigraphy and diagenesis are commonly studied exclusively from each other. However, common parameters dictate the character and evolution of both types of analysis, including climate, sediment composition, rates and relative changes of sea level, and tectonics. Specifically, many attributes imparted onto sedimentary rocks during deposition have a marked affect in the later digenetic evolution of any given sedimentary rock body, and can be predicted by a sequence stratigraphic framework (Morad et al., 2000; Morad et al., 2010; Morad et al., 2012). Interpreting diagenesis within a sequence stratigraphic framework may lead to a more accurate prediction of reservoir quality. Diagenetic analysis is based on standard thin section techniques, findings of which are summarized in appendix B. A paragenetic evolution has been interpreted for discrete rock units delineated by key sequence stratigraphic surfaces. Diagenetic processes have been assigned to diagenetic regimes defined by Choquette and Pray (1970) including eogenetic, mesogenetic, and telogenetic regimes.

Sequence One

Sequence one is comprised of lithofacies CMbr and CBl. Only part of sequence one was documented in outcrop, and is interpreted as a highstand systems tract. Petrographic analysis of sequence one HST indicates many attributes commonly associated with carbonate packages located below subaerial exposure surfaces both at

outcrop, and petrographic scale including karstification and dolomitization (Railsback, L.B., et al., 2012; Morad, 2012).

The paragenetic evolution of sequence one is outlined in figure 45. An intertidal carbonate depositional environment characterized by microbial mats and brachiopods led to primary fenestral and sheltered porosity development (Choquette and Pray, 1970). Early marine seafloor cementation occluded a large majority of this pore space, yet some remained. As base level fell sequence one was subaerially exposed. A freshwater lens approached sequence one, causing meteoric weathering and karstification that is observed in outcrop (Handford and Loucks, 1993). Periodic incursions of seawater onto the exposed ramp may have increased the magnesium to calcium ion ratio leading to early dolomitization evident from euhedral dolomite rhombohedron (Hardie, 1987). Sequence one was then buried with this magnesium-rich water causing further dolomitization, interpreted from zoned dolomite indicating multiple generations of dolomitization (Figure 45). While in the mesogenetic regime, silica was mobilized and precipitated as microcrystalline quartz cement possibly by an increase in temperature/pressure or pH (Boggs, 2009, p. 285). Sequence one was then uplifted in the telogenetic regime where a mosaic of calcite spar occluded remaining fracture porosity.

Sequence Two

Sequence two is composed of lithofacies Fsgo, Fml, Fcm, Fsr, and Cma, and is interpreted as a HST. The paragenetic evolution of sequence two is outlined in figure 46. Although the stratigraphic architecture of sequence two is cryptic at best, some diagenetic

Figure 45: Sequence One Paragenesis

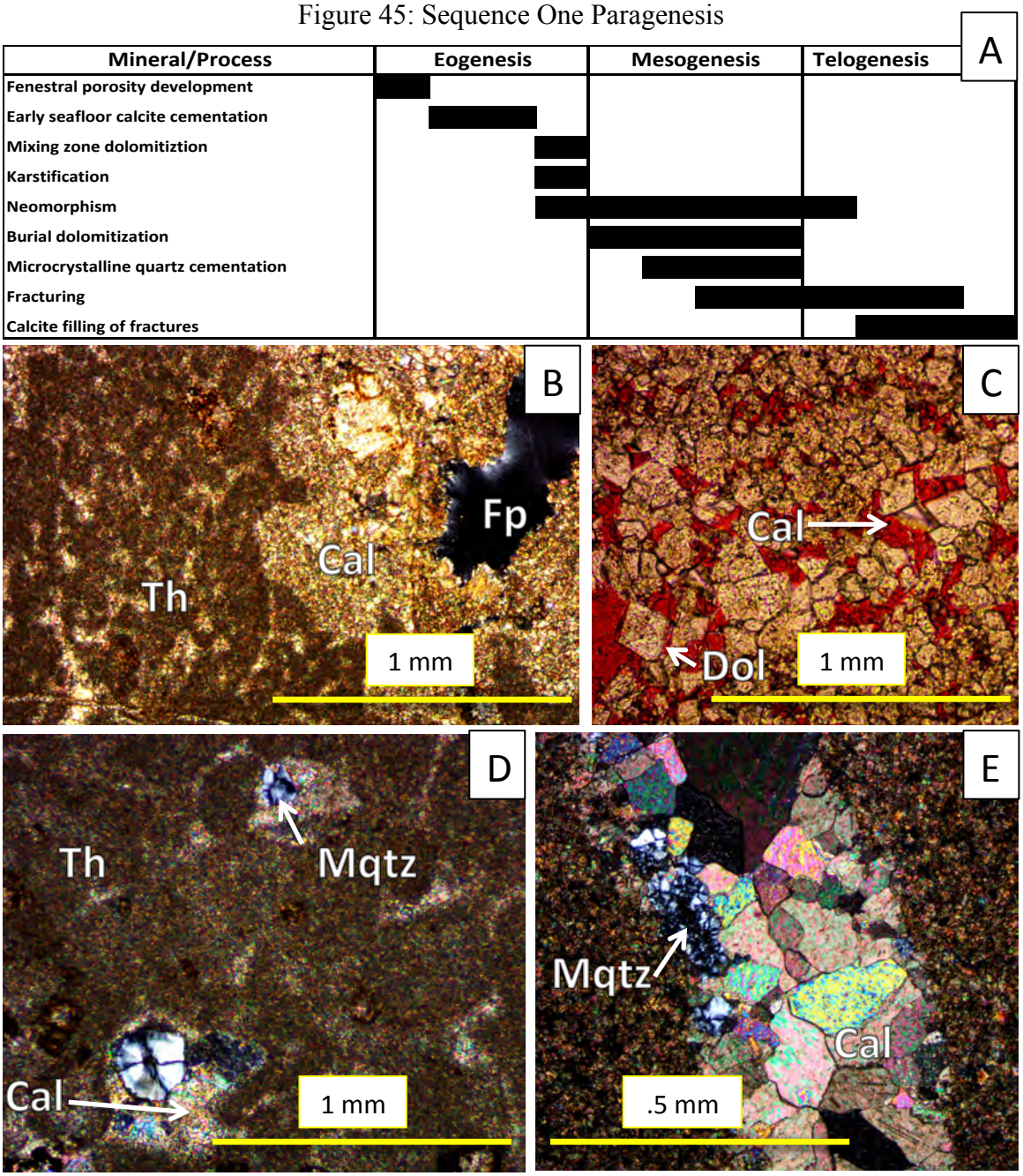
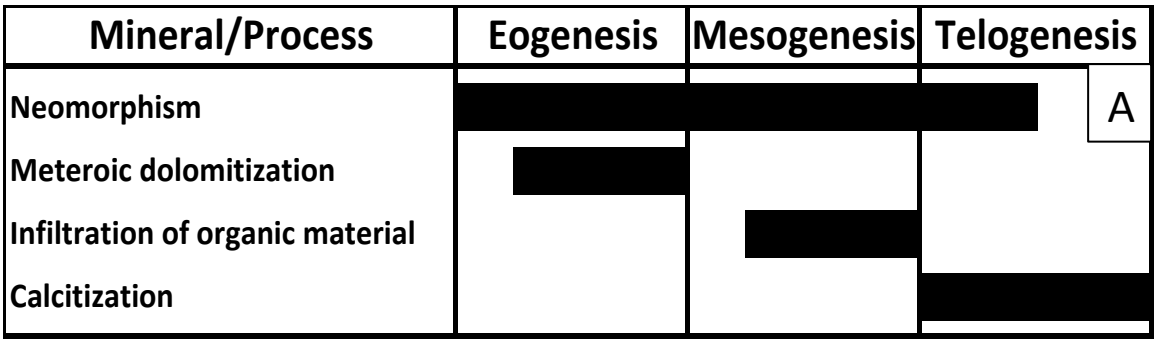


Figure 45: Sequence One Paragenesis: A) Paragenesis overview. B) 4X XPL view of sample LG-8.25.13-2 showing thrombolitic texture (Th), and fenestral porosity (Fp) partially occluded by early marine calcite cement (Cal). B) 10 XPL view of of sample MC-7.27.13-2 showing dolomite rhombahedrons indicating eogenetic to mesogenetic dolomitization (Do) set in telogenetic calcite cement stained red by alizarin red. D) 10X XPL view of sample LG-8.25.13-3 showing porosity occlusion by calcite microcrystalline quartz (Mqtz). E) 4x XPL view of sample LG-8.25.13-1 showing a mesogenetic fracturing that has been filled with a first generation of microcrystalline quartz cement (Mqtz), followed by a second generation of sparry calcite mosaic (Cal).

Figure 46: Sequence Two Paragenesis



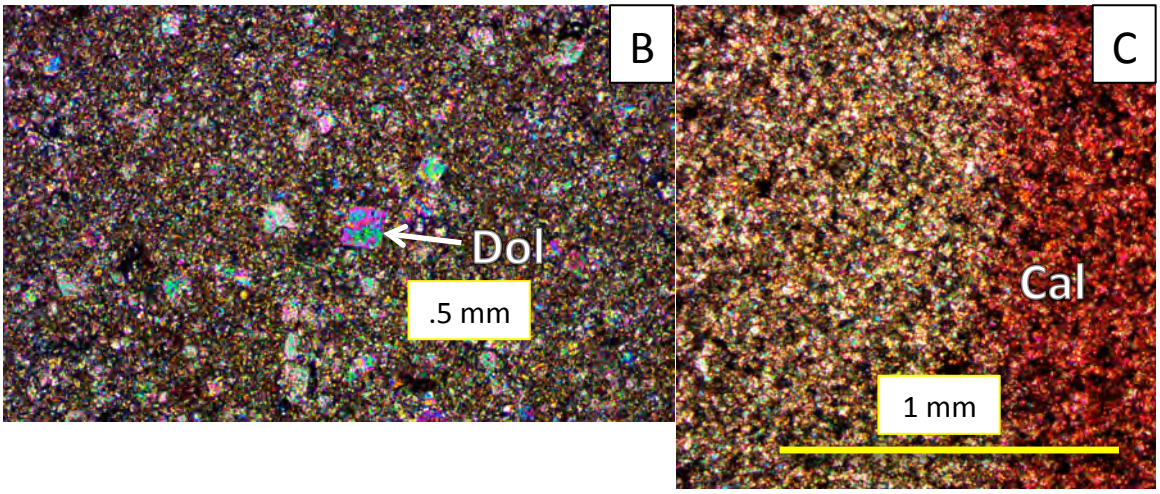


Figure 46: Sequence Two Paragenesis: A) Paragenesis overview. B) 10 XPL view of sample MC-8.10.13-1 showing both aggrading and coalescive neomorphism that produce a porphyrotopic texture with dolomite rhombohedrons (Gregg and Sibley, 1984). E) 4x XPL view of sample MC-7.27.13-4 showing calcitized sample in the telogenetic regime. Half of this thin section is stained red from alizarin red.

features are discernable. Petrographic analysis indicates a highly neomorphosed (Folk, 1965) fabric this is consistent with large amounts of alteration associated with rock packages below unconformable surfaces (assumed to be characterized by vadose zone conditions) (James and Choquette, 1984). It is possible that the original composition of this rock package included framework grains, although any evidence of such has been destroyed by neomorphism. Additionally a porphyrotopic dolomite fabric (Gregg and Sibley, 1984) indicates dolomitization that may have been caused by a number of mixing-zone models that are consistent with rock packages below sub-aerially exposed surfaces (Flügel, 2004 p. 331). During and after uplift, sequence two experienced recrystallization to more thermodynamically-stable calcite (Figure 46).

Sequence Three

Transgressive Systems Tract

The sequence three TST is composed of lithofacies Fmo and Fcm with subordinate Cps. These lithofacies indicate deposition very near or below fair weather wave base. Therefore, cementation and pore fluids associated with the TST deposit are likely of a subtidal affinity, and have not experienced meteoric cementation (Morad, 2012) (Figure 47).

The single thin section representing sequence three TST is sample SP-8.8.13-7 (lithofacies Cps), and is not representative of siliciclastic intervals included in this systems tract. Incorporated within the micritic matrix is a significant amount of clay that is cemented by microcrystalline calcite. During burial, tectonic as well as lithostatic

Figure 47: Sequence Three TST Paragenesis

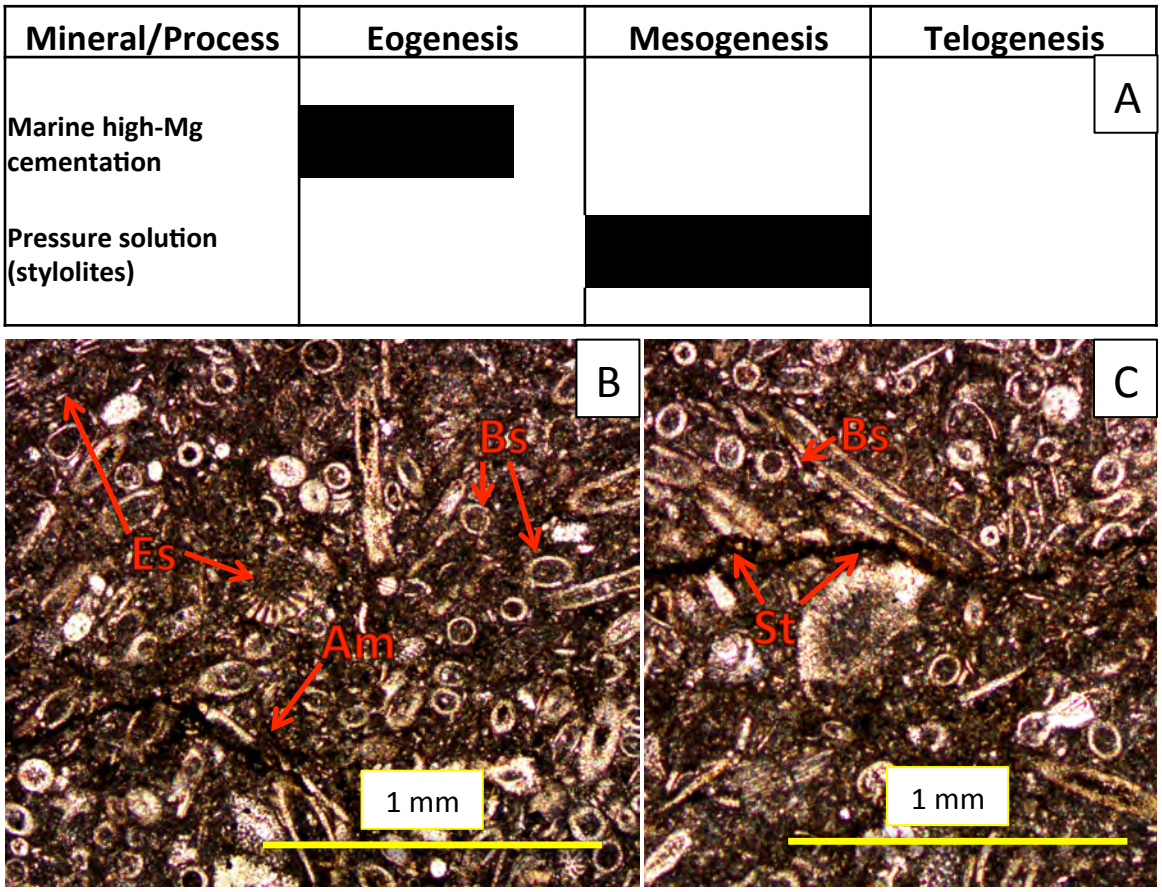


Figure 47: Sequence Three TST Paragenesis: A) Paragenesis overview. B) 4X PPL view of sample SP-8.8.13-7 showing echinoderm (Es) and brachiopod (Bs) spines that are oblate-shaped framework grains, and have been hydrodynamically sorted parallel to bedding.

stresses caused orthosilicates to rotate perpendicular to net stresses creating stylolites (Aharonov and Katsman, 2009) (Figure 47).

