

STRATIGRAPHIC ANALYSIS OF THE JURASSIC ELLIS GROUP AND
PALEOTECTONICS IN NORTH-CENTRAL MONTANA: DECIPHERING THE
HISTORICALLY ENIGMATIC “BELT ISLAND”

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2011

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ACKNOWLEDGEMENTS

I am indebted to my advisor, Dr. David Bowen for his time, knowledge, data and equipment to facilitate this project. I would like to thank my thesis committee, Dr. David Lageson and Dr. James Schmitt, for their time and attention to this project and my professional development as a geologist. Thank you to Dr. Michael Gardner for in depth discussions on sedimentology and stratigraphy and exposure to such influential papers of both. Thank you, in general, to the Montana State Earth Sciences Department for equipping me with the resources to conduct this research. Thank you to the Haldemann Family, Meissner Family, and Mitchell Family for granting me access to their ranch land and conversation on the history of the land. Thank you to Karen Maddaus of the MBOGC for being so helpful with procuring additional core data.

This research project was funded through Big Sky Carbon Sequestration Partnership by the U.S. Department of Energy and the National Energy Technology Laboratory, through award number: DE-FC26-05NT42587.

A basin full of thank you's to my peers: Bryan Anderson, Evan Gearity, Travis Jester, Jesse Melick, and Jeannette Wolak for in-depth discussions...even the esoteric. A special thank you to Jimmy Goolsby for his persistence on championing the importance of graduate school, correct he was. To my family: I could not have completed this journey without your love and support, forever grateful I am. I believe an honorable mention is in order for the show "Family Guy", in keeping me from getting too caught up in my research and losing focus of how awesome science really is.

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ABSTRACT

“Belt Island”, an influential positive structure during the Jurassic, is widely represented in the geologic literature from 1948 to present. Introduced as primarily a stratigraphic anomaly in isopach maps of the Ellis Group, the inherent spatial and temporal context was loosely constrained. In subsequent literature, it is widely referenced in a structural context, though support is lacking for originating paleotectonics and stratigraphic data is minimal.

Do the stratigraphy, sedimentology, and regional tectonics support the theory of a paleogeographic/paleotectonic high in north-central Montana during the Middle to Late Jurassic during the deposition of the Ellis Group? What are the tectonic explanations for such a feature if one did persist throughout said time?

This project looked at outcrops and cores of the Ellis Group from around the project area. A lithofacies characterization was assembled based on rock properties. Utilizing previous work on lithostratigraphy, biostratigraphy, and regional unconformities and integrating these data with the lithofacies characterization a sequence stratigraphic framework was assembled. This sequence stratigraphic framework was applied to an extensive subsurface well database to generate a geologic framework over the project area.

The distributions of lithofacies do support the theory of a large feature in the project area during the deposition of the Ellis Group. The stratigraphic architecture as well supports this theory, and additionally adds a spatial and temporal constraint to the feature. With the integrated sequence stratigraphic framework, it is apparent there was regional syntectonic activity influencing deposition.

With the ability to put a temporal and spatial constraint on the paleotectonic feature it is possible to understand through time how this feature behaved. This allows the research to state that the feature originally known as “Belt Island” was the paleogeographic area of non-deposition and erosion of a larger peripheral bulge. This lithospheric flexure would have been the reaction to the crustal loading to the west during the Western North America Cordilleran Orogeny.

CHAPTER 1 - INTRODUCTION

Part I: Objective

The objective of this project is to better understand the historically enigmatic “Belt Island” feature. The delineation and definition of this feature has evolved based on improved understanding of geologic processes through time and the quality and increased availability of subsurface data. Since its original usage, the concept has been often misapplied and changed in its application by subsequent authors. “Belt Island” is the product of structural geology, preserved in the stratigraphic record of the Jurassic Ellis Group. The overarching question of this research is: does the stratigraphy and sedimentology of the sedimentary rocks comprising the Ellis Group support the theory of a large paleogeographic/paleotectonic feature in north-central Montana during the Jurassic and does the evidence support or contradict the geologic conditions postulated to control the presence of this feature?

This project investigated outcrops and cores across north-central Montana and assembled geologic profiles of the Ellis Group at key locations to delineate the distribution of lithofacies. If present during Ellis Group deposition, a large feature would have had a direct influence on the sedimentary processes and related deposits.

Additionally, a stratigraphic framework was constructed based on lithostratigraphy, published biostratigraphy, and mapped regional unconformities. Combining these data provides the foundation for developing a chronostratigraphically significant framework.

This sequence stratigraphic framework allowed for correlation of outcrops, cores, and geophysical well logs across the project area, enabling interpretation of coeval strata.

The project also incorporated an understanding of local structure and the paleotectonics of north-central Montana. The Sweetgrass arch, the Western North American Cordillera, and the Great Falls tectonic zone were investigated, yielding an informative and modern context to the “Belt Island” feature. This made it possible to interpret the paleotectonic elements that controlled the location and timing of the “Belt Island” feature.

Part II: Project Area, Ellis Group, and “Belt Island”

“Belt Island” is a concept that has evolved through time and in the literature. As such, it is important to understand the historical context, through the contributions of previous authors to the collective understanding on these two topics. Furthermore, it is important for the reader to understand that the full geographical extent of both the Ellis Group and “Belt Island” do extend beyond the boundaries of the project area and the scope of this research. The purpose of this research is to clarify the influence of the “Belt Island” feature on the sedimentary rocks known as the Ellis Group in north-central Montana as defined by the project area boundary. The subsequent chapters will focus on the elaboration of the geological context, with some additional historical context where pertinent.

Project Area:

The project area is bounded by the Western North America Cordilleran Fold and Thrust Belt to the west, the Bear's Paw Mountains to the east, the International border with Canada to the north, and the southern boundary is delineated by the southern county lines of Teton and Chouteau Counties. More specifically the project area comprises the Montana counties of Glacier, Toole, Liberty, Hill, Pondera, Teton, Chouteau, and the western portion of Blaine County (Figure 1). The use of these boundaries facilitates subsurface data management, which is organized by county.

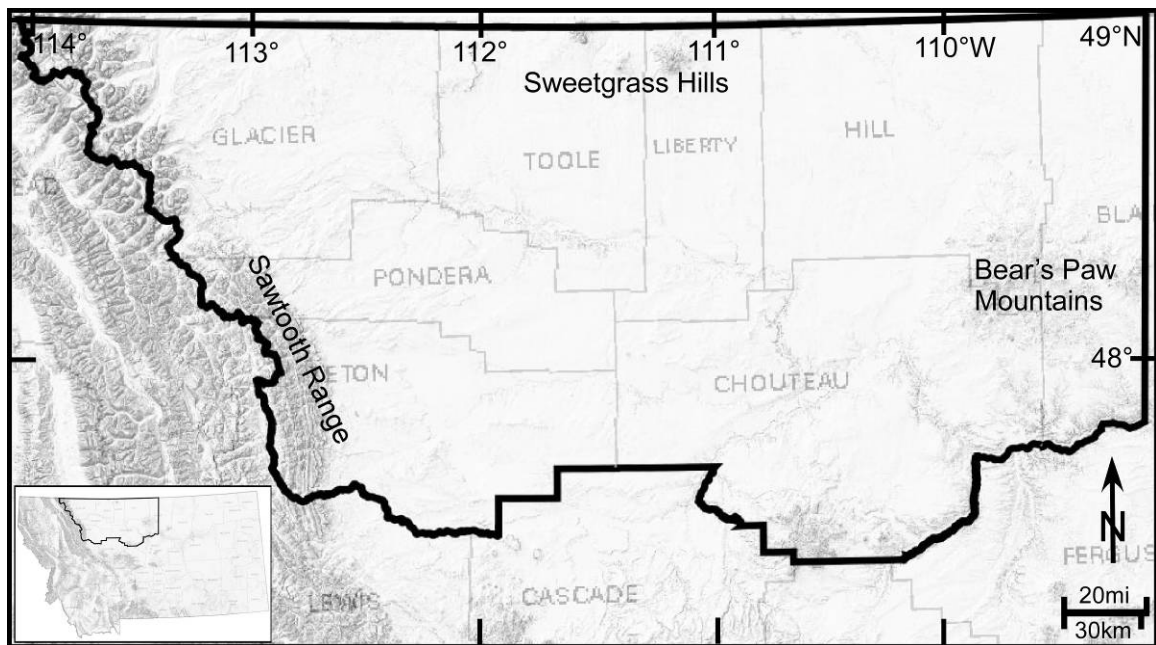


Figure 1: Project area. The insert map in the lower left of this figure shows the location of the project area within the state of Montana. The larger map shows the project area boundary (bold black line) as it follows the eight counties where surface and/or subsurface data were utilized. The research stopped at the 49th parallel (United States, Canadian border). The Sawtooth Range is a subordinate mountain range on the greater Western North America Cordilleran Fold and Thrust Belt. Note the latitude and longitude markers for global reference.

Ellis Group:

The Jurassic rocks of the Ellis Group were first described by F.V. Hayden, and by A.C. Peale in two separate chapters of the “Sixth Annual Report of the United States Geological Survey of the Territories Embracing Portions of Montana, Idaho, Wyoming, and Utah; being a Report of Progress of the Explorations for the Year 1872 (Hayden, 1873). The first appearance of the name “Ellis Formation” was in A.C. Peale’s work on “The Paleozoic section in the vicinity of Three Forks, Montana” of 1893. W.H. Weed (1896) was the first in published works to assign the name “Ellis” to rocks in north-central Montana. Cobban (1945) after detailed outcrop and subsurface analysis in the greater north-central Montana region, moved to change the Ellis from a formation to a group. The Ellis Group type section was designated by W.A. Cobban, R.W. Imlay, and John B. Reeside, Jr. (1945) in Gallatin County, Montana at the type locality in Section 19, Township 2 South, and Range 7 East. “The Ellis (Jurassic) is one of the most important formations of the plains area in relation to the oil industry, as it is both a source and a reservoir of oil” (Sanderson, 1931). There is presently a positive structure in the general paleogeographic area that “Belt Island” occupied, known as the “Sweetgrass arch”, first described by Stebinger (1916). Internal nomenclature of the Ellis Group changes over the Sweetgrass arch (Figures 2 and 3). On the western flank of the Sweetgrass arch the Ellis Group is comprised of the Sawtooth, Rierdon, and Swift Formations in ascending order (Nordquist, 1955). The Ellis Group on the east flank of the Sweetgrass arch is comprised of the Piper, Rierdon, and Swift Formations in ascending order.

The reader should be aware that although this was proposed not all subsequent authors subscribe to this naming criterion. Therefore, the name Sawtooth (and its members) were then and are still used outside of the applicable area, where the Piper naming system is much more appropriate based on lithologic differences. As this paper shows, there are fundamental differences in these two formations based on regional tectonism affecting the sedimentology and subsequently the stratigraphy of each in different ways.

“Belt Island”:

A major paleogeographic feature described in the literature in west-central Montana during Jurassic time and defined as: “...the Big Snowy, Little Belt, and Big Belt uplifts, the southern part of the Sweetgrass arch south of the Marias River, and probably the Little Rocky Mountains uplift were united and formed a low, irregular-shaped island, herein called [“Belt Island”]...” (Imlay et al., 1948, map). This feature influenced the stratigraphic framework and lithofacies distributions comprising the Ellis Group. However, the degree of influence, paleogeographic position, and causal explanations (if presented at all) are inconsistent by subsequent authors (in particular Schmitt, 1953; Nordquist, 1955; Peterson, 1957; and Peterson, 1972). Schmitt (1953) implies “Belt Island” and Kevin-Sunburst dome are synonymous which is in disagreement with the original definition and the zero-isopach area of the map, which by name would place “Belt Island” in a different paleogeographic area from the definition. Schmitt (1953) is the first paper since the inception to show it as more of a peninsula than an island in all figures; based on the westward edge being limited by the western edge of Jurassic rocks.