Highstand Systems Tract

Sequence three HST is composed of carbonate lithofacies CFss, CMa, CWeb and WSab. This assemblage of lithofacies is entirely located below fair weather wave base, and hence meteoric weathering is not interpreted to be a factor throughout diagenesis. Upon deposition, fenestral porosity developed within stromatoporoids encrusting framework grains. Stromatoporoids' siliceous skeleton broke down, silicified framework grains, and occluded pore space (Henderson, 1984) (Figure 48). Penecontemporaneously, an early seafloor high-Mg calcite, dog's tooth cement filled in pore space followed by a mesogenetic blocky calcite cement. During burial, lithostatic stress produced stylolites parallel to bedding in argillaceous intervals. Upon uplift, this interval experienced fracturing, and subsequent infilling with calcite cement (Figure 46). Carbonate depositional environments representing sequence three HST were poisoned by the siliciclastic shoreface environments of sequence three FSST that prograded into the Sappington basin (Figure 48).

Falling Stage Systems Tract

Sequence three FSST is composed of lithofacies Ssw, Fsm, Sr, Sl, and CGio. Apparent in all samples of sequence three FSST are the occurrence of quartz overgrowths around quartz grains that have apparently been fragmented from a previously quartz-cemented sedimentary rock (Figure 49).

Figure 48: Sequence Three HST Paragenesis

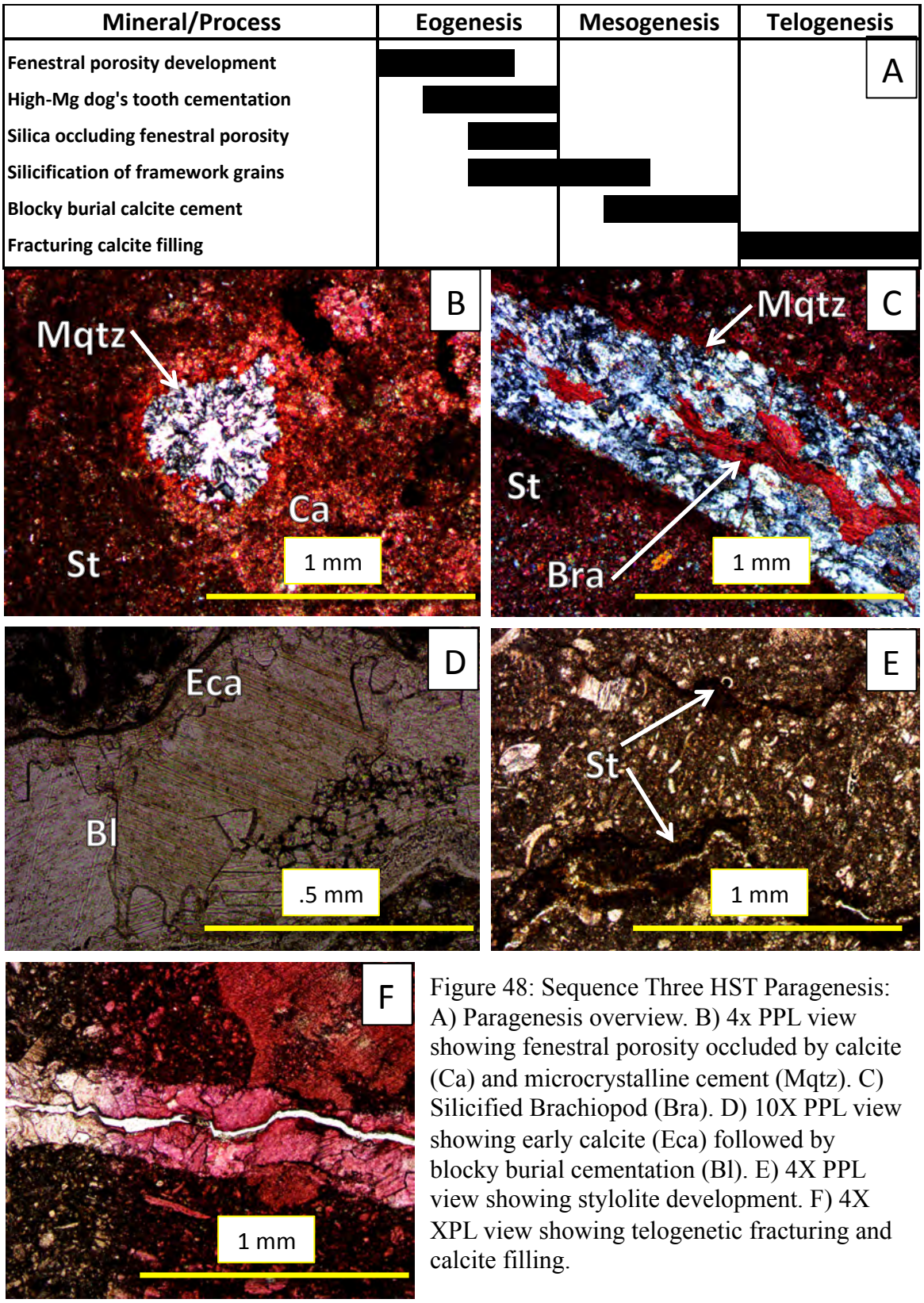


Figure 48: Sequence Three HST Paragenesis: A) Paragenesis overview. B) 4x PPL view showing fenestral porosity occluded by calcite (Ca) and microcrystalline cement (Mqtz). C) Silicified Brachiopod (Bra). D) 10X PPL view showing early calcite (Eca) followed by blocky burial cementation (Bl). E) 4X PPL view showing stylolite development. F) 4X XPL view showing telogenetic fracturing and calcite filling.

Figure 49: Sequence Three FSST Paragenesis

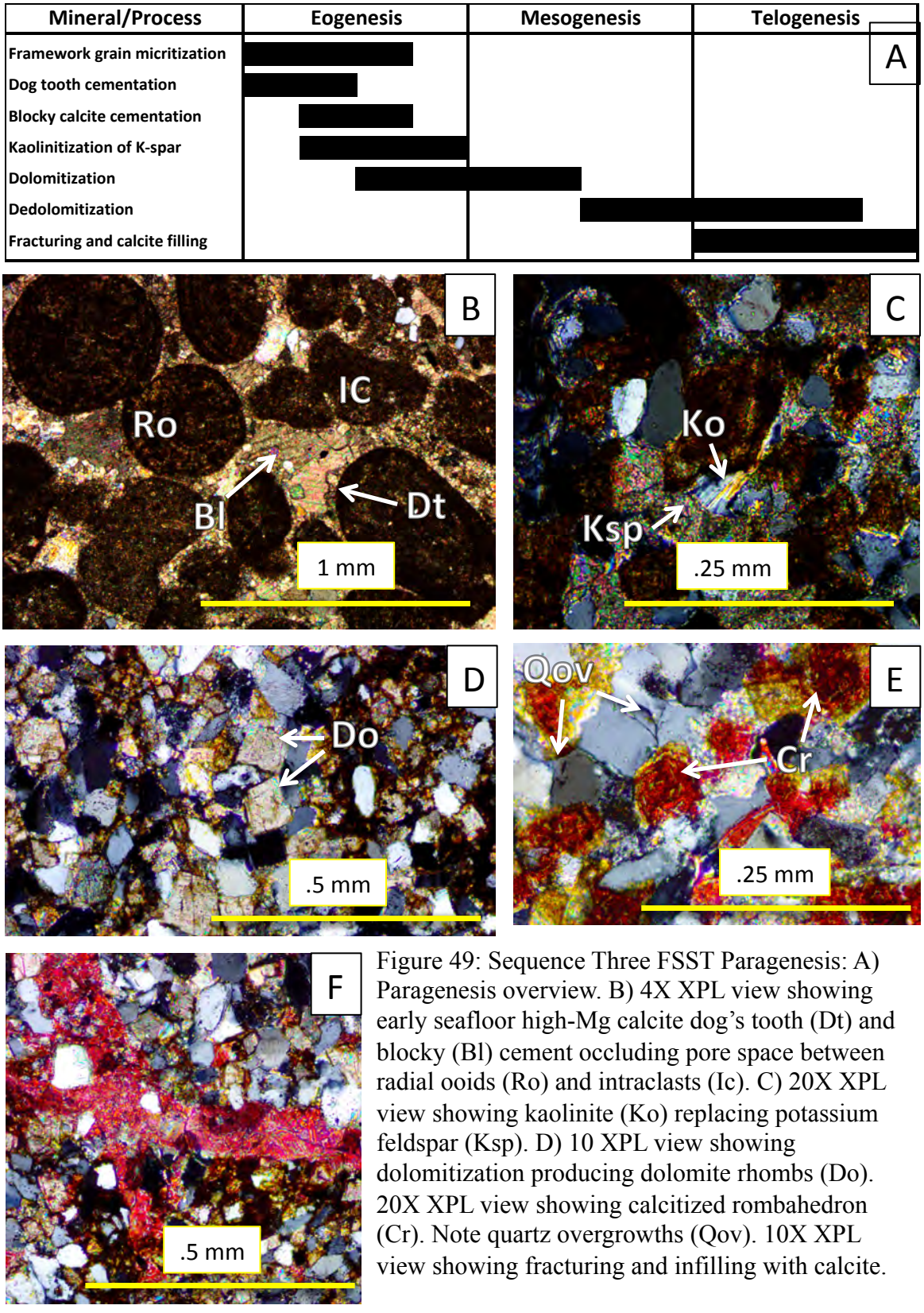


Figure 49: Sequence Three FSST Paragenesis: A) Paragenesis overview. B) 4X XPL view showing early seafloor high-Mg calcite dog's tooth (Dt) and blocky (Bl) cement occluding pore space between radial ooids (Ro) and intraclasts (Ic). C) 20X XPL view showing kaolinite (Ko) replacing potassium feldspar (Ksp). D) 10 XPL view showing dolomitization producing dolomite rhombs (Do). 20X XPL view showing calcitized rombahedron (Cr). Note quartz overgrowths (Qov). 10X XPL view showing fracturing and infilling with calcite.

Sequence three FSST experienced several generations of cementation, the first of which occurred in the eogenetic regime. Lithofacies CGio indicates an ooid shoal depositional environment in the stratigraphically highest parasequence that experienced two generations of eogenetic cementation: isopachous dog tooth cementation followed by blocky calcite cementation (Figure 49). Both types of cement are associated with early marine and marine phreatic cementation (Flügel, 2004, p. 294-295). These two generations of cement occluded pore space in facies CGio, creating a permeability barrier that did not allow for later dolomitization that is observed in permeable siliciclastic intervals.

Siliciclastic intervals experienced kaolinitization of unstable potassium feldspar grains. This process may have been induced during maximum normal regression of relative sea level, and a brief incursion of meteoric waters (Worden and Morad, 2003). Euhedral dolomite rhombohedrons may have formed during this period of maximum sea level regression by mixing zone dolomitization processes (Morad et al., 1998). Alternatively, dolomitization may have occurred in a burial environment where an excess of magnesium within pore waters (Boggs, 2009, p. 402-403). Following dolomitization, a period where pore waters favored the stability of calcite ensued likely in the telogenetic regime. This period saw previously-precipitated dolomite rhombohedrons replaced by calcite as evident from alizarin red staining (Figure 49). Concurrently, HST B experienced a period of fracturing, and filling with calcite spar.

Sequence Four

Sequence four TST and a HST are diagenetically interpreted together, and are shown in figure 50. Lithofacies composing sequence three include Ssw, Fml, Fmo, and Cweb. Similar to sequence four TST, a rise in relative sea level caused lowered siliciclastic dilution of organic material, resulting in an organic-rich rock. Interbedded with organic rich layers is lithofacies Ssw that dominates petrographic interpretation. Lithofacies Ssw in this interval is less mature than previously encountered sandstones, possibly owing to a lesser degree of reworking and compositional maturation. This facies shows early sea floor calcite cementing quartz grains, yet not completely occluding pore spaces (Figure 50). The HST deposit of sequence four does indicate complete occlusion of pore space by blocky calcite cementation, owing to a larger supply of carbonate material (Morad et al., 2010).

This occlusion of pore space in the carbonate HST deposit did not allow for later fluid movement and subsequent dolomitization, as did the remaining pore space in the siliciclastic TST intervals. The lower degree of compositional maturity associated with lithofacies Ssw lead to kaolinitization of feldspar grains (Worden and Morad, 2003). Finally, dolomite rhombohedrons are replaced by calcite upon uplift as indicated by characteristic dolomite rhombohedrons stained with alizarin red (Figure 50).

Summary

The Devonian-Mississippian system of western Montana shows a distinctive diagenetic evolution framed within a sequence stratigraphic framework. Porosity has

Figure 50: Sequence Four TST and HST Paragenesis

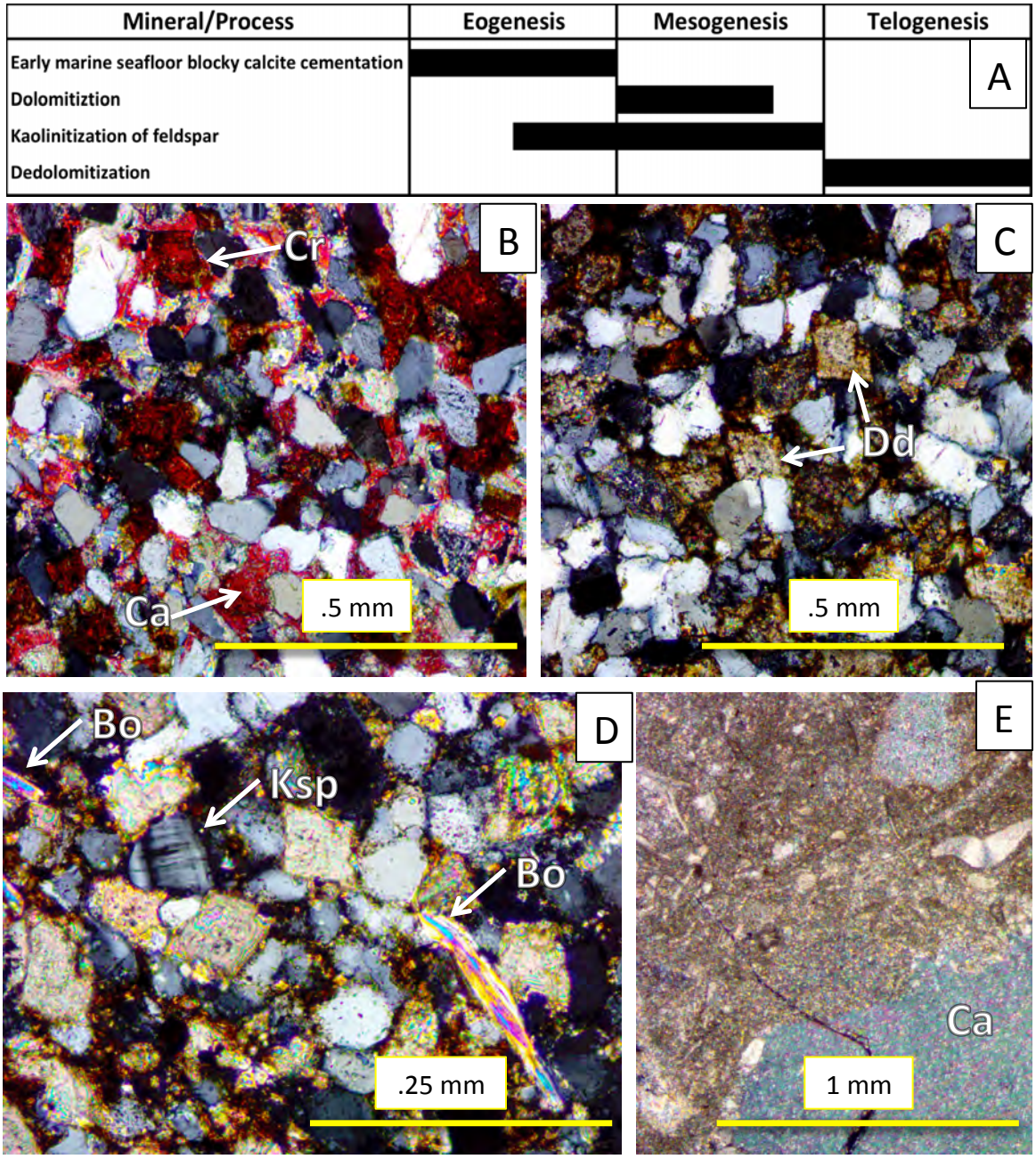


Figure 50: Sequence Four TST B Paragenesis: A) Paragenesis overview. B) 10X XPL view of sample AV-8.20.13-9 showing early seafloor blocky calcite cementation (Ca), and telogenetic dedolomitization shown by red calcite rohmbahedron (Cr). C) 10X XPL view of sample AV-8.25.13-2 showing deolomitization (Dd). D) 20X view of sample MC-8.10.13-6 showing a qualitatively lower-maturity sandstone than observed in the HST of sequence three, indicated by biotite (Bo) and potassium feldspar (Ksp) indicate a lower maturity. E) 4X XPL view of sample AV-8.20.13-11 showing calcite framework grains suspended in a microcarbonate matrix, and early marine blocky calcite cementation (Ca) that has completely occluded pore space.

been largely occluded by multiple generations of carbonate cement throughout all regimes of diagenesis. The most pervasive porosity destruction is interpreted to occur during the eogenetic and mesogenetic stages, including high-Mg calcite dog's tooth, blocky mosaic calcite, and finally dolomite cement.

CHAPTER 6 – SUMMARY AND CONCLUSIONS

The combined affects of regional eustatic sea level change (Moerner, 1981) and tectonic movements dictated by basement lineaments are the two main factors interpreted to have controlled sedimentary distribution during the Late Devonian to Early Mississippian strata in western Montana. Overall, the sequence stratigraphic interpretation is similar to that of other authors (Smith and Bustin, 2000; Nagase, 2014), although differs in some aspects.

Interpretation of this project is biased towards stratigraphy, and spatially biased to the Sappington basin. Stratigraphic architecture supplies the preponderance of data for this study, and interpretation relies highly on stratigraphic concepts. This project did not incorporate a large amount of structural interpretation. For example, cross sections have been projected along strike to assumedly achieve a spatially accurate depiction during deposition. However, this step was taken without restoring the structural configuration of the basin, which may change the sequence stratigraphic interpretation. Assumptions such as these may be sources of error, and discount the value of conclusions drawn.

Additionally, interpretations are highly derivative from the Sappington basin, as the highest resolution data—outcrop—is encountered here. Interpretations derived here were then extrapolated to geophysical well logs. This technique, while very pragmatic, presents a number of uncertainties. Geophysical well logs are by definition derivative; they record one aspect of a rock body, and are non-unique. Sedimentary structures or diagenetic alterations are not able to be discerned, and thus may be inaccurately extrapolated from outcrop. However, sequence stratigraphic concepts have been

demonstrated to enable correlation between outcrop and geophysical logs (Van Wagoner et al., 1990).

Although uncertainty exists, this study finds that overall the Late Devonian to Early Mississippian strata in western Montana indicate a long term eustatic relative sea level fall followed by a long-term eustatic relative sea level rise that is overprinted by third-order sequences as well as tectonic movements. Maximum relative sea level fall resulted in rejuvenation of siliciclastic source terrains, and propagation of the Acadian unconformity. Long term base level rise resulted in return to carbonate deposition that is typical of Paleozoic Laurentia. Third order sequences (Vail et al, 1977) identified and mapped in this study overprint this longer term relative sea level movement.

Stratigraphic distribution is in part controlled by structural features. Tectonic elements controlling sediment distribution include the Beartooth shelf, Pendroy fault zone, Sappington basin, and WCSB. The Beartooth shelf was likely a paleo high during deposition of sequence three, as outcrop analysis indicates increasing depositional energy associated with increasingly shallower water depths towards the Beartooth shelf, although the nature of the Pendroy fault zone remains unclear due to a lack of outcrop data near this area. Sedimentary architecture is defined as the combination of deposition and preservation. Thus it is possible that the Pendroy fault zone may have been a paleo high during deposition or may have been subsequently uplifted, and eroded material in this area. The Pendroy fault zone paleo high may be an early manifestation of the Mississippian Central Montana uplift (Woodward et al., 1997). The Sappington basin appears to be early manifestation of the Mississippian central Montana trough, and is

likely controlled by Precambrian a basement lineament between the Medicine Hat and Wyoming basement provinces (Dorobeck et al., 1991). The WCSB is a persistent sedimentary basin throughout much of the Paleozoic, the most distal reaches of which are defined by the Prophet trough (Sandberg, 1988).

The sequence stratigraphic interpretation provides a framework from which to predict reservoir properties. Porosity throughout the studied interval has been demonstrated to be largely occluded by a number of carbonate cement generations. Although in some cases it is nebulous which cement generations may be generated in which regime, petrographic analysis indicates pore space was largely occluded during eogenetic and mesogenetic regimes, with subordinate occlusion in the telogenetic regime. This distinction has important implications for reservoir properties, as cement generated during the telogenetic regime would not exist in the subsurface. Differentiation of cement generation timing may be somewhat achieved by the use of cathodoluminescence techniques, but is beyond the scope of this project.

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APPENDICES

APPENDIX A

CORE AND OUTCROP SECTIONS

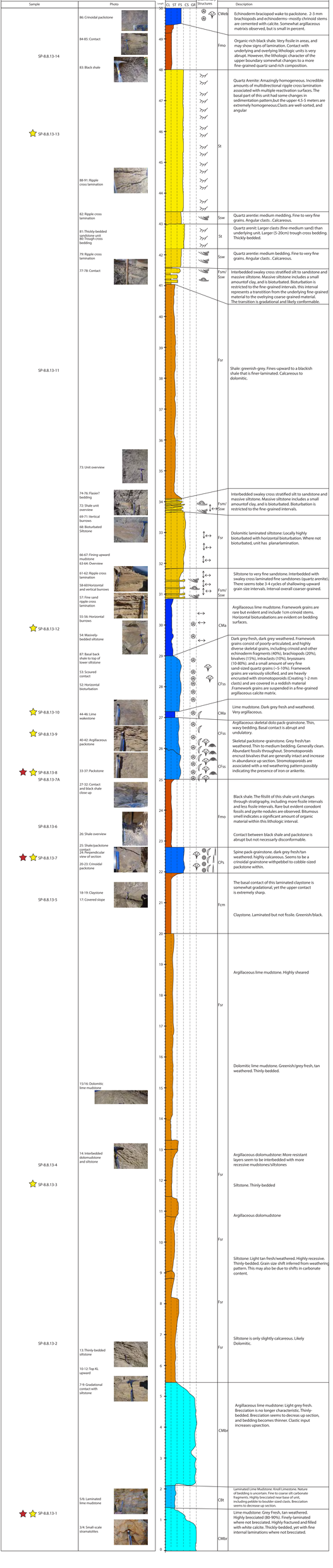
Outcrop Name: Moose Creek	Outcrop Location: NE 1/4, NW1/4, S9, T6S, R5E	Outcrop Length: 25 M.

MS WS PS GS BS
CL ST FS CS GR
Sedimentary Structures
Length

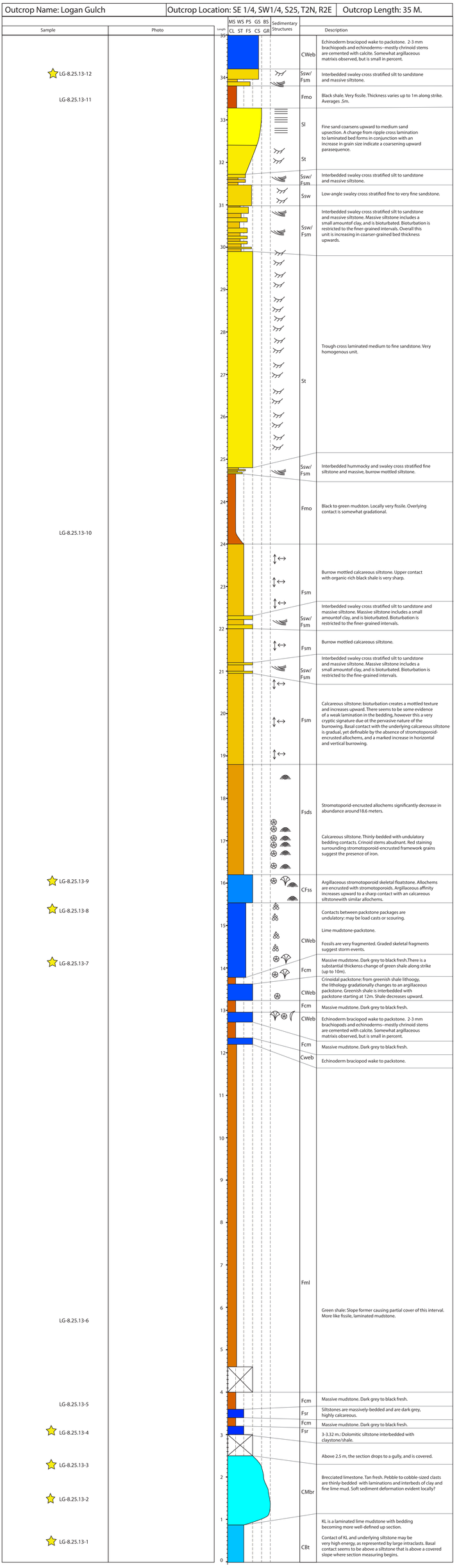
Sample	Photo	Description
		CWeb: Echinoderm braciopod wake to packstone. 2-3 mm brachiopods and echinoderms--mostly chrinoid stemss are cemented with calcite. Somewhat argillaceous matrix is observed, but is small in percent.
MC-7.27.13-12		Fsm/Ssw: Multidirectional swaley cross stratified silt to very-fine sandstone interbedded with massive (often horizontally and vertically biotrubated) silt- to mudstone. There is an initial abundance of swaley cross stratified siltstone at the base, with a systematic increase towards the center of this unit, then a slight increase towards the top.
MC-8.10.13-6		
MC-7.27.13-11		
MC-7.27.13-10		Sl: Parallel laminated medium quartz arenite. Quartz framework grains are cemented with a calcite cement, and are strongly parallel laminated, and dipping in one dominant direction at about 4-5 degrees. Bioturbation is absent. Overlying contact is extremely abrupt, bud does not appear to be scoured.
		St: Trough cross bedded fine-medium quartz arenite. multidirectional trough cross bedding with evidence of reactivation surfaces throughout. Planar tabular stratification is evident, but rare. Bioturbation is absent.
MC-8.10.13-5		CGoi: Oolitic grainstone. Parallel lamination. Allochems are composed of ooids, and intraclasts. Small amount of silt-sized quartz present.
MC-7.27.13-9	43-45: Planar laminated upper siltstone	Massive mudstone. This bed varies in preservation along strike and seems to be erosional in nature.
MC-8.10.13-4	40: Upper siltstone overview 39: Sample MC-8.10-13-4	
	38: Sample MC-8.10.13-3	
MC-8.10.13-3	31-33: Bioturbation	Fsm/Ssw: Multidirectional swaley cross stratified silt to very-fine sandstone interbedded with massive (often horizontally and vertically biotrubated) silt- to mudstone. There is an initial abundance of swaley cross stratified siltstone at the base, with a systematic increase towards the center of this unit, then a slight increase towards the top.
MC-8.10.13-2	30: Subcritical ripples 28-29 Parasequence overview	
	27: Ravinement surface	Fsm: Massively-bedded siltstone with strange pits (horizontal bioturbation?). Very well sorted. Abrupt boundary on top of unit seems to be slightly scoured.
MC-7.27.13-8	26: Well-sorted fine sandstone (top of parasequence 25: Massively-bedded siltstone with pits 25: 2 Parasequences?	Ssw/Fsm: Interbedded swaley cross stratified silt to sandstone and massive siltstone. Massive siltstone includes a small amount of clay, and is bioturbated. Bioturbation is restricted to the fine-grained intervals.
MC-7.27.13-7	24: Sand body 23: Highly biturbated very fine sandstone 22: Black lime wakestone	Fsm/Fcm: Fine-very fine sandstone and massive mudstone/ claystone. Siltstone intervals are highly biotrubated and show a systematic increase in grain size upward.
		CFsr: Stromotoporoid rugose, echinoderm, barachiopod floatstone. Large clastic increase at 17.5 m.
		CMa: Argillaceous lime mudstone
		CFsr: Stromotoporoid rugose, echinoderm, barachiopod floatstone. Fossil suite remains consistant, however abundance and articulation decrease from 16m to 17.5 m.
MC-7.27.13-6		
	18-21: Overview and articulated fossils	CMa: Argillaceous lime mudstone
		CWeb: Brachiopod, crinoid, rugose wake to packstone
MC-8.10.13-7		CMa: Argillaceous lime mudstone
		CWeb: Carbonate affinity and fossil articulation increases up section. New allochems observed include 2-4 cm. rugose corals
		CMa: Argillaceous lime mudstone
MC-7.27.13-5		CWeb: Wakestone: Clasts up to pebble size. Fossils are hydronamically sorted into planar beds. This unit may represent descreet turbidite events that are shed from a distal reef complex. Allochem include brachiopods (~50%), crinoid stems (~40%), and bivalve tests (~10%).
	17: Packstone event bed	CMa: Lime mudstone. Dark grey fresh and weathered. Very argillaceous.
MC-8.10.13-8		Fsds: Massively bedded stilstone: possibly a transgressive systems tract where fines from Antler allochthon are shed into a deep basin, and coarse sediment fragment is deposited updip.
	13-16: Bioturbation	Fsmgo: High frequencey graded bedding with organic material. Highly bioturbated. Critters likely mining organic material at base of graded beds.
MC-7.27.13-4	12:Iron Concretion	Fsds: Siltstone: White to tan. Massively bedded. very well sorted. Iron concretions near fractured areas. Slightly fossiliferous (about 5%). Iron concretions form around bivalve and other fossils .
MC-8.10.13-1	11: Breccia pipe	
	10: Well-sorted siltstone	Iron concretions are concentrated in the bleached areas (breccia pipes?), and seem to be controlled by the degree of fracturing (fluid flow?).
MC-7.27.13-3		
	8-9: Contact- Possible sequence boundary	Contact is very abrupt. Both upper and lower areas of contact seem to be altered by fluid flow. Upper limestone is higly oxidized which may indicate subaerial exposure, and subsequent presence of a sequence boundary. Contact is undulatory along strike with up to 1m of relief.
	6-7: Finely-laminated lime mudstone	Brecciation is observed along strike, and does not seem to be systematically increasing or decreasing. Beccia clasts are pebble to boulder-sized and seem to be composed of the host rock. In other words, they seem to be insitu.
		Laminations seem to becoming finer upsection
MC-7.27.13-2		Finely-laminated lime dolomudstone
	4-5: Knoll Limestone outcrop overview	
		CBt: Fine laminations throughout.
	2: Boulder-sized breccia clasts	
		Laminated Lime Mudstone: Knoll Limestone. Nature of bedding is uncertain. Fine to coarse silt carbonate fragments. Highly brecciated near base of unit, including pebble to boulder sized clasts. Brecciation seems to decrease up section.
MC-7.27.13-1		CMbr: About 90-95% carbonate/10% angular brecciated clasts