Nordquist (1955) is more of a review on the matter of “Belt Island” and is focused on the east and west transition in nomenclature of the Sawtooth and Piper Formations over the axis of the Sweetgrass arch. It is important to know that the stratigraphy of the area is of utmost importance, as it is the primary reason for the delineation of “Belt Island” based on zero-isopach lines. “Regionally the marine Jurassic can be separated into lithogenetic units whose characteristics appear to be directly related to the presence of sedimentary environments, the nature of which was governed by the position and relative activity of the various paleotectonic elements” (Peterson, 1957). Peterson (1957) went on to state that “Belt Island” affected the sediments and the faunal distributions by influencing the currents, salinities, and temperatures of the marine waters during the time of deposition. Peterson (1972) is a substantial assimilation of the previous work on the Ellis Group (Jurassic in general) and the “Belt Island” feature. Based on the collection of previous work, Peterson (1972) states “Lithofacies patterns...do not suggest that [“Belt Island”] was an important local source of clastic materials” (p. 177). See Figure 2 for a general outline that encompasses the multiple authors’ descriptive areas. Chapter 2 goes into greater detail of the multiple authors’ analysis, data sources, and potential causal explanations for, and paleogeographic placement of “Belt Island”. A subsequent problem in the literature concerning the terms “Belt Island” and “Sweetgrass arch” is that they are often misapplied as interchangeable, exacerbating the enigmatic nature of the feature. These reasons emphasize that although the “Belt Island” feature is widely recognized, it is not adequately understood.

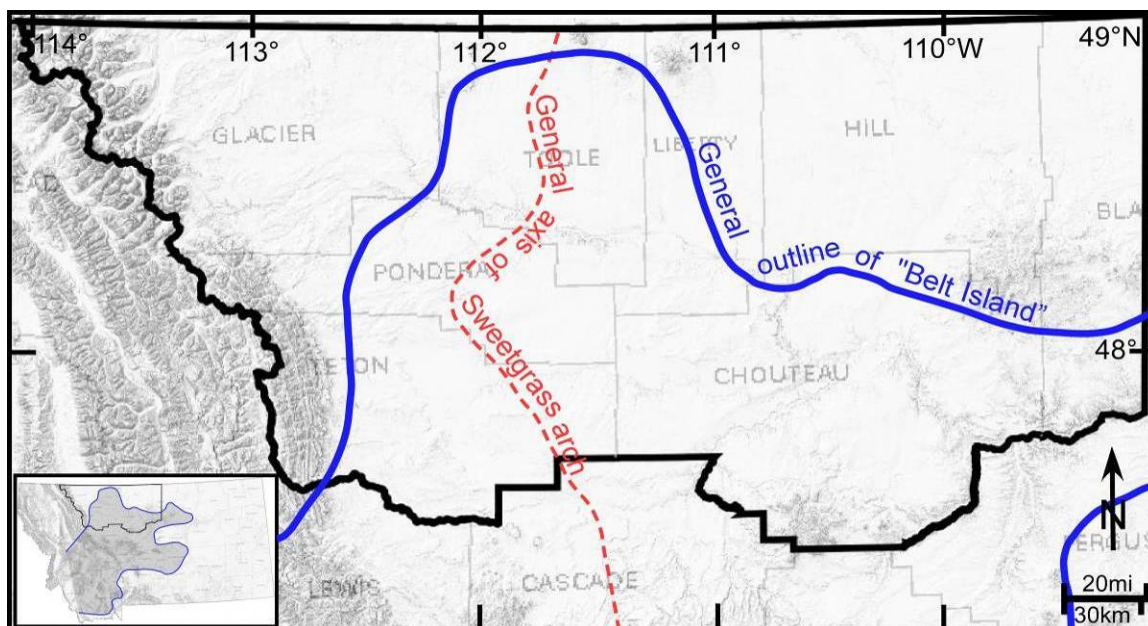


Figure 2: “Belt Island” and Sweetgrass arch. General outline of “Belt Island” (blue solid line) encompasses the majority of outlines. The general axis of the Sweetgrass arch (dashed red line) as modified from Nordquist (1955).

Period	Epoch	Stage	Age (Ma)	Duration myr		< - Sweetgrass arch - >		
						Western	Eastern	
Jurassic	Late	Kimmeridgian	155.7	4.9	Ellis Gp.	Swift Fm.		
		Oxfordian		5.5			Sandstone Mbr. Shale Mbr.	
	Middle	Callovian	161.2	3.5				
		Bathonian	164.7	3.0		Rierdon Fm.		
		Bajocian	167.7	3.9		Sawtooth Fm.	Siltstone Mbr. Shale Mbr. Sandstone Mbr.	Piper Fm. Bowes Mbr. Firemoon Ls. Mbr. Tampico Sh. Mbr.
						171.6		

Figure 3: Stratigraphic column, modified from the works of Hayes (1984) and Gradstein et al. (2004). This column shows the relative time of deposition of the four formations that make up the Ellis Group. Note the change in nomenclature of the basal formations, this is in reference to the east and west slope of the Sweetgrass arch, as discussed in the literature and shown in Figure 2.

Part III: Significance of Research

Building on previous work and generated data on lithofacies characterization, lithostratigraphy, biostratigraphy, and regional unconformities, this project assembled a high-resolution chronostratigraphically significant framework of the Jurassic Ellis Group in north-central Montana. This framework allowed for a regional sequence stratigraphic interpretation that constrains lithofacies distributions of the Ellis Group in north-central Montana. This framework fills a geographic gap in previous author's interpretations of the sequence stratigraphy of the Ellis Group and thus fills an important gap in the understanding of the Jurassic System in Western North America. Inherent to this sequence stratigraphic framework is the applicability to place in a spatial and temporal context "Belt Island"; clarifying its enigmatic nature.

The Ellis Group is important to the future of resource management in north-central Montana. Additional oil and gas potential exists in the Ellis Group, both in undiscovered resources and for enhanced production in depleting oil and gas fields through enhanced oil/gas recovery techniques (EOR / EGR) utilizing carbon dioxide flooding (Orr, 1984) (Wennekers, 1985) (Holt et al., 1995) (Oldenburg and Benson, 2001) (Oldenburg et al., 2004). Further potential resides in exploiting the Ellis Group's rock properties that allow it to be a regional seal (Nordquist, 1968) to the underlying Paleozoic carbonates (Dolson et al., 1993; Dolson and Piombino, 1994) that have potential as a sink for geologic carbon sequestration (GCS) (Holt et al., 1995).

This research adds to the collective understanding of the Ellis Group. The geologic framework serves as a foundation to better understand migration of subsurface fluids, both external and internal to the Ellis Group. This enables more environmentally sound and economically beneficial resource management methods to be implemented. Whether the goal is to extract the resource or sequester it, better understanding of the stratigraphy and lithofacies of the Ellis Group is paramount.

CHAPTER 2 – GEOLOGIC SETTING

This chapter presents a summary of the geologic setting for this project, through previous work. It incorporates a more detailed review of the previous stratigraphic work on the Ellis Group. The chapter elaborates on the pertinent and arguably influential structural and tectonic features. Finally, the last section separately addresses the grammatically, literary, and geologically enigmatic nature of “Belt Island”.

Ellis Group: A Review on the Lithostratigraphy and Biostratigraphy

It is important to note that much of the early work was made possible by guide fossils (namely ammonoids, cephalopods, and bivalves). Therefore, the beginnings of the lithostratigraphic Ellis Group are closely intertwined with the biostratigraphy. It is important to remember the evolution in nomenclature from formation to group of the Jurassic Ellis. Additionally the basal formation name change within the project area, Sawtooth and Piper Formations, west and east respectively (Figure 2 and 3). As stated in the introduction, not all naming systems were adhered to throughout the years of scientific and resource exploration, the various names are included for what might be called, “translation” purposes.

Piper Formation:

The Piper Formation type locale is located to the south of Piper, Montana, just outside of the project area. The lithology at the type section has very little in common with the lithology noted in outcrop and core of the project.

This is common outside of the project area where the Piper Formation was dominated by a restricted marine environment of deposition versus within the project area where it is shelf to shallow marine in characteristics. The formation is partitioned into three members listed below in chronostratigraphic order.

Tampico Shale Member: This member is the basal member of the Piper Formation. Nordquist (1955) termed it the Tampico Shale Member, however in core and outcrop the entire interval is only sandstone within the project area. It ranged in the project area from zero to tens of feet in thickness. It unconformably overlies the Madison Group which correlates to the J-2 regional unconformity of Pipiringos and O'Sullivan (1978). There appears to be a surface just below the stratigraphic top that appears to be more of a diastem than long term hiatus. *Defonticeras* was discovered in this member placing it in the Bajocian Stage (Imlay et al., 1948).

Firemoon Limestone Member: The middle member of the Piper Formation was found to have multiple names in use as well (Kolstad, Firemoon Limestone Member, Piper Lime, and Piper Limestone). Nordquist (1955) named it the Firemoon Limestone Member, and it is predominantly just limestone within the project area. This member has vertical variation of zero to tens of feet within the project area. This member appears to share a conformable contact with the Tampico Shale Member. *Defonticeras* was discovered in the lower portion of this member placing it in the Bajocian Stage (Imlay et al., 1948). *Cranocephalites* can also be found in this member placing it in the Bathonian Stage (Imlay, 1945).

Bowes _____ Member: The upper member of the Piper Formation appears to have only the name it was given as named by Nordquist (1955), other than in the earlier years just being referred to as the upper member. This member appeared to be present over most of the project area, ranging from zero to tens of feet to some isolated areas of over 100 feet. It rests unconformably over the Firemoon Limestone Member; it is unknown whether this disconformity is intra-regional or possibly a regional unconformity, it was not mentioned by Pipiringos and O'Sullivan (1978). *Arctocephalites* have been discovered and therefore is placed in the Bathonian Stage (Imlay, 1945). Deposits that appear to be algal bound were determined to be *Lithothamnium ellisianum* (Howe and Goldman, 1925).

Sawtooth Formation:

The Sawtooth Formation is named for the Sawtooth Range in which the type section is, particularly Rierdon Gulch in Section 23, Township 24 N, Range 9W (Cobban, 1945). This locale resides within the project area and between SRCFS and SWRFS and therefore is very similar to the lithology seen in outcrops and cores. The formation is partitioned into three members listed below in chronostratigraphic order.

Sandstone _____ Member: This is the basal member of the Sawtooth Formation as coined by Cobban (1945), but also went by other names: basal sandstone, Emrick sand, Bannatyne sand, Crow Indian Lake Member, and basal stray sands. This member ranges in thickness from zero to tens of feet within the project area.

It rests unconformably over the Madison Group, this interface being the J-2 regional unconformity of Pipiringos and O'Sullivan (1978). *Defonticeras* was discovered in this member placing it in the Bajocian Stage (Imlay et al., 1948).

Shale Member: The middle member of the Sawtooth Formation as termed by Cobban (1945). This member ranges in thickness from zero to over 100 feet. It rests conformably over the Sandstone Member. *Defonticeras* was discovered at the base in this member placing it in the Bajocian Stage (Imlay et al., 1948). *Cranocephalites* can be found in this member placing it in the Bathonian Stage (Imlay, 1945).

Silts tone Member: The upper member of the Sawtooth Formation as termed by Cobban (1945), however it has been referred to as the Conrad Member. This member ranges from a few feet to many tens of feet over the project area. This member overlies the Shale Member. *Arctocephalites* have been discovered in these deposits and therefore is placed in the Late Bathonian Stage (Imlay, 1945).

Rierdon Formation:

The Rierdon Formation is named from the type section Rierdon Gulch in Section 23, Township 24 N, Range 9W (Cobban, 1945). Although there are limestone beds within the formation, the formal name is just Rierdon Formation, not Rierdon Limestone as has been used by some authors. The formation was separated by Peterson (1957), and him alone, into lithologically dissimilar "members", however no subsequent authors took to this, nor was there any naming of separate lithostratigraphic members. The formation ranges from zero or near zero to hundreds of feet within the project area.

The formation rests conformably over the Sawtooth and Piper Formations. The Rierdon formation shows fossils of *Arctocephalites* for the Bathonian Stage, ascending to *Cadoceras*, *Kepplerites*, and *Cosmoceras* of the Callovian Stage (Imlay, 1945).