Covered Slope

Outcrop Name: Sacajawea Peak	Outcrop Location: SE 1/4, SE1/4, S21, T2N, R6E	Outcrop Length: 50 M.



Outcrop Name: Logan Gulch	Outcrop Location: SE 1/4, SW1/4, S25, T2N, R2E	Outcrop Length: 35 M.



Outcrop Name: Antelope Valley	Outcrop Location: NE 1/4, NE1/4, S2, T1S, R2W	Outcrop Length: 43 M.

MS WS PS GS BS CL ST FS CS GR

Sample	Photo	Sedimentary Structures	Description
AV-8.20.13-11 AV-8.20.13-9	100-1104. Sandstone/Limestone contact	CWlrb	Echinoderm bracioopd wake to packstone. 2-3 mm brachiopods and echinoderms--mostly chrinoid stems are cemented with calcite. Somewhat argillaceous matrixis observed, but is small in percent. Basal contact is very sharp.
		Ssw/ Fsm	Interbedded swaley and microhummocky cross stratified fine to very fine sandstone and massive calcareous siltstone. Siltstone is highly bioturbated, and often vertically penetrates bed boundaries.
AV-7.29.13-7		St	
AV-8.20.13-10			Trough cross bedded calcareous fine to medium quartz arenite. Extremely homogenous. Trough cross bedding dominates with common reactivation surfaces. Planar tabular lamination is event, yet rare. Basal contact is
			Interbedded swaley cross stratified fine to very fine calcareous siltstone. Overall, this unit seems to be systematically decreasing in grain size.
		Ssw	Dominantly swaley cross stratified fine to very fine calcareous sandstone with minor micro hummocky cross stratification.
		Ssw/ Fsm	Fine sandstone. Slightly Smaller grain size than areas stratigraphically adjacent (very fine sandstone).
	100-1100. RCL and laminated sandstone 100-1104. Coarsening upward sand package	Ssw	Dominantly swaley cross stratified fine to very fine calcareous sandstone with minor micro hummocky cross stratification.
		St	Trough crossbedded fine to very fine sandstone.
AV-7.29.13-6 AV-8.20.13-8	100-1095 Low angle trough cross bedded	Ssw	Swaley cross stratified fine to very fine calcareous sandstone.
		Ssw/ Fsm	Swaley cross stratified fine to very fine calcareous sandstone interbedded with highly bioturbated calcareous siltsone.
		Ssw	Swaley and hummocky cross stratified fine to very fine calcareous sandstone. This interval shows a systematic increase in grain size up section, yet sedimentary structures remain constant. Basal contact with the laminated mudstone is highly abrupt, but does not seem to be scoured.
		Fmsl	
	100-1092. Greenish grey shale		
AV-8.2.13-7			Greenish-grey shale. This has been sampled in previous outings
		Fsm	Calcareous siltstone. Highly bioturated
	100-1090. Bioturbated HF Sandstone	Ssw/ Fsm	Discreet 1 cm beds of hummockky and swaley cross stratification interbedded with highly bioturbated calcareous siltstone.
	100-1089. Bioturbated siltstone		
AV-8.2.13-6		Fsm	Calcareous siltstone: bioturbation creates a mottled texture and increases upward. There seems to be some evidence of a weak lamination in the bedding, however this a very cryptic signature due ot the pervasive nature of the burrowing.
			Calcareous siltstone. Bioturbation seems to be absent at the basal contact, yet increases upward. Clastic influence has led to the decline of the carbonate factory by 20.5 m.
AV-8.20.13-7 AV-7.29.13-5	100-1087. Silty packstone		
	100-1086. Mudstone Event bed	CFss	Clastic influence seems to increase upsection. Skeletal wakestone: Stromotoporoid encrusting less abundant upsection. Fossil abundance/size/ articulation decrease upsection.
AV-7.29.13-4 AV-8.20.13-6		CMa	Lime mudstone. Dark grey fresh and weathered. Very argillaceous.
AV-8.20.13-5	100-1085. Skeletal packstone	CFss	Skeletal Packstone. Framework grains consist of dominantly 1-3 cm crinoids stem fragments, bivalve tests and brachiopod tests. Many of the framework grains are encrusted with stromotoporoids. A reddish residu is associated with stromotoporoids, as well as silicification of framework grains- brachiopod tests in particular. Fossil abundance and articulation increasing upward, yet remains constant.
AV-7.29.13-3 AV-8.20.13-4 AV-8.2.13-5	18.5m		
AV-8.20.13-3	100-1082. Clay/limestone contact		Skeletal wakestone.
AV-8.2.13-4		Fmo	Black shale. Slightly reddish. Contact with overlying unit is quite abrupt. Pyrite nodules and radiating fingers throughout intervals evident, but not common.
			Green shale. Slope is partially covered.
	100-1081. Claystone		Green Shale. Partially covered slope
		Fmsl	
AV-8.2.13-3	100-1080. Siltstone/claystone contact		
AV-8.20-13-2			Green shale. Contact with underlying siltstone is gradational.
		Fsr/ Fcm	Siltstone: Same as below, but clay laminations begin to become relevant and increase in frequencey and volume up section
	100-1079. Clay beds in top of siltstone package 100-1078. Basal siltstone	Fsr	Siltsone: Tan fresh/tan weathered. Light red spots (1-2 cm and elongate) may indicate burrows. Weathering seems to indicate thin bedding, yet appears massive in other areas. Equivalent to siltstone at Moose Creek? Should be be basal sequence boundary.
AV-7.29.13-2			
AV-8.2.13-2 AV-8.20.13-1			
			Covered slope.
		CBt	
		CMbr	Lime mudstone: Grey Fresh, tan weathered. Highly brecciated (80-90%). Finely-laminated where not brecciated. Highly fractured and filled with white calcite. Thickly-bedded, yet with fine internal laminations where not brecciated.
AV-8.2.13-1		CBt	Laminated Lime Mudstone: Knoll Limestone. Nature of bedding is uncertain. Fine to coarse silt carbonate fragments. Highly brecciated near base of unit, including pebble to boulder sized clasts. Breccuation seems to decrease up section.
		CMbr	

Outcrop Name: Lone Mountain	Outcrop Location: SW 1/4, SE1/4, S5, T4N, R1W	Outcrop Length: 11 M.

Sample	Photo	Length	MS WS PS GS BS / CL ST FS CS GR	Sedimentary Structures	Description
	100-1002 to 100-1003: Crinoidal packstone and contact 100-1001: Ripple cross lamination	11		CWeb	Echinoderm braciopod wake to packstone. 2-3 mm brachiopods and echinoderms--mostly chrinoid stems are cemented with calcite. Somewhat argillaceous matrixis observed, but is small in percent.
LM-8.14.13-5	100-0999: Scoured contact 100-1000: Lenticular bedding 100-0996 to 100-0998: Planar lamination	10		Ssw	Basal contact appears to be scoured. Swaley cross stratified fine to very fine sandstone.
LM-8.14.13-1	100-0994 to 100-0995: Overview			Ssw/ Fsm	
LM-8.14.13-2		9		Fsm	Thinly-bedded siltstone. Very discontinuous.
				Ssw	Well-sorted very fine sand-sized hummocky cross stratified limey sandstone.
LM-8.14.13-4				Fsm	Thinly-bedded lime siltstone. Coarsens upward. Highly bioturbated.
	100-0990 to 100-0993: Well-sorted fine sandstone and sedimentary structures	8		Ssw	Swaley cross stratified fine to very fine sandstone.
	100-0988 to 100-0989: Thinly bedded siltstone and bioturbation			Fsm	Calcareous siltstone: bioturbation creates a mottled. There seems to be some evidenceof a weak lamination in the bedding, however this a verycryptic signature due ot the pervasive nature of the burrowing.
	100-0987: Thinly bedded lime siltstone	7			Covered slope.
LM-8.1.13-3		6		Ssw	Fine-very fine quartz arenite. Low angle swaley cross bedding. Medium Bedding. Trough cross bedding goes in two directions indicating tidal influence.
	100-0985 to 100-0986: Fine to very fine sand quartz arenite				
LM-8.14.13-3		5			Covered slope.
	100-0983: Burrows 100-0982: Unit overview	4			
				Fsm	Thinly-bedded caclitic very fine sandstone. This unit becomes more calcic upsection and the mud fraction decreases. Sed Structures of small-scall trough cross bedding increases upsection
	100-0978 to 100-0981: Burrows	3			
LM-8.1.13-2	100-0982: Small-scale trough cross bedding 100-0978: Very fine siltstone	2			
				Fsr	Thinly-bedded dolomitic siltstone. Dark grey fresh, tan to whiteish grey weathered. Thin beds seem to be separated by fine laminations of finer material.
	100-0997: Laminated dolomitic siltstone	1			
LM-8.1.13-1		0			

APPENDIX B

PETROGRAPHY SPREADSHEET

Petrography Excel Sheet

Thin Section	Sequence Strat Body	Lithofacies	Framewok Grains																					Cement Types															Diagenetic Features								
			Skeletal											Non-Skeletal										Silica			Carbonate																			
																											Crystal Size			Cement Type																	
			Spines (brachiopod/echioderm	Mollusc (undifferentiated)	Crinoids	Echinoderm (undifferentiated)	Bryozoa	Rugose Coral	Brachiopod	Cyanobacteria	Encrusting Stromotorporids	Amorphous Organic Matter	Intraclasts	Peloids	Radial Ooids	Concentric Ooids	Clay	Quartz	Feldspar	Lithics	Micas	Opaques	Overgrowth	Chalcedony	Microcrystalline	Micritic	Microspar	Spar	Drusy	Fibrous	Botryoidal	Dog Tooth	Blocky	Granular	Microcrystalline	Radiaxial	Dolomitization	Dedolomitization	Stylolites	Neomorphism	Clay infiltration	Calcite-Filled Fracture	Kaolinite replacing K-Spar	Siliscification	Qtz. Overgrowth
MC-7.27.13-11	SEQ 4 TST	Fsm																																												
MC-8.10.13-6	SEQ 4 TST	Fsm																																												
MC-8.10.13-12	SEQ 4 TST	Fsm																																												
MC-7.27.13-12	SEQ 4 TST	Fsm																																												
LG-8.25.13-12	SEQ 4 TST	Fsm																																												
AV-8.20.13-9	SEQ 4 TST	Fsm																																												
AV-8.20.13-11	SEQ 4 HST	Cweb																																												
SP-8.8.13-13	SEQ 3 HST B	St																																												
MC-8.10.13-3	SEQ 3 HST B	Ssw																																												
MC-8.10.13-2	SEQ 3 HST B	Ssw																																												
MC-7.27.13-9	SEQ 3 HST B	Cgoi																																												
MC-7.27.13-8	SEQ 3 HST B	Fsm																																												
MC-7.27.13-7	SEQ 3 HST B	Fsm																																												
MC-7.27.13-10	SEQ 3 HST B	Sl																																												
AV-8.20.13-8	SEQ 3 HST B	Ssw																																												
AV-8.20.13-10	SEQ 3 HST B	St																																												
LM-8.14.13-5	SEQ 3 HST B	Ssw																																												
LM-8.14.13-4	SEQ 3 HST B	Ssw																																												
LM-8.14.13-3	SEQ 3 HST B	Fsm																																												
LM-8.14.13-1	SEQ 3 HST B	Ssw																																												
LM-8.14.13-2	SEQ 3 HST B	Ssw																																												
MC-8.10.13-7	SEQ 3 HST A	Cweb																																												
MC-7.27.13-6	SEQ 3 HST A	CFsr																																												
SP-8.8.13-9	SEQ 3 HST A	CFss																																												
SP-8.8.13-8	SEQ 3 HST A	CFss																																												
SP-8.8.13-12	SEQ 3 HST A	Cma																																												
SP-8.8.13-10	SEQ 3 HST A	CFss																																												
LG-8.25.13-9	SEQ 3 HST A	CFss																																												
LG-8.25.13-8	SEQ 3 HST A	Cweb																																												
LG-8.25.13-7	SEQ 3 HST A	Cweb																																												
AV-8.20.13-7	SEQ 3 HST A	Fsr																																												
AV-8.20.13-4	SEQ 3 HST A	CFss																																												
AV-8.20.13-5	SEQ 3 HST A	CFss																																												
SP-8.8.13-7	SEQ 3 TST	CPs																																												
MC-8.10.13-1	SEQ 2 HST	Fsds																																												
MC-7.27.13-4	SEQ 2 HST	Fsds																																												
MC-7.27.13-3	SEQ 2 HST	Fsds																																												
LG-8.25.13-4	SEQ 2 HST	Fsr																																												
SP-8.8.13-8	SEQ 3 HST	CFss																																												
MC-7.27.13-2	SEQ 1 HST	CBt																																												
MC-7.27.13-1	SEQ 1 HST	CMbr																																												
LG-8.25.13-3	SEQ 1 HST	CBt																																												
LG-8.25.13-2	SEQ 1 HST	CBt																																												
LG-8.25.13-1	SEQ 1 HST	CBt																																												
AV-8.20.13-1	SEQ 1 HST	Fsr																																												

APPENDIX C

ALPHA WELL INFORMATION

UWI (APINum)	Well Name	County	Township	Range	Section	NISKU FM.	POTLATCH ANHYDRITE	LOGAN GULCH MBR.	TRIDENT MBR.	LOWER SHALE TONGUE	SAPPINGTON FM.	COTTONWOOD CANYON MBR.	SEQ1	SEQ2	SEQ3	SEQ3 MFS1	SEQ4 BOUND	SEQ4 MFS
25005050010000	GOVT	BLAINE	26N	20E	23	5312	5319	5307	5235	5230			5312	5307	5235	5230	5230	
25005050020000	FT BELKNAP	BLAINE	28N	23E	3	4609	4562	4538	4535	4529	4515	4506	4609	4538	4535	4529	4515	4506
25005050170000	SAVOY	BLAINE	31N	24E	26	4674	4635	4614	4607	4598	4568	4560	4674	4614	4607	4598	4568	4560
25005052270000	N CHINOOK UNIT	BLAINE	35N	19E	16		4983	4966	4944	4935	4915			4966	4944	4935	4915	
25005210410000	KUHR	BLAINE	29N	19E	14	887	877	869	821	781			887	869	821	781	781	780
25005211020000	DEHLBOM	BLAINE	30N	18E	3	4852	4791	4784	4744	4744			4852	4784	4744		4744	4741
25005213760000	STATE	BLAINE	29N	21E	10	3179	3141	3134	3108	3108	3096		3179	3134	3108		3096	3092
25005214200000	SONNENBURG LENA	BLAINE	34N	19E	24	5070	5009	4993	4981	4972	4954		5070	4993	4981	4972	4954	4953
25005218910000	KELLER	BLAINE	28N	18E	19	4955	4894	4882	4844	4844			4955	4882	4844		4844	4842
25005221900000	SANFORD	BLAINE	24N	18E	33	5162	5169	5160	5120	5120			5162	5160	5120		5120	5117
25005225370000	GARDINER	BLAINE	32N	21E	33	4628	4696	4675	4656	4656	4632			4675	4656		4632	4629
25005233100000	STATE	BLAINE	37N	20E	36	5500	5445	5428	5406	5394	5368			5428	5406	5394	5368	5367
25013210010000	STATE `G`	CASCADE	20N	3W	36	4063	3927	3910	3870	3863	3851	3846	4063	3910	3870	3863	3851	3846
25013210020000	NEUMAN RANCH ETAL	CASCADE	22N	2E	31	2625	2506	2487	2457	2451	2441		2625	2487	2457	2451	2441	
25013210030000	SMELSER-UTP	CASCADE	22N	1E	22		2645	2633	2600	2589				2633	2600	2589	2589	
25013210100000	ANDERSON	CASCADE	20N	2E	33	2039	1934	1917	1890	1882	1869		2039	1917	1890	1882	1869	1868
25013210190000	GOLLAHER	CASCADE	17N	2E	18	2675	2549	2528	2512	2500	2472	2469	2675	2528	2512	2500	2472	2469
25013210290000	ANDERSON-HOVELAND	CASCADE	20N	2E	15	2144	2058	2025	2004	1997	1980		2144	2025	2004	1997	1980	1977
25013210380000	FRANTZICH	CASCADE	19N	4E	15	1754	1694	1681	1656	1650	1636		1754	1681	1656	1650	1636	1634
25013210430000	XD FRIEDMAN	CASCADE	20N	2E	26	2125	2021	1999	1974	1966	1949		2125	1999	1974	1966	1949	1947
25013210470000	HALKOA-HALVAR	CASCADE	19N	4E	22	2036	1999	1989	1950	1937	1918		2036	1989	1950	1937	1918	1915
25013210480000	RSGL PARTNERSHIP	CASCADE	20N	2E	24	2096	1990	1968	1947	1941	1922		2096	1968	1947	1941	1922	
25015210030000	KNUDSON	CHOUTEAU	23N	8E	21	3140	3043	3030	3013	3002				3030	3013	3002	3002	
25015210410000	ONSTAD	CHOUTEAU	26N	4E	34	3369	3275	3256	3213	3209				3256	3213	3209	3209	
25015211280000	HIGGENS	CHOUTEAU	27N	6E	30	3758	3665	3656	3605	3599				3656	3605	3599	3599	
25015214930000	LIPPERT	CHOUTEAU	26N	7E	17	3676	3582	3573	3525	3521			3676	3573	3525	3521	3521	
25015214970000	BIERWAGEN	CHOUTEAU	28N	10E	25		4024	4016	3985	3985				4016	3985		3985	3984
25015215040000	VANDEL FARMS	CHOUTEAU	24N	4E	31	3000	2896	2877	2872	2867	2845	2840	3000	2877	2872	2867	2845	2840
25015215160000	SADA WOODS	CHOUTEAU	27N	3E	21	3260	3184	3170	3121	3117				3170	3121	3117	3117	
25015216220000	TRUNK	CHOUTEAU	23N	14E	29	4205	4167	4159	4137	4133			4205	4159	4137	4133	4133	
25015216290000	HERMAN MAURER	CHOUTEAU	25N	3E	5	3192	3091	3070	3020	3015			3192	3070	3020	3015	3015	
25015216300000	FEDERAL	CHOUTEAU	29N	12E	2		4201	4192	4136	4136				4192	4136		4136	4134
25015216360000	STATE	CHOUTEAU	26N	7E	16	3570	3481	3473	3427	3421			3570	3473	3427	3421	3421	
25015216440000	FEDERAL	CHOUTEAU	29N	11E	10	4184	4102	4094	4048	4048			4184	4094	4048		4048	4046
25015216550000	ONSTAD	CHOUTEAU	25N	4E	22	3138	3034	3014	2979	2979				3014	2979		2979	2977
25015216730000	DANBROOK	CHOUTEAU	24N	12E	32	3796	3728	3718	3705	3699			3796	3718	3705	3699	3699	
25031210020000	MOATS	GALLATIN	2S	6E	1	12215	12180	12154	12135	12130	12055	12049	12215	12154	12135	12130	12055	12051
25031210030000	BRAINARD-B	GALLATIN	4N	4E	26	11321	11289	11244	11215	11209	11143	11137	11321	11244	11215	11209	11143	11137
25035211860000	BLACKFEET TRIBAL	GLACIER	34N	8W	28	6399	6170	6160	6160	6144	6128	6122	6399	6160	6160	6144	6128	6122
25035213790000	BLACKFEET TRIBAL	GLACIER	37N	6W	3	5046	4854	4829	4829	4817	4801	4792		4829	4829	4818	4803	4792
25035214990000	BLACKFEET	GLACIER	37N	8W	19	6170	5947	5933	5933	5927	5914	5908	6170	5933	5933	5927	5914	5908
25035215110000	JOHNSON	GLACIER	37N	9W	12	6146	5906	5895	5895	5887	5877	5862	6146	5895	5895	5887	5877	5862
25035216230000	HYLAND	GLACIER	37N	6W	36	4575	4470	4460	4460	4445	4346		4575	4460	4460	4444	4349	4346
25035216640000	MAGEE	GLACIER	30N	10W	7	9483	9208	9188	9188	9175	9161			9188	9188	9175	9161	9158
25035217600000	SOUTH CUTBANK CREEK	GLACIER	33N	7W	6	5765	5565	5547	5547	5532	5506	5499		5547	5547	5532	5506	5499
25035218420000	MUNTZING	GLACIER	37N	6W	11	4900	4707	4694	4694	4680	4662	4652	4900	4694	4694	4679	4662	4652
25035219680000	TRIBAL	GLACIER	37N	7W	34	5158	4936	4923	4923	4910	4899	4891	5158	4923	4923	4910	4899	4891
25041050770000	R E BAIR	HILL	34N	9E	28	4448	4348	4336	4266	4262	4246		4448	4336	4266	4262	4246	4239
25041051060000	ERICKSON	HILL	36N	15E	12	5101	5035	5028	4943	4943	4921		5101	5028	4943		4921	4918
25041051830000	ROBERT F LANGEL	HILL	37N	9E	18	4502	4384	4370	4314	4311	4292		4502	4370	4314	4311	4292	4291
25041211160000	STATE	HILL	31N	13E	36	4408	4360	4352	4281	4281			4408	4352	4281		4281	4279
25041213070000	BIG G GRAIN FARM	HILL	30N	8E	18	4143	4051	4042	3970	3967			4143	4042	3970	3967	3967	
25041213150000	SIEMENS	HILL	29N	8E	24		3768	3754	3709	3709				3754	3709		3709	
25041221410000	CONWAY	HILL	34N	11E	20	4740	4639	4628	4572	4572			4740	4628	4572	4572	4572	4571
25041223390000	ANDERSON	HILL	30N	9E	2	4384	4290	4279	4220	4216			4384	4279	4220	4216	4216	
25041223580000	STATE	HILL	31N	12E	18	4574	4494	4486	4427	4427			4574	4486	4427	4427	4427	4424
25045050070000	J W DOVER	JUDITH BASIN	12N	14E	19	2531	2542	2526	2482	2475			2531	2526	2482	2475	2475	
25045050310000	DENZILL NOLL	JUDITH BASIN	16N	15E	30	5596	5605	5590	5559	5551			5596	5590	5559	5551	5551	
25045050350000	J W BODNER	JUDITH BASIN	16N	8E	2		1649	1640	1567	1561				1640	1567	1561	1561	
25045210170000	TODD	JUDITH BASIN	17N	14E	32		5120	5110	5079	5074				5110	5079	5074	5074	
25045210180000	SCHYE	JUDITH BASIN	16N	15E	22		5418	5412	5373	5369				5412	5373	5369	5369	
25051051540000	FEDERAL-BLACKJACK	LIBERTY	36N	5E	3	3098	2978	2958	2900	2897	2874			2958	2900	2897	2874	2871
25051216390000	DULL	LIBERTY	37N	4E	24	3130	3010	2993	2933	2930	2911		3130	2993	2933	2930	2911	2910
25051216580000	FEDERAL	LIBERTY	36N	5E	13	3086	2968	2955	2889	2884	2868		3086	2955	2889	2884	2868	2867
25073050030000	INGEBORG BAKKEN	PONDERA	26N	1E	22	3136	3004	2993	2937	2930			3136	2993	2937	2930	2930	
25073050060000	HEMSTAD	PONDERA	26N	2E	20	3147	3024	3011	2960	2952			3147	3011	2960	2952	2952	
25073053170000	HALL	PONDERA	27N	2E	6	3189	3080	3074	2997	2997			3189	3074	2997		2997	
25073054690000	STATE 6444-61	PONDERA	30N	1W	36	3476	3360	3346	3256	3256			3476	3346	3256	3255	3256	3256
25099050060000	DON HADLEY	TETON	22N	2W	12	3154	3023	3004	2968	2958			3154	3004	2968	2958	2958	
25099050140000	STATE	TETON	23N	1W	16	2974	2845	2826	2777	2769				2826	2777	2769	2769	
25099050210000	LEROY A NELSON	TETON	23N	2W	3	3096	2970	2949	2903	2896				2949	2903	2896	2896	
25099050230000	YEAGER	TETON	23N	6W	6	6077	5909	5890	5853	5841	5831		6077	5890	5853	5841	5831	5828
25099050260000	ERICKSON ETAL	TETON	24N	1E	34	3030	2902	2885	2855	2850			3030	2885	2855	2850	2850	
25099050270000	FLORENCE I FLICK	TETON	24N	1E	30	2949	2828	2814	2766	2759			2949	2814	2766	2759	2759	
25099050410000	T M GOODMUNDSON	TETON	24N	1E	18	2984	2860	2845	2801	2790			2984	2845	2801	2790	2790	
25099050450000	STATE	TETON	24N	1W	16	3147	3021	3003	2947	2940			3147	3003	2947	2940	2940	
25099050580000	CRISTMAN	TETON	24N	1W	6	3163	3032	3013	2960	2950			3163	3013	2960	2950	2950	
25099050690000	TOREN	TETON	25N	4W	26	3256	3106	3089	3038	3038			3256	3089	3038		3038	
25099051540000	E W THOMPSON	TETON	26N	2W	26	3145	3004	2993	2932	2924			3145	2993	2932	2924	2924	
25099053870000	GITCHEL	TETON	27N	6W	9	4639	4479	4463	4417	4409			4639	4463	4417	4409	4409	
25099053930000	STATE	TETON	27N	5W	4	3865	3687	3677	3622	3618			3865	3677	3622	3618	3618	
25099054820000	STATE	TETON	26N	1E	34	2762	2649	2621	2598	2592			2762	2621	2598	2592	2592	
25099070030000	FERRIS	TETON	24N	3W	20	3145			2922	2922					2922		2922	
25099210160000	SWANBERG-UTP	TETON	23N	1E	33	2839	2721	2705	2665	2656	2653		2839	2705	2665	2656	2653	
25099210300000	BANNATYNE-TOECKES	TETON	24N	2W	12	2861	2727	2709	2671	2663			2861	2709	2671	2663	2663	
25099210380000	BANNATYNE-TOECKES	TETON	24N	2W	12	3066	2918	2899	2840	2833				2899	2840	2833	2833	
25099210420000	PEARSON BROTHERS	TETON	22N	5W	32	5371	5218	5200	5160	5153	5141		5371	5200	5160	5153	5141	5140
25099210640000	CECIL R CARNEY JR	TETON	24N	3W	23	3319	3177	3158	3106	3099			3319	3158	3106	3099	3099	
25099211040000	MCDONNELL	TETON	24N	7W	6	7027	6728	6698	6658	6650	6646			6698	6658	6650	6646	6643
25099211180000	BALSAM-STATE	TETON	25N	3W	26	3008	2869	2855	2791	2782				2855	2791	2782	2782	
25099211190000	MOUNATIN FUEL-STATE	TETON	25N	3W	16	3182	3027	3013	2951	2946				3013	2951	2946	2946	
25099211430000	DERNOVICH	TETON	27N	8W	1	5523	5336	5316	5284	5276			5523	5316	5284	5276	5276	
25099211460000	NEW ROCKPORT COLONY	TETON	24N	3W	26	3304	3171	3153	3109	3103			3304	3153	3109	3103	3103	
25099211470000	HODGEKISS FARMS	TETON	22N	5W	18	5342	5195	5173	5134	5129	5120		5342	5173	5134	5129	5120	5118
25099211610000	LARSON	TETON	22N	5W	1	4429	4283	4271	4229	4223	4216		4429	4271	4229	4223	4216	4211
25099211670000	PERKINS IRA ETAL	TETON	27N	6W	4	4738	4543	4534	4487	4482				4534	4487	4482	4482	
25099211680000	PAMBURN UNIT	TETON	25N	8W	21		2007	1975	1953	1943				1975	1953	1943	1943	
25099211790000	EVILSIZER	TETON	27N	8W	21	6365	6052	6026	5986	5978				6026	5986	5978	5978	