Swift Formation:

The Swift Formation is the upper most formation of the Ellis Group, and gets its name from the type section at Swift Reservoir (SWRFS), in Section 27, Township 28 N, and Range 10W (Cobban, 1945). The Swift Formation is comprised of a lower Shale Member and an upper Sandstone Member.

Shale Member: The Shale Member ranges in thickness from zero to tens of feet in the surface and subsurface. The basal contact is the J-4 regional unconformity of Pipiringos and O'Sullivan (1978) with the Rierdon Formation, most often a "belemnite conglomerate" and commonly associated with a glauconite rich sandstone. The Shale Member was determined to be diachronous across the early and late Oxfordian based on both *Quenstedtoceras* and *Cardioceras* (Imlay, 1945).

Sandstone Member: This member, as the Shale Member, was broken out by Cobban (1945) based on its mappable lateral extent. This member has the local term of "ribbon sand". The member ranges in thickness from zero to tens of feet, occasionally over a hundred feet, the zero isochore areas of this member are due to post-Jurassic erosion. The member rests predominantly in conformity with the underlying Shale Member. The upper boundary of the unit appears to be a paraconformity with the Morrison Formation.

This J-5 regional unconformity of Pippingos and O’Sullivan (1978) may be expressed as either a disconformity or a correlative conformity. The Sandstone Member appears to be Oxfordian based on the presence of *Cardioceras* (Imlay, 1945).

Structural Setting

This section shows the strong correlation of notable tectonic features, in particular the Sweetgrass arch, the Great Falls tectonic zone (GFTZ), and the Western North American Cordillera, within and proximal to the project area. It sets the stage for the obvious overprint and or juxtaposition of said features and the far reaching implications in explaining “Belt Island” in a modern context. Chapter 7 goes into further detail on these features.

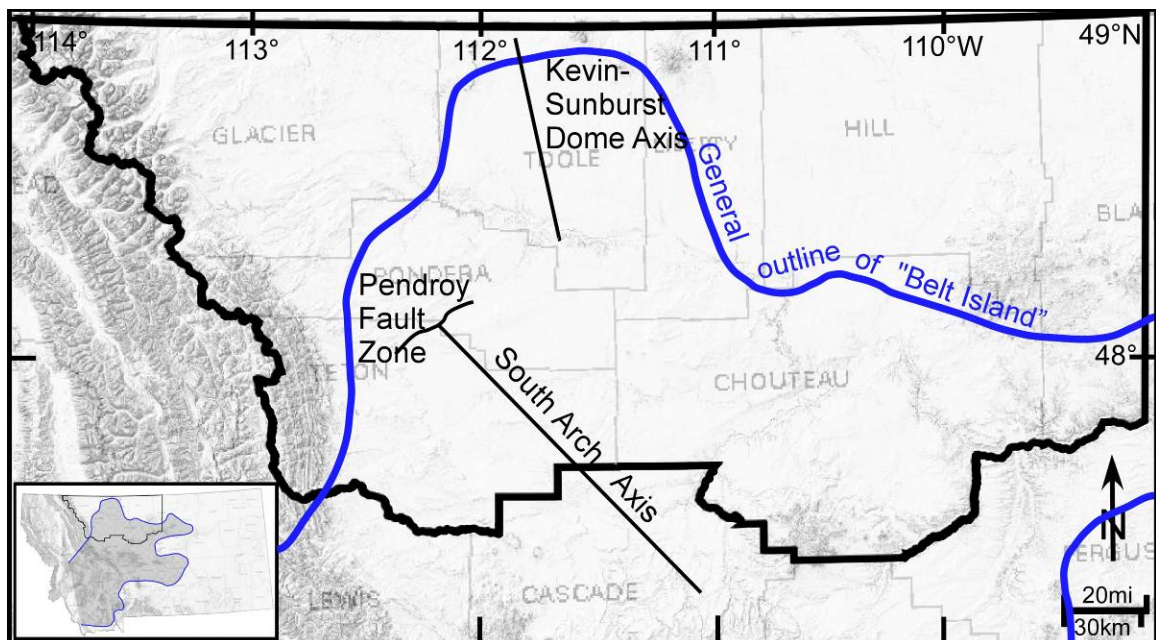


Figure 4: Sweetgrass arch and “Belt Island”. The South arch and Kevin-Sunburst dome make up the greater Sweetgrass arch in Montana; north into Canada, other features are present. The South arch has a downward trajectory to the northeast-trending Pendroy fault zone, where the Sweetgrass arch general axis steps northeast to join the Kevin-Sunburst dome axis.

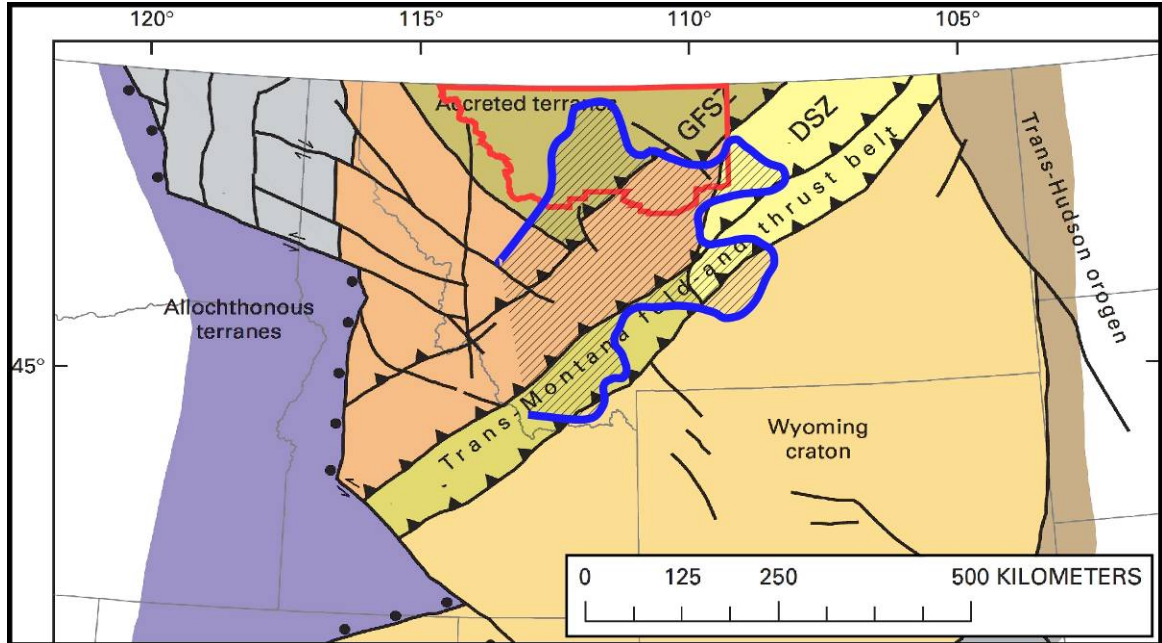


Figure 5: General outline of “Belt Island” over the Great Falls tectonic zone. Project area border is the red line and “Belt Island” general outline in blue. Note the correlation between “Belt Island” (Middle to Late Jurassic) and the greater Great Falls tectonic zone (origin in the Paleoproterozoic). The base map is modified and generalized to stay within the scope of this project; see (Sims et al., 2004) for more details on the basement geology of the area.

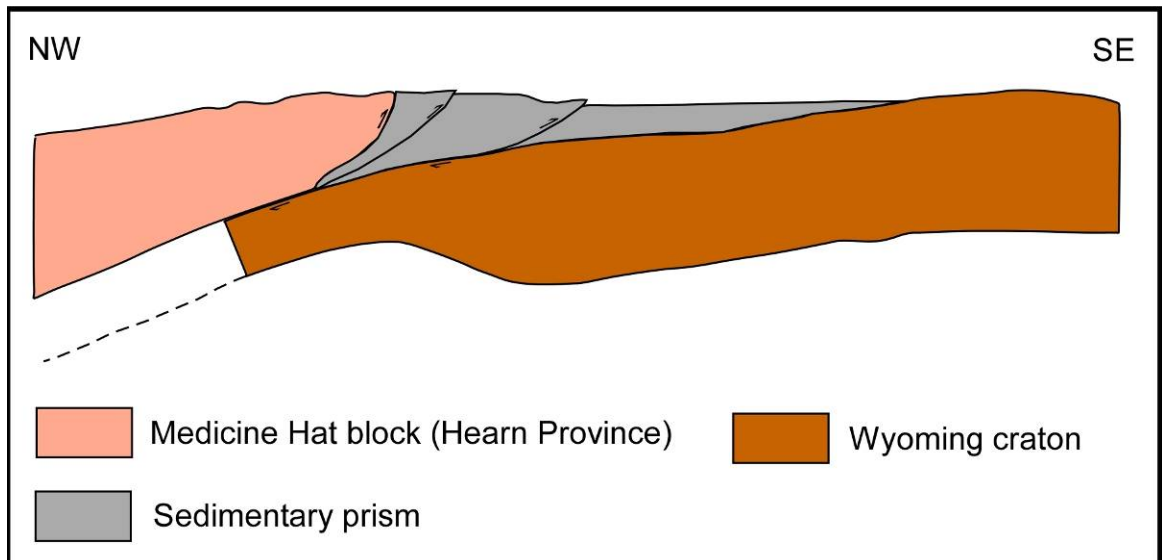


Figure 6: Generalized cross section of the Trans-Montana Orogeny (Paleoproterozoic) leading to the development of the Great Falls tectonic zone. This cross section compliments Figure 5. Modified from Sims et al. (2004).



Figure 7: Paleogeographic map of Western North America around 160Ma during the Oxfordian (Blakey et al., 2003). This shows the development of the cordillera to the west of the project area and change in paleobathymetry across the project area. Note the project area (black line) and the general outline of “Belt Island” (blue line).

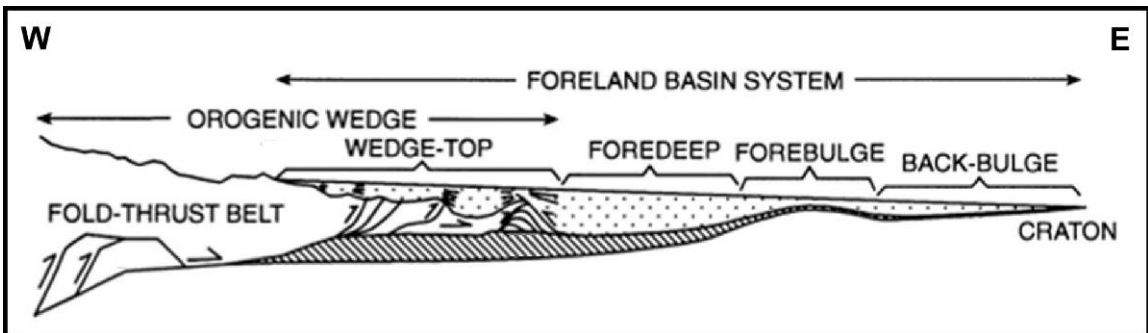


Figure 8: General cross section of a developing foreland basin system (DeCelles and Giles, 1996). This cross section just compliments Figure 7 and it is not intended to imply a direct correlation.

The Sweetgrass arch is a modern day feature in north-central Montana that is emplaced in nearly the same paleogeographic space as did “Belt Island”, see Figure 4. It is a large scale arch, of which the South arch comprises a portion of “Belt Island” as defined by Imlay et al. (1948).

Note the influence on the shape of the general outline of “Belt Island” by the components of the Sweetgrass arch.

The Great Falls tectonic zone is displayed nicely in Figures 5 and 6. Figure 5 in particular shows the strong correlation between the northeast trending feature, known as the Great Falls tectonic zone, and “Belt Island”. The general outline of “Belt Island” does appear to have a northeast trend to it as well.

The Western North American Cordillera and the development of a foreland basin system in and near the project area, plays a large role in explaining “Belt Island” in a modern context; separately and coupled with the GFTZ and the Sweetgrass arch. Note the cordillera just to the west of the project area in Figure 7; this would be the “orogenic wedge” of Figure 8. Figures 7 and 8 together begin to assemble a picture of what tectonics were active during the Middle to Late Jurassic and where the “Belt Island” feature would have been in a developing foreland basin system.