25099211870000	AZNOE-AGRIBIZ	TETON	26N	4W	1	3394	3236	3223	3162	3157				3223	3162	3157	3157	
25099211910000	SERIAL-FEDERAL	TETON	23N	8W	21	3838	3651	3626	3607	3602	3592		3838	3626	3607	3602	3592	3592
25099212340000	USA	TETON	21N	3W	6	3988	3857	3838	3786	3782	3768		3988	3838	3786	3782	3768	3766
25099212730000	HOLMES	TETON	24N	4W	26	3206	3054	3034	2983	2976				3034	2983	2976	2976	
25099212750000	LUINSTRA	TETON	24N	3W	29	3129	2982	2962	2907	2900			3129	2962	2907	2900	2900	
25101072570000	C THISTED	TOOLE	36N	1E	17	3291	3139	3128	3118	3095	3007		3291	3128	3118	3095	3007	
25101075730000	FREDA BROWN	TOOLE	37N	2W	9		3586	3571	3571	3550	3428			3571	3571	3550	3428	3426
25101077270000	GOEDDEZ-AGEN	TOOLE	35N	3W	16	3162	2991	2978	2973	2961	2879		3162	2978	2973	2961	2879	2874
25101212080000	ENNEBERG	TOOLE	35N	3W	6	4069	3887	3877	3873	3860	3794		4069	3877	3873	3860	3794	3790
25101212750000	CULLEN-WEDIN	TOOLE	33N	1E	18	2955	2809	2799	2729	2721	2686			2799	2729	2721	2686	
25101213660000	BATTS	TOOLE	33N	1W	12	2831	2673	2664	2600	2592	2549		2831	2664	2600	2592	2549	
25101214490000	LLOYD DANIELSON	TOOLE	35N	1W	17	2990	2826	2814	2808	2784	2699		2990	2814	2808	2784	2699	
25101214500000	STATE-TOWER	TOOLE	33N	2W	16		2847	2839	2784	2780				2839	2784	2780	2780	
25101214980000	STATE-CARDEN	TOOLE	34N	1E	16	2921	2760	2750	2688	2679	2637		2921	2750	2688	2679	2637	
25101214990000	SELINA IRELAND	TOOLE	35N	1E	19	3204	3037	3001	2997	2969	2891			3001	2997	2969	2891	
25101215880000	ALLEN	TOOLE	35N	1W	2	3349	3190	3173	3173	3149	3057		3349	3173	3173	3149	3057	
25101216610000	JOHANNSEN	TOOLE	34N	1E	26	2954	2814	2807	2719	2713	2688		2954	2807	2719	2713	2688	
25101216670000	TRUE STATE	TOOLE	35N	2E	32	3310	3164	3154	3098	3082	3023			3154	3098	3082	3023	3022
25101216950000	KASTEN	TOOLE	35N	1W	27	2897	2742	2733	2720	2699	2628		2897	2733	2720	2699	2628	
25101217490000	ANDERSON	TOOLE	35N	1W	29	2812	2659	2642	2637	2618	2539			2642	2637	2618	2539	
25101217550000	J FEY	TOOLE	37N	2E	33	3516	3377	3365	3329	3320	3248			3365	3329	3320	3248	3243
25101222730000	O`LAUGHLIN	TOOLE	37N	1E	20	3084	2930	2919	2919	2896	2801		3084	2919	2919	2896	2801	
25101224620000	STATE	TOOLE	35N	1W	36	2902	2742	2735	2709	2693	2629		2902	2735	2709	2693	2629	
25101224640000	FARMS L S	TOOLE	34N	1E	18	2934	2784	2776	2720	2712	2663		2934	2776	2720	2712	2663	
25101224670000	KANNING FARMS	TOOLE	34N	2E	7	3127	2981	2975	2885	2879	2852		3127	2975	2885	2879	2852	2850
25101224790000	WESTER-MORSE	TOOLE	33N	1E	25	2930	2809	2800	2700	2695	2685		2930	2800	2700	2695	2685	
25101225030000	KOLSTAD	TOOLE	34N	2E	15	3182	3037	3027	2945	2939	2917		3182	3027	2945	2939	2917	2915
25101225040000	SUPHELLAN	TOOLE	34N	1E	5	2975	2825	2817	2753	2745	2701		2975	2817	2753	2745	2701	2699
25101225050000	DYRDAHL	TOOLE	33N	2E	35	3037	2907	2901	2808	2802			3037	2901	2808	2802	2802	
25101225700000	WIEGAND C J JR	TOOLE	35N	1E	31	2910	2735	2724	2680	2672	2618		2910	2724	2680	2672	2618	2615
25101226010000	HENDLEY	TOOLE	34N	1E	6	3006	2859	2849	2793	2784	2737		3006	2849	2793	2784	2737	
25101226070000	ZIMMERMAN REALTY	TOOLE	34N	1E	6	2871	2707	2699	2657	2646	2592		2871	2699	2657	2646	2592	2589
25101226330000	HENDLEY	TOOLE	34N	1E	6	2942	2794	2782	2734	2724	2674		2942	2782	2734	2724	2674	
25101226630000	SUTA	TOOLE	36N	1W	26	3580	3431	3418	3410	3389	3297			3418	3410	3389	3297	3295
25101226850000	SUTA	TOOLE	35N	1W	3	3331	3181	3169	3169	3140	3051		3331	3169	3169	3140	3051	3050
25101227080000	KANNING	TOOLE	33N	1E	25	2912	2788	2780	2689	2683	2665		2912	2780	2689	2683	2665	
25101227210000	SUTA	TOOLE	36N	1W	34	3491	3343	3330	3323	3301	3211			3330	3323	3301	3211	3208
25101227400000	SKESLIEN	TOOLE	32N	1E	28		2726	2719	2619	2614				2719	2619	2614	2614	
25101227550000	TORDALE	TOOLE	35N	1E	21	3320	3169	3161	3135	3115	3043		3320	3161	3135	3115	3043	
25101228900000	GUITH	TOOLE	33N	2E	10	3007	2883	2876	2782	2777	2768		3007	2876	2782	2777	2768	2766
25101228930000	CELSIUS-STATE	TOOLE	34N	1E	4	2974	2823	2817	2752	2744	2704		2974	2817	2752	2744	2704	
25101229070000	WIEGAND	TOOLE	35N	1E	31	2912	2762	2750	2713	2701	2647		2912	2750	2713	2701	2647	2645
25101229180000	SUPHELLEAN	TOOLE	34N	1E	5	2978	2828	2818	2763	2753	2703		2978	2818	2763	2753	2703	
25101229260000	SUPHELLEN	TOOLE	34N	1E	5	2964	2816	2806	2755	2744	2690		2964	2806	2755	2744	2690	
25101229270000	GRINDE	TOOLE	35N	1E	33	2980	2816	2808	2755	2745	2691		2980	2808	2755	2745	2691	2689
25101229360000	GREAT NORTHERN	TOOLE	35N	2W	6	3058	2892	2879	2875	2860	2769		3058	2879	2875	2860	2769	2766
25101229370000	DIX MONT STATE	TOOLE	36N	3W	36	3119	3014	3001	3001	2980	2891		3119	3001	3001	2981	2890	2887
25101229650000	TURNER	TOOLE	35N	1E	22	3306	3158	3146	3114	3098	3030		3306	3146	3114	3098	3030	3027
25101229840000	STATE	TOOLE	35N	1E	32	2986	2833	2824	2773	2763	2710		2986	2824	2773	2763	2710	
25101230100000	B&B RANCH	TOOLE	35N	1E	14	3307	3173	3145	3136	3099	3022			3145	3136	3099	3022	3019
25101230110000	GRINDE	TOOLE	35N	1E	17	3331	3177	3166	3159	3132	3054		3331	3166	3159	3132	3054	3050
25101230120000	STATE	TOOLE	35N	2E	16	3382	3225	3219	3173	3160	3102		3382	3219	3173	3160	3102	3099
25101230180000	SUN	TOOLE	36N	3W	13	3452	3258	3254	3254	3234	3125		3452	3254	3254	3234	3125	3122
25101230200000	STATE	TOOLE	34N	1E	16	2936	2782	2774	2710	2703	2657		2936	2774	2710	2703	2657	
25101230210000	REDDING	TOOLE	33N	1E	34	2829	2699	2692	2601	2596	2577		2829	2692	2601	2596	2577	
25101230220000	FLB-WIEGAND	TOOLE	33N	1E	3	2914	2772	2767	2684	2676	2647		2914	2767	2684	2676	2647	
25101230240000	THORPE	TOOLE	36N	3W	2	3410	3242	3228	3228	3209	3106		3410	3228	3228	3209	3106	3100
25101230440000	CELSIUS	TOOLE	34N	1E	4	2974	2817	2809	2746	2737	2696		2974	2809	2746	2737	2696	2695
25101230950000	DEVLIN	TOOLE	34N	1W	2	2841	2667	2661	2634	2618	2554		2841	2661	2634	2618	2554	2551
25101231250000	ZIMMERMAN REALTY	TOOLE	35N	1E	31	2839	2689	2680	2638	2628	2570		2839	2680	2638	2628	2570	
25101231510000	TURNER	TOOLE	35N	1E	34	3075	2916	2909	2850	2842	2789		3075	2909	2850	2842	2789	
25101233930000	MONTEX	TOOLE	34N	1E	21	3000	2854	2843	2775	2766	2716		3000	2843	2775	2766	2716	
25101234050000	STATE OF MONTANA	TOOLE	34N	1E	3	2964	2808	2798	2724	2717	2674		2964	2798	2724	2717	2674	
25101234830000	CELSIUS	TOOLE	34N	1E	4	2969	2808	2799	2731	2724	2691		2969	2799	2731	2724	2691	2688
25101235450000	STATE	TOOLE	34N	1E	4	2977	2819	2812	2747	2739	2694		2977	2812	2747	2739	2694	
25101235930000	O`BRIEN	TOOLE	34N	1E	9	2968	2808	2801	2740	2731	2686		2968	2801	2740	2731	2686	2685
25101236560000	STATE	TOOLE	35N	1W	16	2999	2846	2836	2832	2805	2718		2999	2836	2832	2805	2718	2717
25101236660000	WIEGAND	TOOLE	35N	1E	31	2950	2802	2789	2756	2744	2686		2950	2789	2756	2744	2686	
25101236670000	WIEGAND	TOOLE	35N	1E	31	2988	2842	2833	2788	2778	2719		2988	2833	2788	2778	2719	
25101236680000	WIEGAND	TOOLE	35N	1E	32	2995	2840		2784	2774	2722		2995		2784	2774	2722	2720
25101236690000	STATE	TOOLE	35N	1W	36	2929	2782	2769	2738	2722	2661		2929	2769	2738	2722	2661	2659
25101237590000	MIDLAND REALTY	TOOLE	36N	2W	25	3261	3095	3086	3083	3062	2974		3261	3086	3083	3062	2974	2972
25101237790000	HELLINGER	TOOLE	33N	2E	30	2986	2858	2853	2761	2755	2739		2986	2853	2761	2755	2739	
25101238070000	NORWOOD	TOOLE	35N	1W	35	2837	2687	2682	2653	2635	2569		2837	2682	2653	2635	2569	2566
25101238420000	WHITSITT	TOOLE	34N	1E	4	2974	2839	2828	2766	2756	2698		2974	2828	2766	2756	2698	2696
25101238430000	SUPHELLEN	TOOLE	34N	1E	5	3015	2856	2847	2783	2772	2716		3015	2847	2783	2772	2716	
25101238440000	GREETAN	TOOLE	35N	1E	32	3031	2844	2834	2775	2765	2714		3031	2834	2775	2765	2714	
25101238450000	EAST CROOKED COULEE	TOOLE	33N	1E	25	2997	2803	2797	2693	2687	2670			2797	2693	2687	2670	
25101238460000	SHORT CREEK	TOOLE	35N	1E	16	3378	3183	3172	3149	3125	3042		3378	3172	3149	3125	3042	
25101238580000	JOHNSTON RUTH	TOOLE	35N	2W	6	3055	2871	2855	2852	2832	2749		3055	2855	2852	2832	2749	
25101238590000	STATE	TOOLE	35N	4W	21	3652	3456	3452	3448	3433	3377	3368	3652	3452	3448	3433	3377	3368
25101239080000	PACE	TOOLE	36N	1W	28	3338	3171	3159	3157	3135	3041		3338	3159	3157	3135	3041	
25013050340000	HAMILTON JOHN S	CASCADE	21N	2W	19	3568	3440	3420	3370	3364	3351		3568	3420	3370	3364	3351	3349
25073052220000	R JOHNSON	PONDERA	27N	2W	7	3297	3166	3158	3070	3070			3297	3158	3070	3069	3070	
25101239730000	CLARK	TOOLE	37N	1E	2	3086	2937	2924	2924	2904	2808		3086	2924	2924	2904	2808	
25067050130000	WINDSOR	PARK	1S	11E	25	8341	8341	8319	8305	8305	8237	8234	8341	8319	8305		8237	8234
25067210090000	HOBBS	PARK	5S	8E	24	5079	5077	5064	5008	5008	4985	4976	5079	5064	5008		4985	4976
25059210040000	KIFF RANCH	MEAGHER	6N	8E	27		11254	11197	11171	11156	11114	11108		11197	11171	11156	11114	11108
25059210060000	KIFF RANCH-BN	MEAGHER	5N	9E	7	8882	8766	8726	8714	8707	8652	8645	8882	8726	8714	8707	8652	8645
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25049210050000	FEDERAL	LEWIS AND CLARK	12N	1W	3	4572	4479	4434	4426	4413	4354	4350	4572	4434	4426	4413	4354	4350
25049210060000	LONG J B	LEWIS AND CLARK	19N	8W	9		10931	10920	10901	10893				10920	10901	10893	10893	
25049210070000	STATE	LEWIS AND CLARK	20N	5W	33	6806	6672	6648	6608	6601	6590	6584	6806	6648	6608	6601	6590	6584
25049210100000	ARCO-STEINBACH	LEWIS AND CLARK	17N	6W	22	10353	10180	10159	10149	10144	10128	10124	10353	10159	10149	10144	10128	10124
25049210120000	COBB A B	LEWIS AND CLARK	20N	9W	36		11913	11901	11885	11879				11901	11885	11879	11879	
25049210140000	KTO	LEWIS AND CLARK	20N	4W	2	4398	4243	4230	4201	4195	4181	4176		4230	4201	4195	4181	4176
25097050250000	BERTHA R CREMER	SWEET GRASS	3N	18E	8		6307	6288	6254	6254				6288	6254		6254	
25097210330000	LUKKES	SWEET GRASS	1N	17E	22		7902	7892	7852	7852				7892	7852		7852	
	MOOSE CREEK							47	36	36	6			47	36	36	6	
	SACAJAWEA PEAK	Gallatin						145	89	82	6	1		145	89	82	6	1
	LOGAN GULCH							110	86	78	6	3		110	86	78	6	3
	ANTELOPE VALLEY							141	86	83	5			141	86	83	7	4
	Lone Mountain										3						3	