“Belt Island”

This section expands on the concept of “Belt Island”, in particular with the inception of this concept through the major contributing works to the matter (Imlay et al., 1948; Schmitt, 1953; Nordquist, 1955; Peterson, 1957; and Peterson, 1972) to the subsequent works that used the concept with no clarification on the enigmatic nature. The focus here is to point out, in detail, the evolution of the concept and in the authors’ opinion why: the degree of influence, paleogeographic position, and causal explanations, if presented at all, are enigmatic and inconsistent.

The author would like to address the usage of isopach maps (previous work) and isochore maps (this project). The previous work (Imlay et al., 1948; Schmitt, 1953; Nordquist, 1955; Peterson, 1957; Peterson, 1972) uses the term isopach in their work, though they do not specify it is highly unlikely that they are showing true stratigraphic thickness and therefore their maps are probably isochore maps. When there is no wellbore deviation data, then an isopach can not be generated. However, the author has decided to leave the original literature as is when cited, and leaves it to the reader to understand that in the author's opinion all maps of this nature are isochore maps.

During the time of working on this research, the author has noticed the seemingly obligatory use of "belt" in the state of Montana; most often made obvious by the numerous audiences' confusion when discussing this topic. Therefore, it seems prudent to address some of the equivocation related to the name. First and foremost, it should be understood that the usage of the name "Belt Island" is in direct reference to the inception of the term by Imlay, Gardner, Rogers, and Hadley in their 1948 "Marine Jurassic Formations of Montana" USGS publication. There is a Mesoproterozoic sedimentary deposit by the name Belt Supergroup (aka Belt Series) that may be referred to as "Beltian". There is the unfortunate case of double use of "*Belt Island*" in reference to an area of presumably missing Belt Supergroup, however this would be to the west and south of the project area and 1.3 billion years prior (Schmidt and Garihan, 1986). There is the use of the Belt area in the literature that can be in reference to the town Belt, Montana, whereby there is good exposure of the Ellis Group.

Additionally, there is the overlap of the Little Belt and Big Belt Mountains, both geographically and in the definition with “Belt Island”. By definition the island was an effect of the mountain uplifts and therefore a separate feature. As for the more general use of it in referring to the belt of disturbed rocks, (aka disturbed belt). Although there is overlap in geography and tectonic explanation it would be inaccurate to use them interchangeably with “Belt Island”. That should address the majority of the questions on the grammatically enigmatic nature of “Belt Island”. Additionally, there is the matter of the aliases used by authors when addressing the “Belt Island” feature or area on a map (belt island trend, belt island complex, boulder high, belt high, belt arch, belt uplift, belt island positive, belt island element).

Imlay, Gardner, Rogers, and Hadley (1948):

This work marks the inception of the concept of “Belt Island”, as stated, cited, and referenced in the introduction for the definition. The work was constructed from 78 surface (outcrop) and subsurface (well) data points throughout the state of Montana. Of the data points, six surface and four subsurface data points were within the current projects boundary; with six more being proximal to the boundary and contributing to the stratigraphic analysis. Thickness intervals were taken from these data points, and in some cases columnar sections were constructed and integrated with paleontologic data. These data allowed for the construction of lithostratigraphic cross-sections and isopach maps. The products generated therein show thinning and omission of certain intervals of the Ellis Group and the datum variant nature of the basal unconformity.

It is this thinning and omission (zero-isopach) that is the foundation of “Belt Island” (see Figures 9, 10, and 11). That is to say, with this low-resolution framework original work, wherever there is missing Ellis Group (all or part) is the paleogeographic location of “Belt Island”.

What is enigmatic about the concept of “Belt Island” is that it is both a cause and effect. “Belt Island” is the effect of uplifted areas causing erosion and or non-deposition of intervals of the Ellis Group. Therefore, the delineation of “Belt Island” is a direct function of the number of data points and level of resolution of the stratigraphic framework. Based on these data the authors conclude that during the “Piper-Sawtooth time” it was only a minor sediment provenance and its major contribution was the partitioning of the Middle Jurassic epeiric sea into multiple basins with further division into embayments. During “Rierdon time” “Belt Island” affected the lithofacies distribution by contributing small amounts of sand and silt to the surrounding sea, and continued partitioning of the epeiric sea. In the “Swift time” pebbles and boulders of chert and quartzite were “furnished” to the surrounding sea. In addition to the effect nature of “Belt Island”, it is apparent that the authors conclude that it is an effect of paleotectonism in the area and not in itself a paleotectonic feature.

Schmitt (1953):

This work is the next significant literary contribution to “Belt Island”. The work is significantly larger in scope than the current research project. The focus was the correlation of the middle and upper marine Jurassic rocks over the very large area of the northern Rocky Mountains-Great Plains.

The work is comprised of 58 data points over portions of Alberta, Saskatchewan, Manitoba, Montana, North Dakota, South Dakota, Wyoming, Idaho, and Utah. Of the 58 data points, there are four surface data points and nine subsurface data points; with five combined data points proximal to the project area for this research.

Schmitt constructed isopach-lithofacies and paleogeologic maps from the data and subsequent analysis. Through the construction of these maps and cross-sections, Schmitt used the same fundamentals as the previous work to determine the general outline of “Belt Island”, e.g. thinning and omission of intervals of the Ellis Group and the association with lithofacies distribution (see Figures 9, 10, and 11). Therefore, with different data points the shape of “Belt Island” changes in paleogeographic extent. Furthermore, since the data points change, so apparently does the perceived western extent of Jurassic rocks, which changes the appearance of “Belt Island” into a peninsula presumably connected to other emergent land to the west. Coupled with the zero-isopach Schmitt notes in the stratigraphic framework the increase in disconformities around the periphery of the area that is therefore “Belt Island”. Schmitt again cites lithofacies distribution, represented as a reduction in grain size away from “Belt Island”, just as in the previous work. It appears in this work Schmitt does not draw a distinction between “Belt Island” being a paleogeographic area and a paleotectonic feature.

Nordquist (1955):

This paper is more of a review on the matters of “Belt Island” and the Ellis Group, and only presents evidence of previous work. An important paper, as it addresses an important matter in constraining the spatial and temporal complexity of “Belt Island”.

The paper discusses in depth the correlation of, and presents evidence in support of the Piper and Sawtooth Formations being coeval. This is important to know when making the argument that some “positive element” was partitioning the sedimentary environments during the deposition of these formations. Additionally, it is important to know that these formations are chronostratigraphically equivalent and that topography of some kind was having an impact great enough on the distribution of lithofacies to cause the difference in naming. Furthermore, the change from lithologically similar deposits (basal sands) to drastically different (siliciclastic vs. carbonates) and then back to lithologically similar and now laterally continuous (Rierdon Formation) shows the dynamic influence of a positive element in a temporal context. Finally, to address some of the naming inconsistencies, this paper does propose a defensible basis for the north-south boundary, incorporating some of the definition of “Belt Island”, for naming of the basal formation of the Ellis Group, Sawtooth or Piper Formation. The real contribution here is that with them both being chronostratigraphically equivalent deposits (down to and including the members), the naming does not effect the temporal and spatial location of “Belt Island” (see Figure 9), in other words, the basal formations can be treated as one unit for mapping and cross-sections.

Peterson (1957):

This work focuses significantly on the lithofacies distribution through the hypothesis that the separable and mappable lithogenetic units that comprise the Ellis Group are a direct indicator (proximal to the project area) of “Belt Island” both spatially and temporally.

The foundation for this work is 158 surface and subsurface data points over portions of Alberta, Saskatchewan, Manitoba, Montana, North Dakota, South Dakota, Wyoming, and Idaho combining stratigraphy, sedimentology, and paleontology to construct isopach maps and cross-sections. Six surface data points and four subsurface data points are within the current projects boundary, with a combined seven others being proximal to the project area.

Peterson purports “[“Belt Island”] was not a major source of clastic sediments during the Jurassic, but its influence upon sedimentary and faunal environments...was probably more profound than has generally been thought” (p. 403). “Belt Island” as a source, or more so the magnitude of influence, is in contrast to some extent with the previous authors. However, in regards to the level of influence it had on the partitioning of marine waters, Peterson proposes it was more profound than the previous authors had thought. That is to say, “Belt Island” had a significant influence on the lithofacies distribution of the Ellis Group. Peterson calls into question the very name and idea of this area “rarely if ever [being] an island” (p. 403). Through claiming that this positive area was submarine a majority of the time as a submarine isthmus challenges the concept of an island. However, a submarine isthmus connects two emergent areas, which would be in keeping with the idea of a “Belt Island” trend. Peterson breaks away from the earlier authors in delineating “Belt Island” by not just zero-isopach lines (see Figures 9, 10, and 11) but as well with the lithofacies distributions through his lithogenetic breakouts and therefore changing the overall paleogeographic area of “Belt Island” beyond the use of different data.

Peterson (1972):

Peterson (1972) is a substantial assimilation of the previous work and is the basis for data used in this work, including the above work and other less significant pieces relative to the scope of this research paper. Early on it is stated that there is “evidence of local, tectonically positive features” “Belt Island” being one of these features (p. 409). He goes on to reiterate a point from Peterson (1957), the distribution of lithofacies do not indicate a significant influence to clastic sediment sourcing, by the “Belt Island” feature. The writer would like to point out the comment about “Belt Island” being a local and tectonically positive feature; once again this is based on the collection of previous works. It seems now “Belt Island” is being referred to as a paleotectonic feature and not just a paleogeographic area where there was significant erosion or non-deposition of the Ellis Group. This inference is further supported by the comment, “Rierdon rocks are present throughout the region except for a zero-area in the vicinity of [“Belt Island”]...” (p. 178). In the beginning the zero-isopach areas *were* “Belt Island”, now it is its own paleotectonic feature. This paper does support the notion of a significant influence of “Belt Island” on the lithofacies distributions of the Ellis Group. It shows the paleogeographic area of “Belt Island” as being in somewhat different areas as the above works, though once again based on different data (see Figures 9, 10, and 11). In conclusion, this paper transitions the concept of “Belt Island” to a causal feature and not a passive feature during the deposition of the Ellis Group.

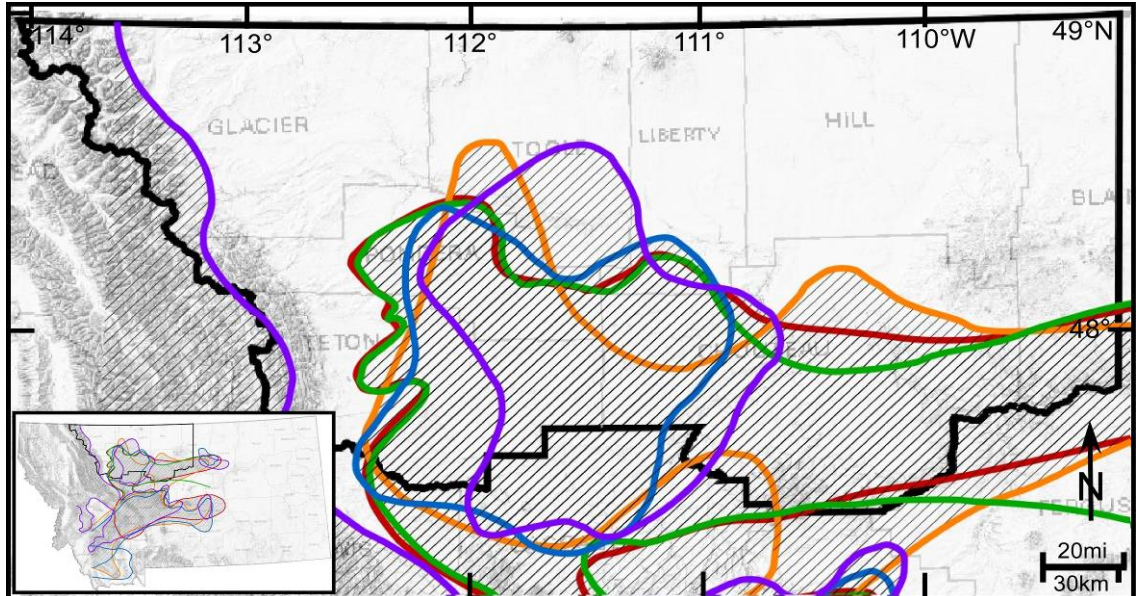


Figure 9: “Belt Island” during deposition of Sawtooth and Piper Formations. This figure shows the outlines of “Belt Island” (hashed area) as delineated by the zero-isopach lines. Imlay et al. (1948) is in red, Schmitt (1953) is in orange, Nordquist (1955) is in green, Peterson (1957) is in blue, and Peterson (1972) is in the purple.

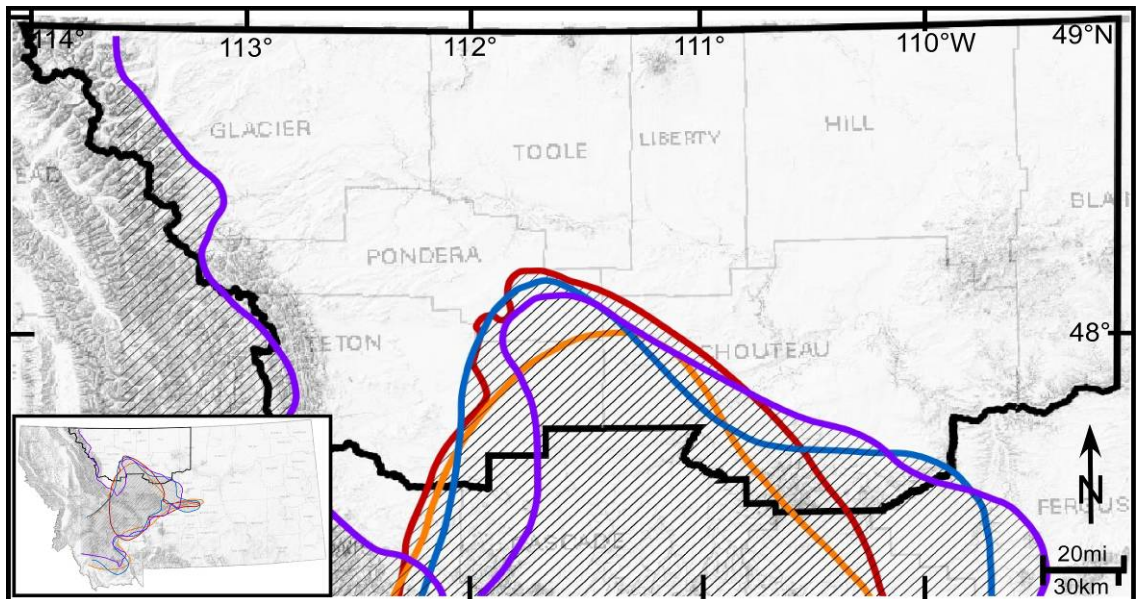


Figure 10: “Belt Island” during deposition of the Rierdon Formation. This figure shows the outlines of “Belt Island” (hashed area) as delineated by the zero-isopach lines. Imlay et al. (1948) is in red, Schmitt (1953) is in orange, Peterson (1957) is in blue, and Peterson (1972) is in the purple.

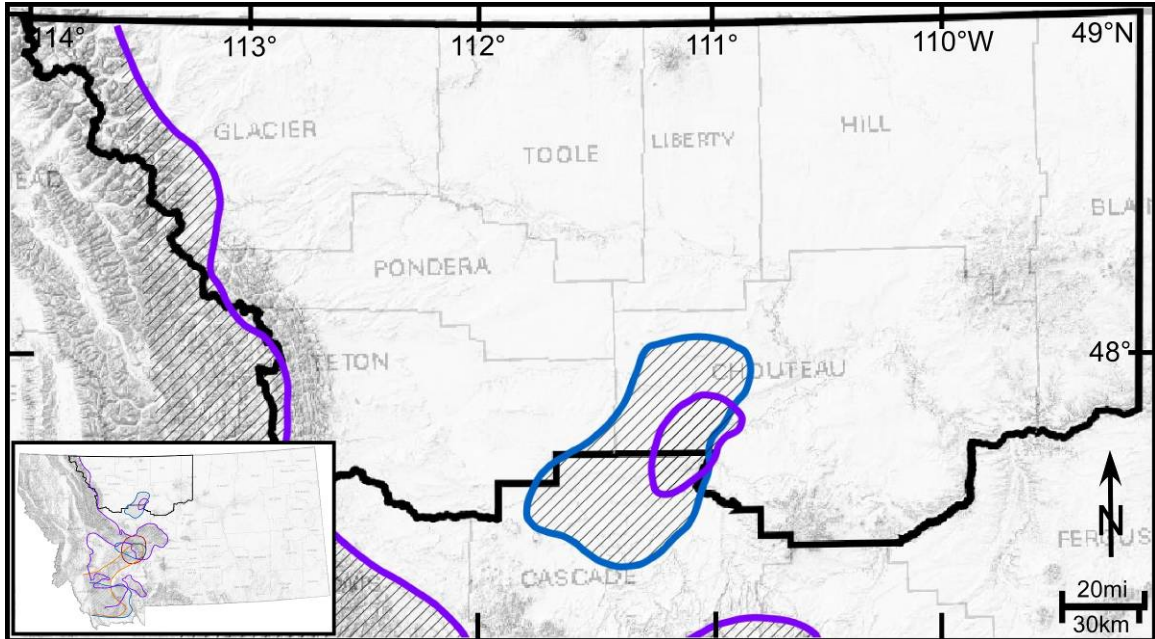


Figure 11: “Belt Island” during deposition of the Swift Formation. This figure shows the outlines of “Belt Island” (hashed area) as delineated by the zero-isopach lines. Imlay et al. (1948) is in red, Schmitt (1953) is in orange, Peterson (1957) is in blue, and Peterson (1972) is in the purple. Imlay et al. (1948) and Schmitt (1953) do not see evidence for “Belt Island” to be in the project area, only to the south, as might be noticed in the insert.

CHAPTER 3 - METHODS

This chapter describes the three main sources of data and details how it was employed to meet the objectives of this study. The overall system of methods employed integrates this multiscale and multisource dataset. A substantial breadth of geologic knowledge was gleaned from the literature search, aiding in high-grading outcrops, providing core analysis data, and contributing greatly to well log correlation. The project utilized outcrop data from field sites that had published measured sections, by field checking and generating new geologic profiles with greater detail to meet the needs of this project. Research continued with the addition of core data from select core geologic profiles generated with the same criteria as the outcrop profiles. Well data was a significant portion of the dataset, specifically using geophysical well logs to correlate stratigraphic surfaces and intervals pertinent to this project. In all, this chapter lays out the methods used in acquiring, processing, and integrating the outcrop data to core data (rock to rock), petrophysical calibration (rock to derived rock properties), and geophysical well log correlation (derived rock properties to derived rock properties).

Outcrops

The project began by utilizing previous descriptions by other authors at four field sites where the Ellis Group could be examined in outcrop. This aided in high-grading the outcrops in the project area and to keep the project within scope. The local stratigraphic architecture and lithofacies relationships were studied and important details were drafted into geologic profiles for each of the four field sites.

Compass and tape measure were used to accurately follow and verify the previous work. It should be noted that in some of the previous work, the scope of investigation was much broader than that of this project. Therefore, at some field sites corrections were made and the final geologic profiles reflect the writer's values. Information gleaned from the general field work will be further discussed in the subsequent chapters.

Sun River Canyon Field Site:

The Sun River Canyon Field Site (SRCFS) is located in Sections 25 and 36 of Township 22N and Range 9W in the Sun River Canyon, Teton County (Figure 12). Here 283 feet of Ellis Group rock description was drafted into a geologic profile from a combined dataset of the writer's field work and previous works (Cobban, 1945; Imlay et al., 1948; Mudge, 1972a, 1972b; and Porter, 1989). There is better exposure of the basal Ellis Group in Section 36, and easier access to the upper Ellis Group in Section 25.

Swift Reservoir Field Site:

The Swift Reservoir Field Site (SWRFS) is located in Sections 26 and 27 of Township 28N and Range 10W in the immediate area of Swift Reservoir, Pondera County (Figure 12). Here 472 feet of Ellis Group rock description was drafted into a geologic profile from a combined dataset of the writer's field work and previous works (Cobban, 1945 and Imlay et al., 1948). In Section 26, the author found better exposure of the lowermost Ellis Group with the rest of the group having excellent exposure in Section 27 along the north shore of the reservoir when reservoir water levels are low.

Sweetgrass Hills Field Site:

The Sweetgrass Hills Field Site (SGHFS) is located on East Butte of the Sweetgrass Hills near the headwaters of Sage Creek in Sections 7, 8, 17, and 18 of Township 36N and Range 5E, Liberty County (Figure 12). Here 297 feet of Ellis Group rock description was drafted into a geologic profile from a combined dataset of the writer's field work and previous works (Cobban, 1945; Imlay et al., 1948; Lopez, 1995, 2002; Porter, 1998; and Sanderson, 1931). Due to the intrusive nature of the Sweetgrass Hills, there is no single location where the complete section of the Ellis Group is preserved. Therefore, this field site involved compiling descriptions from many outcrops across a large area to complete an acceptable and geologically representative geologic profile. The reader may be aware of different spellings for the "hills". It was the writer's decision to use the earlier spelling found in the literature.

Bear's Paw Mountains Field Site:

The Bear's Paw Mountains Field Site (BPMFS) is located in the Bear's Paw Mountains near the headwaters of Suction Creek in Sections 1, 11, and 12 of Township 28N and Range 20E, Blaine County (Figure 12). Here 320 feet of Ellis Group rock description was drafted into a geologic profile from a combined dataset of the writer's field work and previous works (Cobban, 1945; Imlay et al., 1948; Hearn et al., 1964; Howe et al., 1925; Porter, 1996, 1998; and Reeves, 1924). This field site shares some of the same geologic history of intrusive activity as the other sites. Therefore, no single outcrop has complete exposure of the Ellis Group and a compiled section was created.

These mountains have great variation in their spelling. The writer has decided to use the spelling that agrees with the native's story of origin.

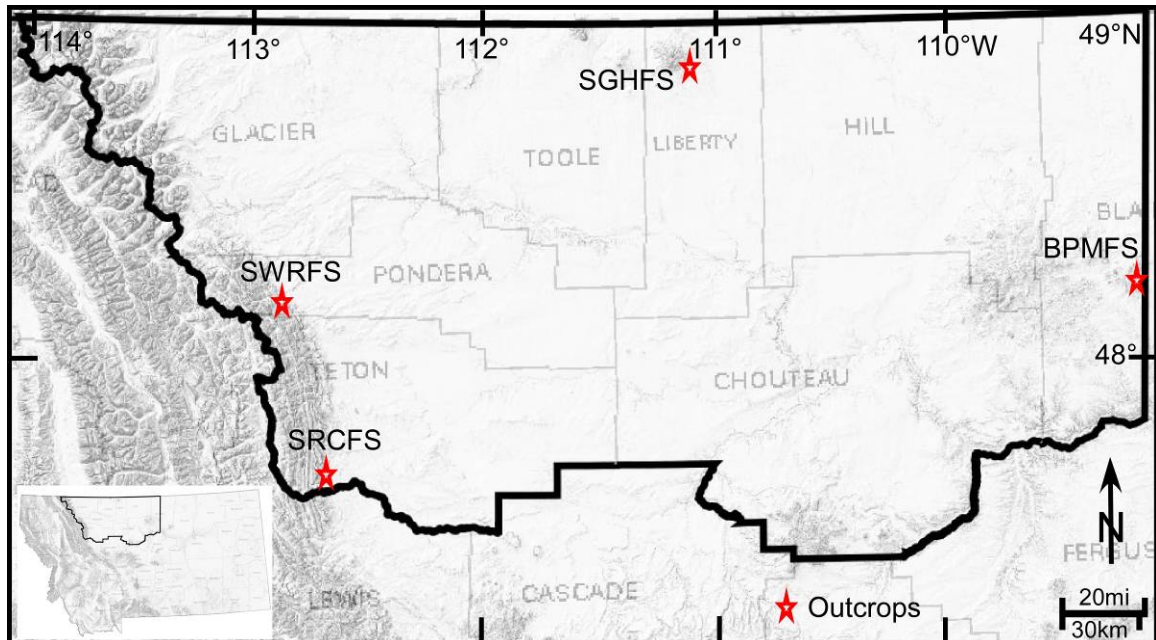


Figure 12: Project outcrops. This map shows the locations of the four outcrops used in this research project. In a clockwise manner, SRCFS is the Sun River Canyon Field Site, SWRFS is the Swift Reservoir Field Site, SGHFS is the Sweetgrass Hills Field Site, and BPMFS is the Bear's Paw Mountains.