APPENDIX D

DEPOSITIONAL ENVIRONMENTS

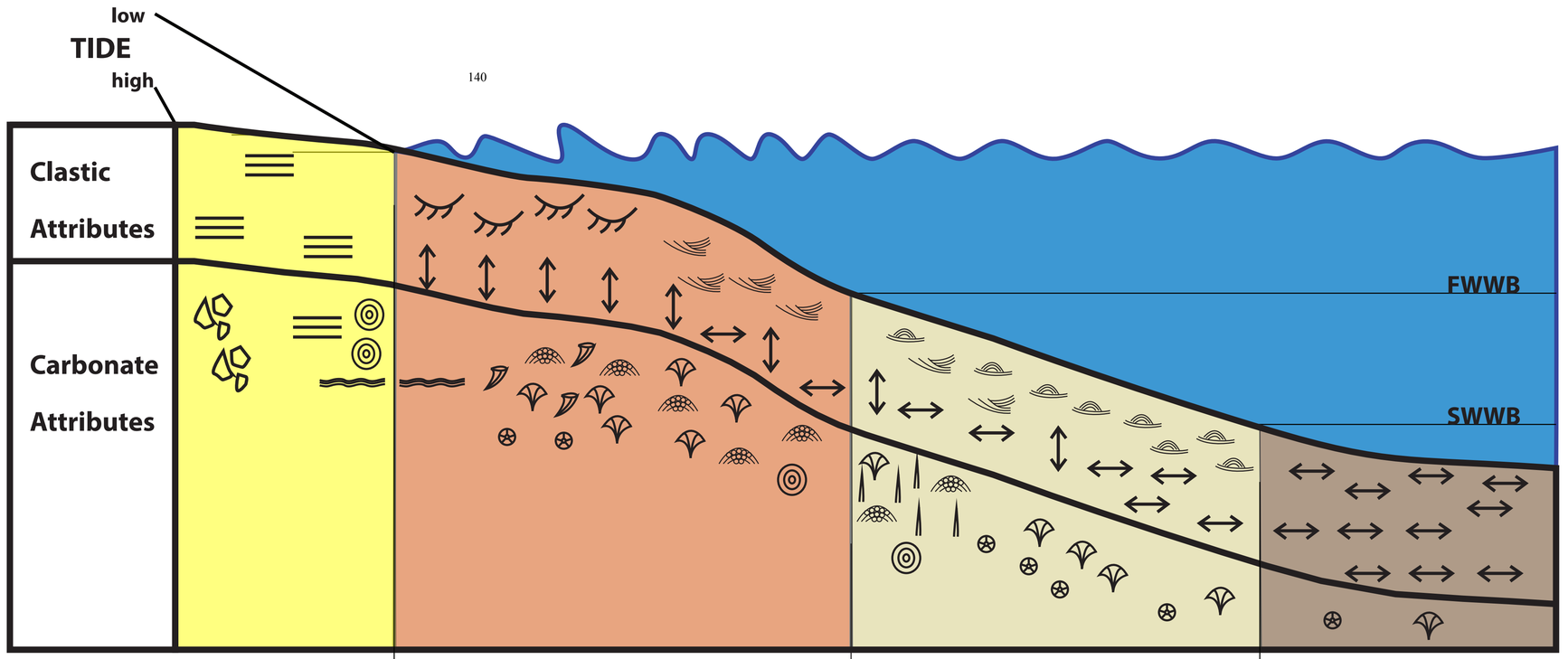
EXPLANATION

Sedimentary Attributes

- Parallel Lamination
- Ripple Cross Lamination
- Swaley Cross Stratification
- Micro hummocky cross stratification
- Horizontal Bioturbation
- Vertical Bioturbation
- Graded Bedding
- Gastropod
- Crinoid
- Rugose Coral
- Brachiopod
- Stromotoporoid (encrusing or not)
- Spine (Echinoderm or Brachiopod
- Ooid
- Brecciation
- Microbial Lamination

Lithofacies

- Sl — Parallel laminated sandstone
- Sr — Ripple cross-laminated fine-medium sand
- Ssw — Swaley cross stratified sandstone
- Fsm — Bioturbated dolomitic siltstone
- Fsgo — Graded organic-bearng siltstone
- Fsds — Dolomitic, stromotoporid-bearing bioturbated siltstone
- Fsl — Dolomitic laminated siltstone
- Fml — Laminated mudstone
- Fcm — Massive claystone
- Fmo — Organic rich mudstone
- CMbr — Carbonate mudstone breccia
- CGio — Ooid interclast grainstone
- CBt — Laminated lime mudstone
- CFsr — Stromotoporoid rugose coral floatstone
- CFss — Stromotoporoid skeletal floatstone
- CPs — Spicule packstone
- CWeb — Echinoderm brachiopod wakestone
- CMa — Argillaceous lime mudstone



Clastic Dep. Environment	Foreshore	Upper Shoreface	Lower Shoreface	Offshore
Sedimentary Processes	Region between mean high tide mean low tide. Wave swash perpendicular to shoreline produces fine-grained parallel-laminated quartz arenite perpendicular to the shoreline.	Extends from below mean low tide to above FWWB. Closer to the shoreline, rip and longshore currents producing medium-fine grained, bidirectional ripple coss laminated sandstones. Closer to FWWB Waves begin to shoal and interact with the sediment-water interface producing fine-grained swaley cross stratified sandstone.	Extends from above SWWB, and below FWWB. Dominated by storm processes during which wave base is lowered, and there is a net delivery of sediment basinward. Lithologies include discrete swaley, and hummocky cross stratified very fine sandstones interbedded with highly bioturbated mudstone.	Hemipelagic to pelagic sedimentation. Slumps and or turbidite deposits may bypass updip sedimentation regions, delivering high-energy depositional patters to the offshore sedimentation region. However, bioturbated mudstone that is delivered offshore by sediment plumes dominates.
Clastic Lithofacies	Sl	Sr, Ssw	Fsm, Fsgo, Fsds, Fsl	Fml, Fmo

Carbonate Dep. Environment	Inner Ramp: Intertidal/Ooid Shoal/Patch Reefs	Middle Ramp	Outer Ramp
Sedimentary Processes	Region between mean high tide mean low tide. Wave swash perpendicular to shoreline produces upper plane beds. Where tides have been suppressed by barriers tidal flats occur, producing low-energy, laminated mudstones, and evaporites. Includes open marine environments ranging from shoals, lagoonal enviroments, and peritidal environments. Energy environemnts are widely varied due to the configuration of sediments (protected, non protected etc.) and accordingly produce a wide variety of lithologies including non-burrowd lime mudstone, oncoid packstone,fenestral bindstone, laminated evaporitic carbonate-bind-stone, ooid, peloid and intraclast sand shoals and evaporites.	Lithologies include dominantly mud, wacke, and packstones that are are often heavily burrowed. Skeletal grains are often abraded. Allochems include echinoderms, bivalves, foraminifers, and corals. Allochems be derived from the upper ramp deposited during storm events.	Thin to medium-bedded fine-grained, often heavily burrowed limestones dominated. Allochems are of nectonic origin, and are generally well-preserved. Carbonate material is ofted mixed with siliciclastic material that was transported by wind.
Clarbonate Lithofacies	CMbr, CGio, CBt, CBt, CFsr, CFss	CFss, CPs, CWeb, CMa	CMa

Ichnofacies		
	Genera	*Skolithos* ←→ ; *Cruziana* ←→
	Species	*Skolithos* ←→ ; *Diplocraterian* ←→ ; *Teichichnus* ←→ ; *Phycosiphon* ←→

APPENDIX E

CROSS SECTIONS

Devonian-Mississippian Three Forks and Lodgepole Formation of Southwest Montana
Lithostratigraphy (non restored, projected along strike)

Datum: Basal Lodgepole Fm.

Section Length (meters)

Lone Mountain — 21 Km. — Antelope Valley — 36 Km. — Logan Gulch — 26 Km. — Sacajawea Peak — 30 Km. — Moose Creek

Cottonwood Canyon Member

Lower Black Shale Tongue

Lodgepole Fm.

Three Forks Formation

Sappington Mbr.

Upper Siltstone Tongue

Medial shale Tongue

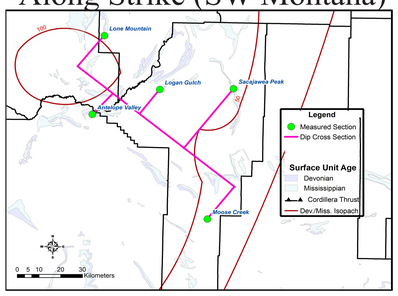
Lower siltstone tongue

Carbonate Tongue

Trident Mbr.

Logan Gulch Mbr.

Outcrop Sections Projected Along Strike (SW Montana)



EXPLANATION

Sedimentary Attributes

- Parallel Lamination
- Trough Cross Bedding
- Swaley Cross Stratification
- Micro hummocky cross stratification
- Horizontal Bioturbation
- Vertical Bioturbation
- Graded Bedding
- Ooid (Raidal and concentric)
- Intraclast
- Gastropod
- Crinoid
- Rugose Coral
- Brachiopod
- Stromotoporoid (encrusing or not)
- Spine (Echinoderm or Brachiopod)

Lithofacies

Sl	Parallel laminated sandstone
Sr	Ripple cross-laminated fine-medium sand
Ssw	Swaley cross stratified sandstone
Fsm	Bioturbated dolomitic siltstone
Fsgo	Graded organic-bearng siltstone
Fsds	Dolomitic, stromotoporid-bearing bioturbated siltstone
Fsl	Dolomitic laminated siltstone
Fml	Laminated mudstone
Fcm	Massive claystone
Fmo	Organic rich mudstone
CMbr	Carbonate mudstone breccia
CGio	Ooid interclast grainstone
CBt	Laminated lime mudstone
CFsr	Stromotoporoid rugose coral floatstone
CFss	Stromotoporoid skeletal floatstone
CPc	Spicule packstone
CWeb	Echinoderm brachiopod wakestone
CMud	Argillaceous lime mudstone

Sampling

- Standard 30 micron thin section (1/2 alizarin red)
- Proposed Large (51x76 mm) microfacies analysis thin section
- Proposed XRD Sample

Devonian-Mississippian Three Forks and Lodgepole Formation of Southwest Montana
Lithostratigraphy (non restored, projected along strike)

← Distal

Proximal →

Lone Mountain 21 Km. Antelope Valley 36 Km. Logan Gulch 26 Km. Sacajawea Peak 30 Km. Moose Creek

Section Length (meters)

2 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50

HST

TST

HST

FSST

TST

HST

HST

Sequence 4 (part)

Sequence 3

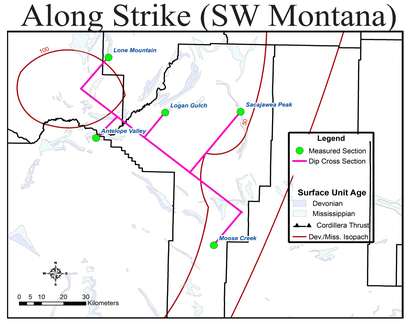
Sequence 2

Sequence 1 (part)

Kaskaskia II

Kaskaskia I

Outcrop Sections Projected Along Strike (SW Montana)



EXPLANATION

- Sl — Parallel laminated sandstone
- Sr — Ripple cross-laminated fine-medium sand
- Ssw — Swaley cross stratified sandstone
- Fsm — Bioturbated dolomitic siltstone
- Fsgo — Graded organic-bearng siltstone
- Fsds — Dolomitic, stromotoporid-bearing bioturbated siltstone
- Fsl — Dolomitic laminated siltstone
- Fml — Laminated mudstone
- Fcm — Massive claystone
- Fmo — Organic rich mudstone
- CMbr — Carbonate mudstone breccia
- CGio — Ooid interclast grainstone
- CBt — Laminated lime mudstone
- CFsr — Stromotoporoid rugose coral floatstone
- CFss — Stromotoporoid skeletal floatstone
- CPs — Spicule packstone
- CWeb — Echinoderm brachiopod wakestone
- CMw — Argillaceous lime mudstone