Each of the four geologic profiles consists of compiled field notes and photos, and previous work that best represent the Ellis Group at that field site and across that area.

This work allowed for a total of 1372 feet of graphic geologic profile of the Ellis Group to be utilized in correlations to core (see full profiles in Appendix B). Furthermore, the outcrop profiles aided in the description of core by providing for a more knowledgeable and focused approach to inspecting and describing them.

Cores

Core research began by locating what cores were available from the project area that contained intervals of the Ellis Group. There are 159 wells that met these criteria. From the 159 wells cored, 16 cores were found to be publicly accessible at the United States Geological Survey (USGS) Core Research Center in Denver, Colorado. The writer inspected the 16 cores and determined 13 cores were usable, three were rejected due to poor quality. The remaining 13 cores allowed for a total of 1036 feet of core to be described and drafted into 13 graphic geologic profiles (see locations in Figure 13, details in Table 1, full profiles in Appendix C). It should be noted that it is common for coring to be done in multiple runs resulting in “multiple cores” coming from one well. With that said, in this project all cored wells are referred to as having one core, regardless of the number of coring runs or separation of interval, therefore 13 cored wells equals 13 cores. Focus was on unit thickness, vertical lithofacies relationships, and important stratigraphic surfaces. Core analysis data (porosity and permeability) was available for 10 of the 13 cored wells from the USGS and the Montana Board of Oil and Gas Conservation (MBOGC).

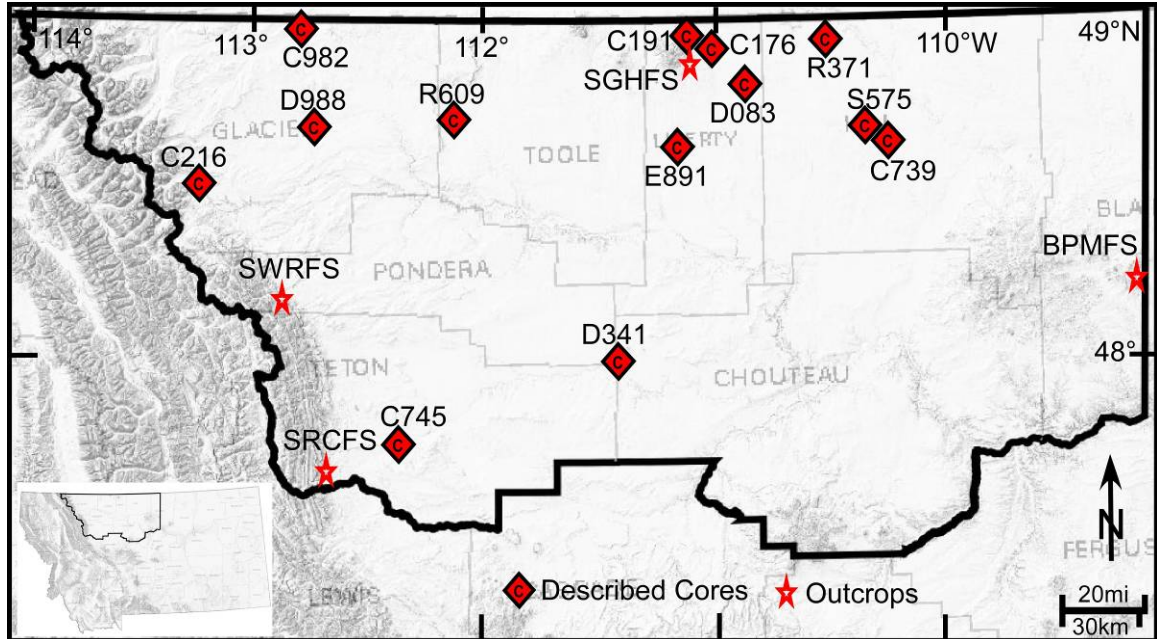


Figure 13: Described cores used for project. This map shows the location of the 13 wells that were cored and publicly available. The labels come from the USGS Core Research Center Library number used to designate the specific well that one or more cores were recovered from.

Table 1: Described cores location data. This table shows specifics for both virtual and physical locations on the 13 cored wells used in this research. Especially the API (this number is unique to the well and associated cores in the USGS, MBOGC, and PETRA[®] databases). Along with the API, the other information can be used together to search for these wells and cores in all the databases utilized in this research.

USGS CODE	API	WELL NAME – NUMBER	COUNTY	TOWNSHIP, RANGE, AND SECTION
C176	25051210120000	CORCORAN-GRAY - #42-26	LIBERTY	37N, 5E, 26
C191	25051053040000	STATE-DARROW – #12-9	LIBERTY	37N, 5E, 9
C216	25035214850000	TWO MEDICINE - #1-3	GLACIER	31N, 12W, 3
C739	25041221560000	JORGENSON - #1R	HILL	34N, 11E, 27
C745	25099211470000	HODGEKISS FARMS - #18-1	TETON	22N, 5W, 18
C982	25035210200000	THELEN - #1	GLACIER	37N, 9W, 13
D083	25051051020000	TEMPEL - #1	LIBERTY	36N, 7E, 30
D341	25015216390000	GEORGE GEMAR - #8-1	CHOUTEAU	25N, 3E, 8
D988	25035211860000	BLACKFEET TRIBAL - #14-28	GLACIER	34N, 8W, 28
E891	25051217250000	UTOPIA UNIT - #14-12XA	LIBERTY	33N, 4E, 12
R371	25041221400000	BERGE - #1	HILL	37N, 9E, 14
R609	25101217700000	DAVIS - #1	TOOLE	34N, 4W, 15
S575	25041221410000	CONWAY - #1	HILL	34N, 11E, 20

At this point in the project, there was an established list of outcrops and cores to be utilized. Furthermore, all of the outcrop and core notes, analysis, photos, and previous work had been compiled into geologic profiles that could be analyzed and correlated across the project area. Correlation began with the preexisting lithostratigraphic nomenclature, allowing for a coarse framework across the project area. Inherent to the lithostratigraphic nomenclature of the Ellis Group, is its biostratigraphic foundation, most notably from the numerous works of R.W. Imlay and W.A. Cobban.

Petrophysical Calibration

It was important to consistently correlate the numerous well logs in this project with respect to the actual rock. This important component to the project was done through basic petrophysical calibration. Basic petrophysical calibration relies on understanding the fundamentals of each logging tool and its expected response to known rock types (*sensu* Asquith and Krygowski, 2004). It should be noted that this project did not do quantitative crossplots, as this would have only been feasible with digitized data. This process involved matching well log response across the entire log suite (i.e. well log interpretation) to the cored rock, thereby calibrating the actual rock properties with the derived rock properties.

This allowed for matching vertical lithofacies relationships to vertical log patterns; lithofacies will be discussed in greater detail in Chapter 4. Furthermore, this work allowed for lateral correlations that were carried through the subsurface via derived rock properties to be confidently tied back to the actual rock that comprises the Ellis Group, both in core and in outcrop. Most importantly, this process permitted a defensible correlation method from the realm of actual rock properties to the derived rock properties.

Well Data

The project's well database, based in PETRA[®], began with a very large number of wells. Therefore, the first step was to exclude the extraneous wells; the wells that did not have data over the Ellis Group. Next, the project aimed to narrow the well database to wells with data that was applicable to this project, specifically wells with relevant and adequate data: well log data, accurate location data, and stratigraphic interval data.

The well database was divided into categories based on the level of substantial evidence of stratigraphic interval data. The wells with the highest quality data were termed "alpha wells". This well group is comprised of the 13 cored wells and the four outcrops as pseudo-wells, totaling 17 wells. The alpha wells were ranked the highest based on their data quality, well logs, and cores being in the public domain. That group had preexisting data in the well database, the stratigraphic interval data was checked against the public database on the MBOGC website, and there is core analysis data for 10 of the 13 cored wells. The subsequent well group was termed "beta wells" this group consists of 140 wells. These wells are the larger group of cored wells across the Jurassic strata that were not inspected nor described. The wells had preexisting data in the well database, some are included in published literature, and the stratigraphic interval data was checked against the public database on the MBOGC website. The next well group was named the "gamma wells" this group is composed of 684 wells. The gamma wells had preexisting data in the well database and the stratigraphic interval data was checked against the public database on the MBOGC website.

Table 2: Well statistics by well category. This table shows the final number of wells for each category after the selection process. The three subsequent fields are statistics that PETRA[®] automatically calculates (well density based on an approximate project area of 19km²). The maximum and minimum distances are the extremes between any two wells in that given dataset.

Category	Number of Wells	Well Density (well/mi ²)	Maximum Distance (mi)	Minimum Distance (mi)
Alpha Wells	17	8.95×10^{-4}	63.3	1.8
Beta Wells	140	7.4×10^{-3}	14.6	0.2
Gamma Wells	684	3.6×10^{-2}	24.2	0.06
All Wells	841	4.4×10^{-2}	27.5	0.01

Now the project consisted of a set of wells in a significant hierarchy that could now be incrementally integrated into the preexisting framework that was constructed through the outcrop to core correlations, through the work of the petrophysical calibration. It should be noted that although the wells were checked against data in the public domain, however if there was a discrepancy, final picks were based on this projects data being the original rock-to-rock correlations. The final dataset was gridded in PETRA[®] for isochore and structure maps. Grid size was estimated from z data and minimum curvature was used for surface style. A no trend-residual surface was used for trend/bias. Limits were set to not extrapolate grid beyond data.

Utilizing the preexisting work on biostratigraphy and the regional unconformities that exist over the project area, the chronostratigraphically significant framework was expanded across the project area with greater resolution; this would become the sequence stratigraphic framework that is discussed in greater detail in Chapter 5. Internal to this framework, lithofacies could be placed in a chronostratigraphically relevant context across the project area.

CHAPTER 4 – SEDIMENTOLOGY

This project investigated outcrops and cores across the project area to assemble geologic profiles of the Ellis Group at various points to better understand the distribution of lithofacies. If present during the deposition of the Ellis Group, a large feature would have had a direct influence on the sedimentary processes and deposits.

Does the distribution of lithofacies comprising the Ellis Group within the project area support the theory of a large feature? Do the different lithofacies support the notion that this large feature influenced regional sea level enough to cause varying salinity, current direction and current intensity as to affect the sedimentary nature of the Ellis Group? Do the lithofacies indicate sediment source coming from the paleogeographic area of the large feature?

This chapter explains the characterization of lithofacies that describe the sedimentary rocks comprising the Ellis Group. The 26 lithofacies were developed from the outcrop field sites and modified as needed to be applicable to the cores utilized in the project. The lithofacies were then grouped according to the properties that were hydrodynamic indicators of the depositional setting into six lithofacies associations. The sedimentology of this project progressed by integrating the lithofacies and lithofacies associations into a chronostratigraphically significant framework.

Lithofacies

Lithofacies Characterization:

In order to classify the rock properties of the Ellis Group, a few hurdles had to be overcome. The group is comprised of four formations and eight members and is a mixed system of siliciclastics and carbonates. The described lithofacies needed to focus on the intrinsic properties of sedimentary rocks that allow coeval, though lithologically different rocks, to be correlated within a chronostratigraphically significant framework. Grain size, grain packing, and proportion of grains to mud fraction were determined to be the primary properties that would be comparable in both siliciclastic and carbonate systems. Second, sedimentary structures were incorporated, as it is understood that it takes equivalent forces acting on a grain to form a given sedimentary structure; regardless of the composition of said grain. Therefore, it was determined to use a more depositionally focused carbonate classification scheme, to fulfill the objectives of this mixed system characterization (*sensu* Dunham, 1962; Embry and Klovan, 1972).

Extracting grain size and sedimentary structures from the rocks allowed the project to characterize the lithofacies based on hydrodynamic indicators that adhere to fundamental laws of physics that act on both siliciclastic and carbonate systems. Grains and grain size can illuminate the source area and integrated with sedimentary structures can record the longitudinal dynamics of the system (i.e. facies tract). The premise for these criteria is essentially this: the forces acting on one clast of sediment (siliciclastic or carbonate) in one system are the same in another, based on the universal nature in which gravity and water move sediment.

Table 3 summarizes the 26 lithofacies of the project. This table describes the fundamental characteristics of each lithofacies and is organized in descending order of interpreted hydrodynamic energy represented by the deposit. Following the table is a write up of each lithofacies, along with photos of both outcrop and core (when possible). The write-ups describe the criteria used to define each lithofacies, basic statistics of each, and supporting literature for the interpreted sedimentary processes.

Table 3: Lithofacies Characterization Summary Table. In descending order of decreasing grain size and interpreted hydraulic energy to generate said sedimentary structure.

Facies	Grain Size and Sedimentary Structures	Description	Sedimentary Processes
Ccb	Conglomerate: cobble-boulder	Cobble to boulder size clasts, clast-supported, structureless, laterally discontinuous, eroded base	Reworked sediments, unidirectional transport, rapid deposition, overall waning sediment gravity flow allowing for erosion then deposition
Cgp	Conglomerate: granule-pebble	Granule to pebble size clasts, clast and matrix-supported, lithologic mixture of clasts, laterally continuous and discontinuous, clasts sometimes imbricated, eroded base	Reworked sediments, unidirectional and bidirectional currents removing fine fraction, in situ reworking
Lfs	Floatstone	Medium to very coarse-grained particles, consisting of carbonate clasts, quartz, ooids, pebble size clasts in part, matrix-supported, no apparent structure internal to bedding	Reworked sediments, unidirectional current/transport, waning flow from erosion to rapid deposition
Lgd	Grainstone: cross-bedded	Medium to very coarse-grained particles, poorly-sorted, quartz, ooids, and carbonate clasts, no carbonate mud noticed, both tabular and trough cross-bedded, with superimposed symmetric and asymmetric ripple cross-lamination, grains and mud drapes found in trough in part	Unidirectional and bidirectional currents, lower flow regime, migrating dune bed forms and ripple bed forms, waxing and waning of current

Table 3: Continued.

Facies	Grain Size and Sedimentary Structures	Description	Sedimentary Processes
Lgs	Grainstone: structureless	Medium to very coarse-grained particles, carbonate clasts, quartz, and ooids; pebble size clasts in part, no apparent structure internal to bedding	Rapid deposition from waning flow
Scd	Sandstone: upper coarse-grained to upper very coarse-grained: cross-bedded	Upper coarse-grained to upper very coarse-grained, dune tabular cross-bedded, angular quartz, subangular chert, base may be scoured and be associated with clasts	Unidirectional current, lower flow regime, migrating dune bed forms
Smd	Sandstone: lower medium-grained to lower coarse-grained: cross-bedded	Lower medium-grained to lower coarse-grained, subangular, trough cross-bedded with superimposed ripple cross-lamination, some ooids and fossil fragments	Unidirectional current, lower flow regime, migrating dune and ripple bed forms
Sms	Sandstone: lower medium-grained to lower coarse-grained: structureless	Lower medium-grained to lower coarse-grained, subangular to angular, no apparent sedimentary structure, occasional quartz clast	Rapid deposition and or bioturbation
Sfp	Sandstone: lower very fine-grained to upper fine-grained: plane parallel lamination	Lower very fine-grained to upper fine-grained, very thin-bedded, parallel laminations, very well-sorted, capped by iron saturation	Unidirectional current, upper flow regime, grains sliding, rotating, and saltating
Sfd	Sandstone: lower very fine-grained to upper fine-grained: cross-bedded	Lower very fine-grained to upper fine-grained, trough cross-bedded	Unidirectional current, lower flow regime, migrating dune bed forms

Table 3: Continued.

Facies	Grain Size and Sedimentary Structures	Description	Sedimentary Processes
Sfr	Sandstone: lower very fine-grained to upper fine-grained: ripple cross-laminated	Lower very fine-grained to upper fine-grained, ripple cross-laminated, symmetrical and asymmetrical, occasionally: flaser bedded with mud partings, well-sorted	Unidirectional and bidirectional currents, lower flow regime, migrating ripple bed forms
Sfs	Sandstone: lower very fine-grained to upper fine-grained: structureless	Lower very fine-grained to upper fine-grained, no apparent sedimentary structure, can be well-sorted, burrowing in part, fossils in part	Rapid deposition and or bioturbation
Sfhs	Sandstone: lower very fine-grained to upper fine-grained: hummocky and swaley cross-stratified	Lower very fine-grained to upper fine-grained, hummocky and or swaley cross-stratified, with fossils	Multidirectional currents, oscillatory waves with minimal lateral migration
Lpd	Packstone: cross-bedded	Carbonate grains, ooids, and quartz grains, grain-supported, carbonate mud-bearing, tabular and trough cross-bedded	Unidirectional current, lower flow regime, migrating dune bed forms
Lpr	Packstone: ripple cross-laminated	Carbonate grains, ooids, and quartz grains, grain-supported, carbonate mud-bearing, ripple cross-laminated	Unidirectional currents, lower flow regime, migrating ripple bed forms
Lpp	Packstone: thin-bedded	Carbonate grains, ooids, quartz grains, grain-supported, carbonate mud-bearing, thin beds that are apparently internally structureless, <i>Gryphaea</i> , capped by mud cracks in part	Rapid deposition and or bioturbation; with periods of subaerial exposure leading to desiccation

Table 3: Continued.

Facies	Grain Size and Sedimentary Structures	Description	Sedimentary Processes
IB 1	Interbedded: lower very fine-grained to upper fine-grained, ripple cross-laminated and clay to medium-silt-rich mudstone	Lower very fine-grained to upper fine-grained sandstone, ripple cross-laminated, interbedded with clay to medium-silt-rich mudstone, lenticular bedded, occasional mud cracks	Fluctuating intervals of unidirectional and bidirectional currents, lower flow regime, migrating ripple bed forms; suspension settling and weak traction currents; periods of subaerial exposure leading to desiccation
IB 2	Interbedded: lower very fine-grained to upper fine-grained and clay to medium-silt-dominated mudstone	Lower very fine-grained to upper fine-grained sandstone, interbedded with clay to medium-silt-dominated mudstone, burrowed, lenticular bedded	Fluctuating intervals of rapid deposition and or bioturbation; unidirectional and bidirectional currents; suspension settling and weak traction currents
Lwk	Wackestone: thick-bedded	Mixture of carbonate grains and fossils (fragmented in part) in predominantly carbonate mud, thick-bedded, scattered <i>Gryphaea</i>	Rapid deposition and or bioturbation, suspension settling
Lwn	Wackestone: thin-bedded	Mixture of carbonate grains and fossils (fragmented in part) in predominantly carbonate mud, thin-bedded, occasional mud cracks	Rapid deposition and or bioturbation; suspension settling, periods of subaerial exposure leading to desiccation
Lwa	Wackestone: algal bound, thin-bedded	Mud-dominated, carbonate grains with carbonate clasts (in situ deformation), thin-bedded, algal remains (<i>Lithothamnium ellisianum</i>)	Algal bound carbonate grains and mud, precipitation of carbonate mud, preferential deformation leading to fragmentation of differentially lithified laminae

Table 3: Continued.

Facies	Grain Size and Sedimentary Structures	Description	Sedimentary Processes
Ms _r	Mudstone: coarse-silt to sand-rich mudstone	Coarse-silt to sand-rich mudstone, bioturbated in part, can be micaceous, can be fossiliferous	Rapid deposition and or bioturbation
IB 3	Interbedded: coarse-silt-bearing and clay to medium-silt-rich mudstone	Coarse-silt-bearing mudstone interbedded with clay to medium-silt-rich mudstone	Fluctuating intervals of waxing and waning energy; suspension settling and weak traction currents
IB 4	Interbedded: coarse-silt to medium-silt-rich mudstone and clay to medium-silt-dominated mudstone	Medium-silt to coarse-silt-rich mudstone interbedded with clay to medium-silt-dominated mudstone, ripple bed forms rarely	Fluctuating intervals of waxing and waning energy; suspension settling and weak traction currents, rarely lower flow regime, migrating ripple bed forms
Mcr	Mudstone: clay to medium-silt-rich mudstone	Clay to medium-silt-rich mudstone, fossiliferous in part	Suspension settling
Mcd	Mudstone: clay to medium-silt-dominated mudstone	Clay to medium-silt-dominated mudstone	Suspension settling
Lm	Mudstone: carbonate	Carbonate mudstone, mud-dominated	Suspension settling

Lithofacies Ccb: This lithofacies is characterized as a conglomerate (C), ranging in grain size from cobble to boulder (cb). Ccb has an occurrence of n=1, with the thickness being 2 ft (0.61m). It is clast-supported, and the light grey limestone clasts are predominantly derived from the underlying stratum, Mississippian carbonates. The matrix is predominantly poorly sorted, brown sandstone.

Neither apparent sedimentary structures, nor internal vertical grading were noted. This lithofacies is laterally discontinuous and was only noted at SRCFS. The base of this lithofacies is an erosional surface. Due to the size of the clasts and the nature of the matrix, this lithofacies is likely the product of a sediment gravity flow (Middleton and Hampton, 1976; Nardin et al., 1979). Based on the lack of grading and coarse nature of the particles, this deposit exhibits the properties of dispersive forces dominating as in a grain flow (Middleton and Hampton, 1976). Based on the properties of this deposit, it is likely to be a product of a subaqueous grain flow (Middleton and Hampton, 1976).



Figure 14: Lithofacies Ccb, example photo from outcrop, modified from Mudge (1972a), at the Sun River Canyon Field Site (SRCFS). Note the rock hammer for scale in the lower center of the picture. Note the line delineating the Jurassic Ellis Group on the left from the Mississippian rocks on the right. This is an area of substantial structural deformation; photo was taken oblique to bedding.

Lithofacies Cgp: This lithofacies is characterized as a conglomerate (C), ranging in grain size from granule to pebble (gp). Cgp had an occurrence of $n=13$, with a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 1ft (0.31m). The deposit is noted as being a mixture of both clast-supported and matrix-supported conglomerate. This lithofacies varies widely in color and composition of clasts, within this grain size range, therefore making these properties worth grouping and different from other lithofacies. This deposit can be both laterally continuous and isolated. Occasionally it does show current influence in the form of imbricated clasts and was deposited on a surface of erosion. The deposits in this lithofacies can in places show normal grading. The clasts appear to be substantially polished without significant abrasion or reduction in size; this is verified in the biological components. The deposits in this lithofacies appear to be reworked in place, as by oscillatory current action reworking the larger components and winnowing out the finer fraction. This coarse lag deposit is followed by subsequent deposition through suspension settling of finer grains and particles, thus becoming incorporated into the reworked base.