Parasequence

Sequence Boundary

Maximum Flooding Surface

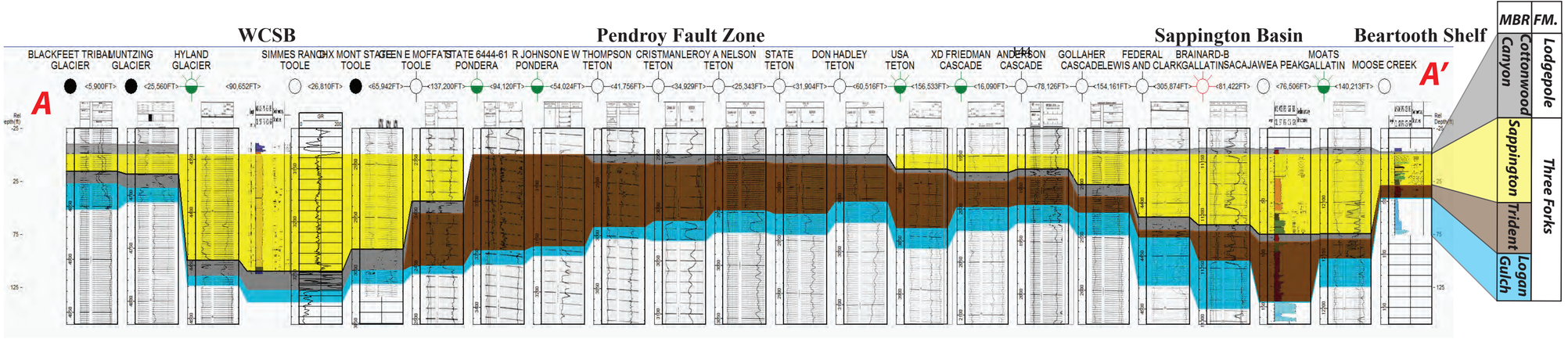
Clinoforms

SP-8.8.13-2 Sample Collected

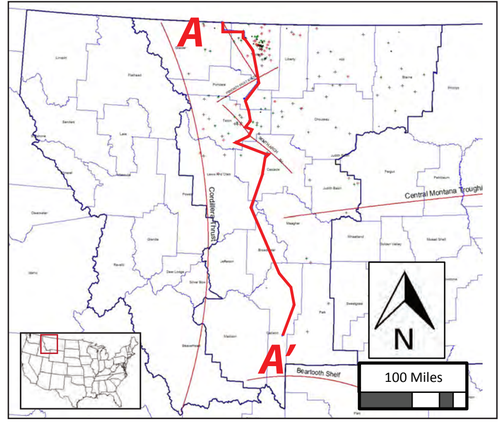
Thin Section Obtained

X-ray Diffraction Sample

North-South Lithostratigraphic Correlation

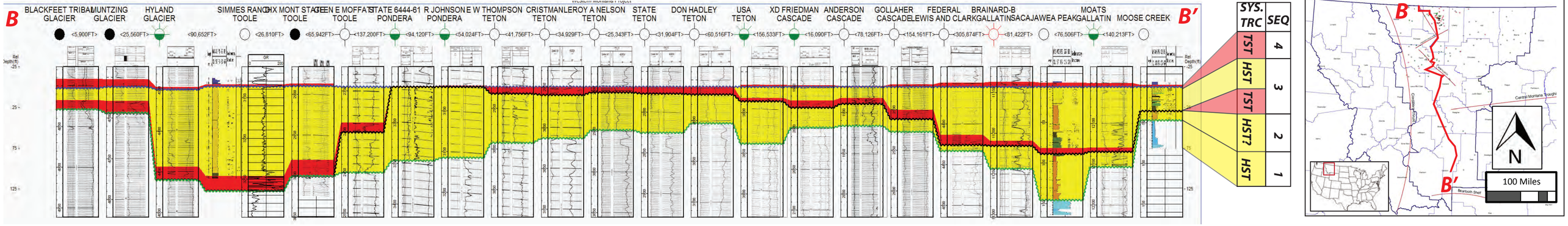


Basemap



North-South Lithostratigraphic correlation

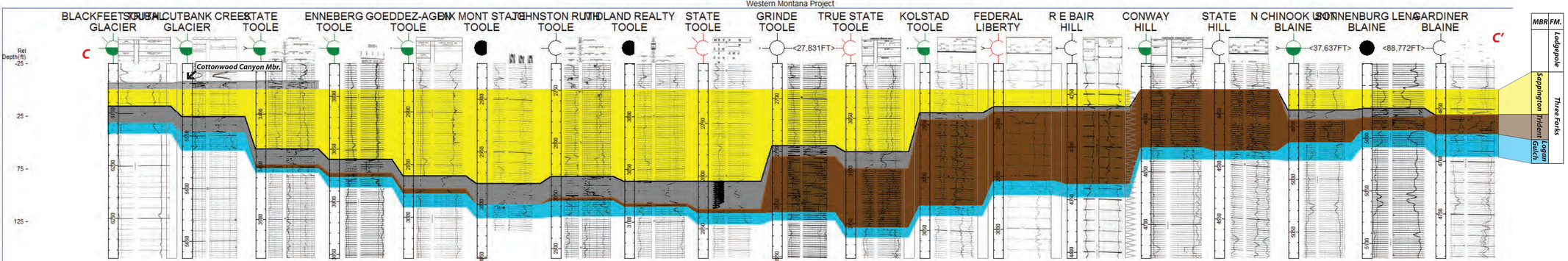
WCSB | **Pendroy Fault Zone** | **Sappington Basin** | **Beartooth Shelf** | **Baemap**



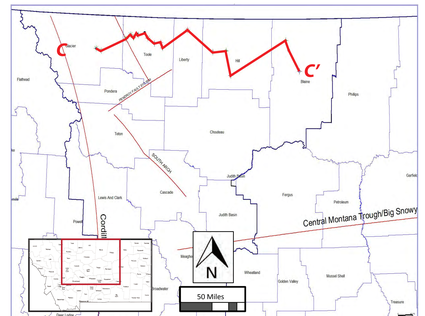
North-South Lithostratigraphic Correlation

Montania Platform | **WCSB** | **Paleohigh** | **To Williston Basin**

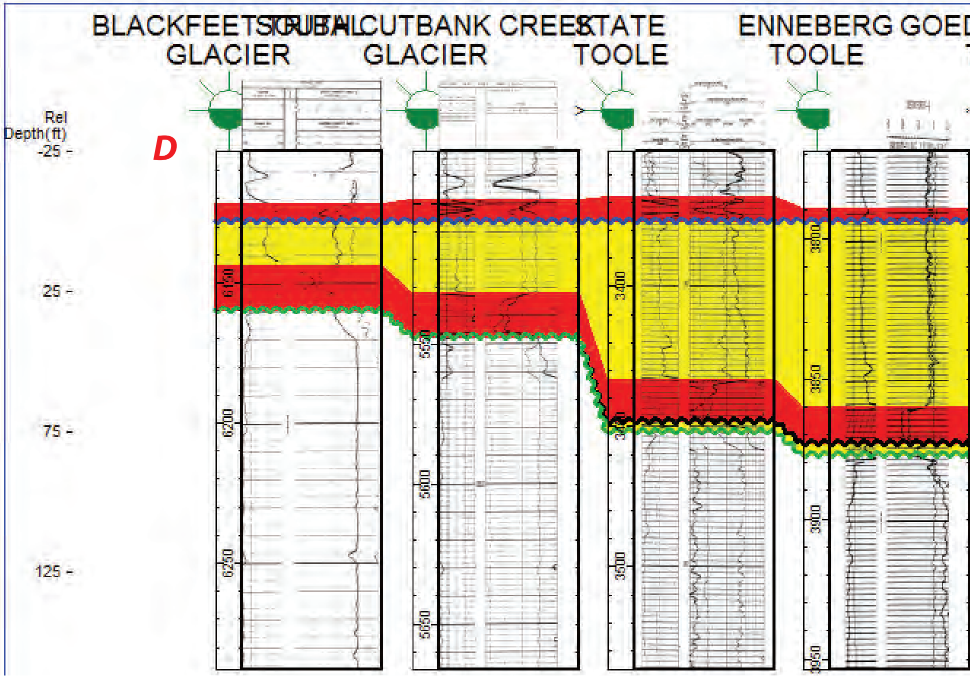
Western Montana Project



Basemap



Montania Platform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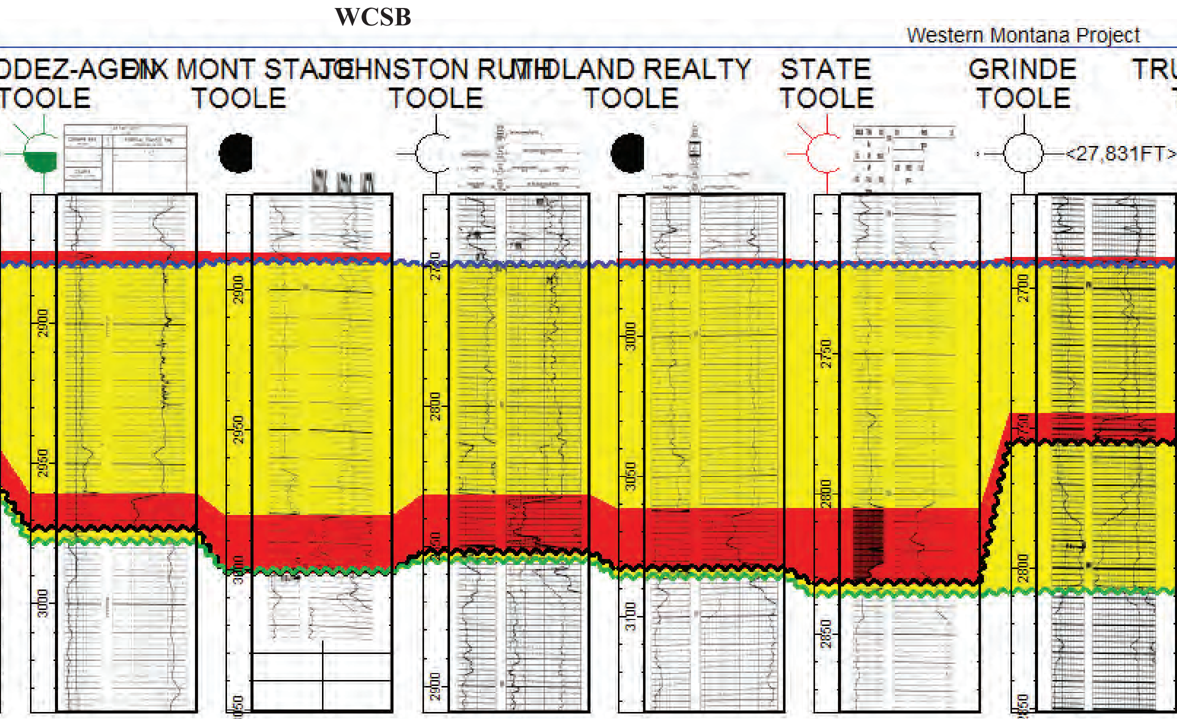
GLACIER
CUTBANK CREEK
GLACIER
STATE
TOOLE
ENNEBERG
TOOLE
GOED
Rel
Depth(ft)
-25
25
75
125
D
6150
6200
6250
5550
5600
5650
3400
3450
3500
3800
3850
3900
3950

East-West WCSB Seq



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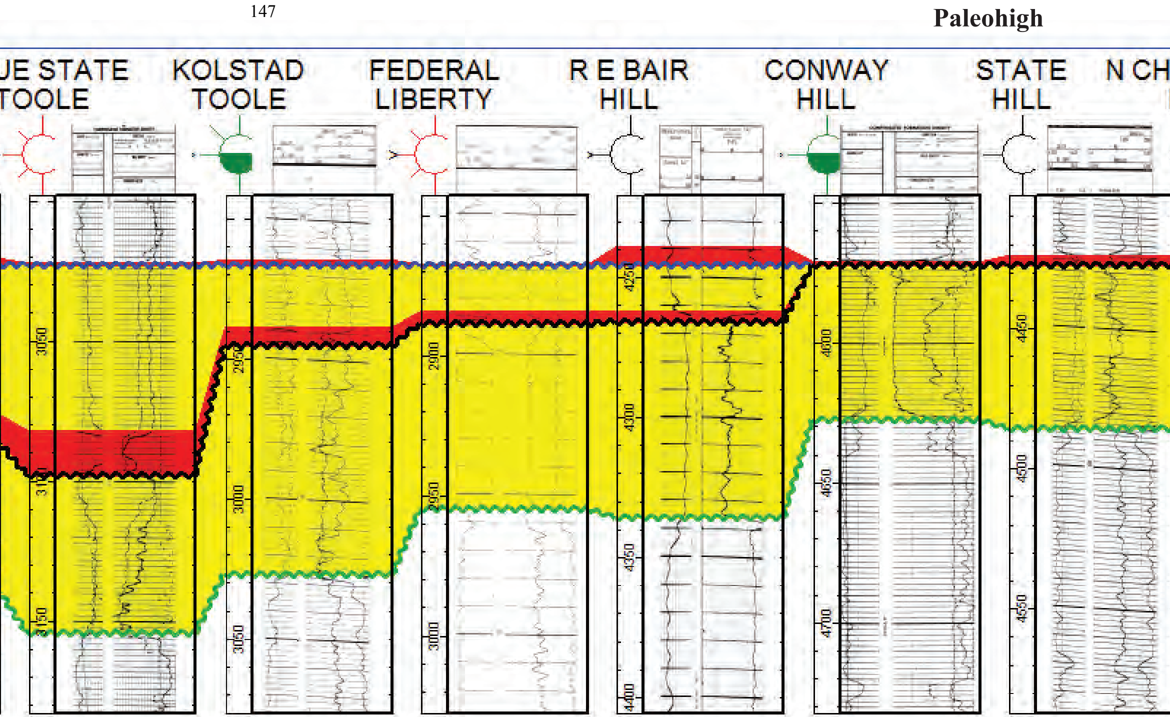
147
Paleohigh
JE STATE TOOLE
KOLSTAD TOOLE
FEDERAL LIBERTY
R E BAIR HILL
CONWAY HILL
STATE HILL
N CH
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3150
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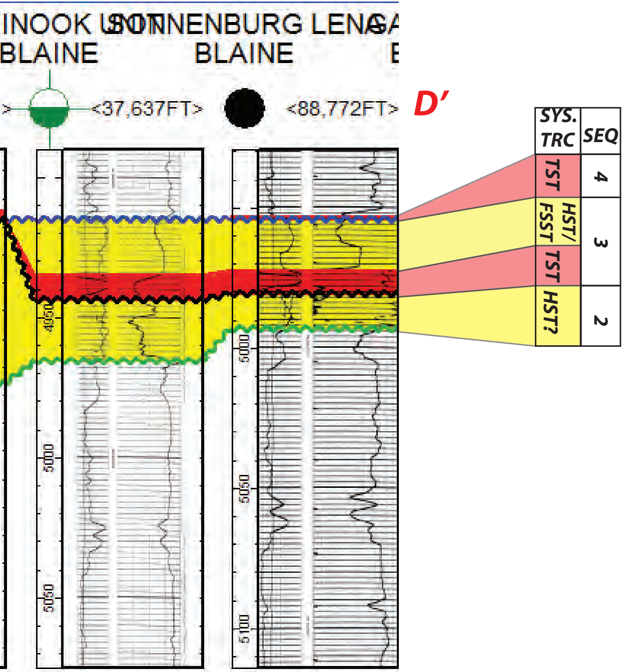
To Williston Basin



INOOK U… SOTNNENBURG LENGA…
BLAINE
BLAINE
<37,637FT>
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SYS. TRC
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HST/ FSST
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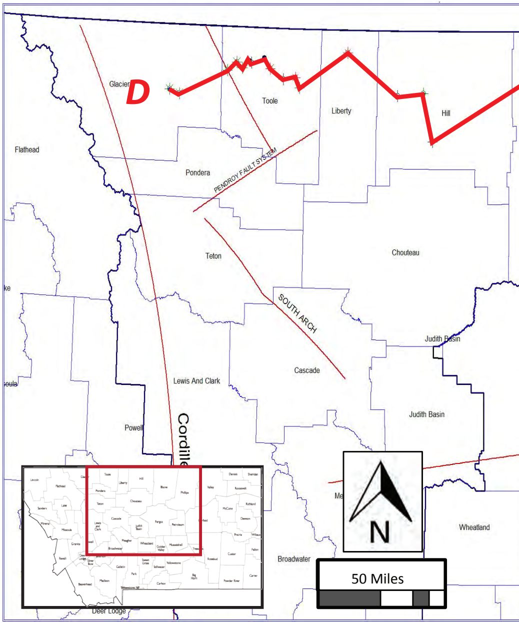
Basemap



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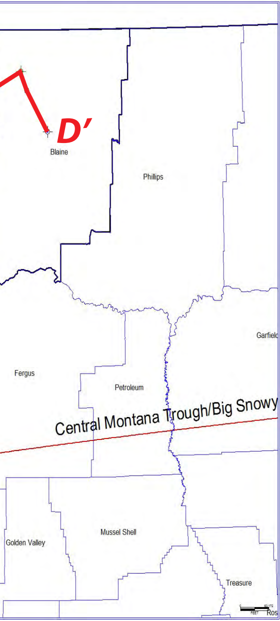
Glacier
Toole
Liberty
Hill
Flathead
Pondera
PENDROY FAULT SYSTEM
Teton
Chouteau
SOUTH ARCH
Judith Basin
Cascade
Lewis And Clark
Judith Basin
Powell
Cordille
Broadwater
Wheatland
Deer Lodge
N
50 Miles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Blaine
Phillips
Garfiel
Fergus
Petroleum
Central Montana Trough/Big Snowy
Golden Valley
Mussel Shell
Treasure
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FEET
Ros