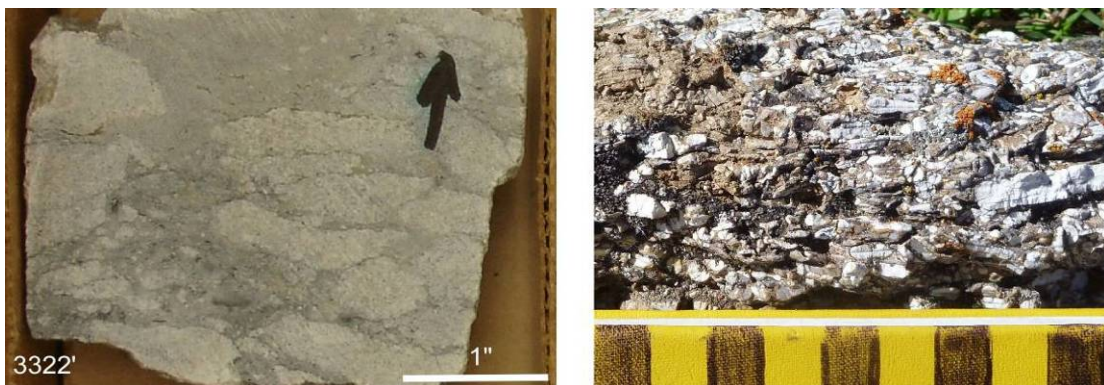


Figure 15: Lithofacies Cgp, example photos from both core and outcrop. The left picture is from the Piper Formation, Tampico Member in Core D083 (3322ft, 1012m). The right picture is from the Swift Formation, Shale Member at BPMFS (247ft, 75.3m). The scale bar in the right photo is in 1cm intervals (0.4in).

Lithofacies Lfs: This lithofacies is characterized as a limestone (L) floatstone (fs) defined as matrix-supported boundstone with components larger than 2mm (0.08in) making up greater than 10%. Lfs had an occurrence of $n=2$, with a minimum thickness of 1.5ft (0.46m) and a maximum thickness of 2ft (0.6m). This deposit consists of carbonate, belemnite clasts, and some quartz clasts of pebble size. The supporting matrix is ooids, quartz grains, and other carbonate grains of medium to very coarse-grained size that are poorly-sorted. This deposit does not appear to have internal sedimentary structures and does appear to be a channel-fill-form in outcrop. This internally structureless deposit coupled with a channel-fill-form profile in outcrop, implies a confined unidirectional flow that experienced rapid deposition. Furthermore, based on the level of preservation of some of the smaller and more delicate corral fragments, there is evidence for a proximal source area.



Figure 16: Lithofacies Lfs, example photos from both core and outcrop. The left picture is from the Piper Formation, Bowes Member in Core C739 (3673ft, 1119.5m). The right picture is from the Piper Formation, Bowes Member at BPMFS (62ft, 18.9m).

Lithofacies Lgd: This deposit weathers to a medium grey, medium tan-grey color in outcrop and on a clean surface appears grey.

The lithofacies is characterized as a limestone (L), cross-bedded grainstone (gd). Lgd had an occurrence of $n=2$, with a minimum thickness of 2.5ft (0.76m) and a maximum thickness of 6ft (1.83m). It is grain-supported with no carbonate mud and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The matrix is poorly-sorted medium to very coarse-grained quartz, ooids, and carbonate grains. Tabular and trough cross-bedding was noted, and in part, with superimposed symmetric and asymmetric ripple cross-lamination. There were isolated grains and mud drapes noted in some of the ripple troughs (toeset). A likely sedimentary process leading to this deposit would be migrating dune bed forms under a unidirectional current (Harms et al., 1975). Additionally, the system would have underwent waxing and waning cycles allowing for the migrating ripple bed forms to form on the dune foresets, as this would require a change in current intensity and direction.



Figure 17: Lithofacies Lgd, example photos from outcrop only, not noted in described cores. The left photo is from the Piper Formation, Bowes Member at BPMFS (76ft to 80ft, 23.2m to 24.4m). The photo shows the cross-bedding dipping to the left (northwest) (scale bar is ~4ft, 1.2m). The right photo is from the same outcrop/interval. This photo shows the cross-bedding with the superimposed ripple cross-lamination. The scale bar in the right photo is ~1ft, 0.3m.

Lithofacies Lgs: This lithofacies weathers in outcrop to a tan and medium grey color, which when fractured has the same color or is brown to black brown.

This lithofacies is characterized as a limestone (L), structureless grainstone (gs). Lgs had an occurrence of $n=4$, a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 2ft (0.6m). It is grain-supported with no carbonate mud and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. Neither internal sedimentary structures nor grading were noted in this deposit. Pebble size clasts were predominantly limestone or bioclastic in origin. The matrix consists of medium to very coarse-grained ooids, carbonate and quartz grains. The deposits labeled as Lgs, can be described as lithologically heterogeneous. They appear structureless, no apparent trend in grading, and by the above definition have no mud fraction. There are no apparent dewatering structures and no burrows or bioturbation was noticed. This appears to be a deposit of a subaqueous grain flow, whereby dispersive forces dominated (Middleton and Hampton, 1976). Regarding the mud fraction, possibilities for this could have been a mud free staging area or striped off during the flow.



Figure 18: Lithofacies Lgs, example photos from outcrop and described core. The photo on the left is from the Piper Formation, Firemoon Member at BPMFS (2ft, 0.6m). Right photo is of the Piper Formation, Bowes Member in Core C739 (3658.5ft, 1115m) (scale bar is 1in, 2.5cm).

Lithofacies Scd: The lithofacies is characterized as a sandstone (S), ranging from upper coarse-grained to upper very coarse-grained (c), with cross-bedding (d).

Scd had an occurrence of $n=2$, a minimum thickness of 1ft (0.31m) and a maximum thickness 1.5ft (0.46m). The grains are predominantly grey angular quartz with black and grey subangular chert, with larger (granule) size clasts noted at base of the deposit in outcrop. In both core and outcrop, the inclined bedding appears to be unidirectional, with no major change in foreset direction relative to the bounding foresets. Based on scale and grain size, it appears to be the product of migrating dune bed forms under lower flow regime conditions (Harms et al., 1975). The base may appear slightly scoured, though no significant relief was noticed.

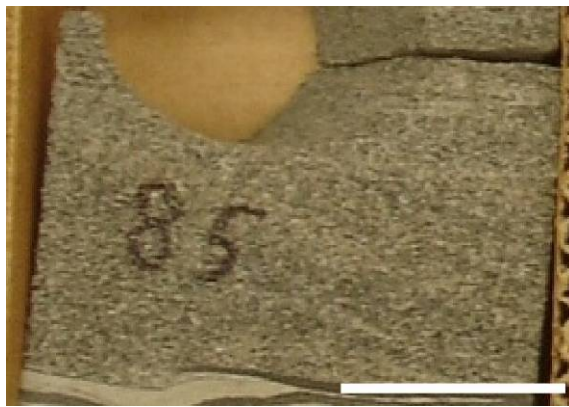


Figure 19: Lithofacies Scd, example photo of described core only. The photo is from the Swift Formation, Sandstone Member in Core E891 (2285ft, 696.5m) (scale bar is 1in, 2.5cm). There was not a high enough quality photo from outcrop to show the details of the lithofacies.

Lithofacies Smd: This lithofacies is characterized as a sandstone (S), ranging from lower medium-grained to lower coarse-grained (m), with cross-bedding (d). Smd had an occurrence of $n=8$, a minimum thickness of 1.5ft (0.46m) and a maximum thickness 21ft (6.4m). The grains are predominantly subangular quartz, with occasional ooids and fossil fragments. This lithofacies weathers to a grey color in outcrop and fractures light grey to clear.

In both core and outcrop, the inclined bedding appears to be unidirectional, with no major change in foreset direction relative to the bounding foresets. Ripple cross-lamination was noticed, in outcrop, superimposed on the trough cross-bedding. Sedimentary processes leading to this deposit would be migrating dune bed forms under a primarily unidirectional current (Harms et al., 1975). The system must have experienced waxing and waning cycles to allow for the migrating ripple bed forms to form on the dune bed forms, as this would require a change in current intensity and direction.

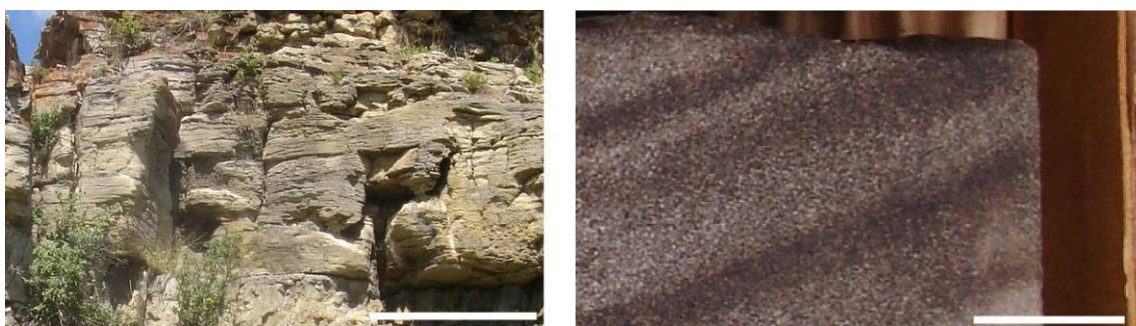


Figure 20: Lithofacies Smd, photos of outcrop and described core. The photo on the left is from the Piper Formation, Bowes Member at BPMFS (65ft to 69ft, 19.8m to 21m). The photo shows the foresets dipping to the left (southwest) (scale bar is ~4ft, 1.2m). The right photo is of the Swift Formation, Swift Sandstone in Core D341 (1802ft, 549.3m) (scale bar is 1in, 2.5cm).

Lithofacies Sms: The lithofacies is characterized as a sandstone (S), ranging from lower medium-grained to lower coarse-grained (m), with no apparent structure (s). Sms had an occurrence of n=18, a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 13ft (3.96m). The grains are predominantly angular quartz, with occasional larger (granule) quartz clasts. This deposit does not appear to have sedimentary structures internal to the beds of varying thickness. It weathers light grey to off white to tan colored in outcrop. In some deposits it can be predominantly glauconite and therefore dark green in color.

Some of the deposits have significant burrow density, while in others there is no apparent sign of bioturbation. It appears that rapid deposition and bioturbation or a combination of the both have been the primary process to account for the structureless nature of this deposit.



Figure 21: Lithofacies Sms, photos from outcrop and described core. The left photo is of the Piper Formation, Bowes Member at SGHFS (58ft, 17.7m) (scale bar is 1in, 2.5cm). The photo shows the apparent structureless nature below the plane parallel laminated sediment. The photo on the right is of the Piper Formation, Bowes Member in Core D083 (3238ft, 987m) (scale bar is 1in, 2.5cm).

Lithofacies Sfp: The lithofacies is characterized as a sandstone (S), ranging from lower very fine-grained to upper fine-grained (f), and plane parallel lamination (p). Sfp had an occurrence of $n=6$, a minimum thickness of 1.5ft (0.46m) and a maximum thickness of 10ft (3.05m). The grains are predominantly well-rounded, very well-sorted quartz grains. Where this lithofacies was observed in outcrop, it was capped by a zone of iron staining or iron cements up to 9 inches (22.3cm) thick. It normally appears buff or tan colored in outcrop. The lithofacies is likely a product of unidirectional flow in the upper flow regime (Harms et al., 1975). In the case of the deposits within this lithofacies that could be interpreted as foreshore; there would obviously be a bidirectional current effect with the returning current being most responsible for the deposit.



Figure 22: Lithofacies Sfp, example photos from outcrop and described core. The left photo shows the lithofacies in outcrop of the Piper Formation, Bowes Member at SGHFS (64ft, 19.5m). The photo on the right is of the Swift Formation, Shale Member in Core C745 (3875ft, 1181m) (scale bar is 1in, 2.5cm).

Lithofacies Sfd: This lithofacies is characterized as a sandstone (S), ranging from lower very fine-grained to upper fine-grained (f), with cross-bedding (d), only in the upper limit of the grain size range. Sfd had an occurrence of $n=1$, with a thickness of 2ft (0.6m). The deposit appears to be a localized event only recognized at BPMFS. It appears to be the product of predominantly unidirectional migrating dune bed forms, under lower flow regime conditions (Harms et al., 1975).



Figure 23: Lithofacies Sfd, example photo of outcrop only. This lithofacies was only noticed in outcrop in the Swift Formation, Sandstone Member at the BPMFS (306ft, 93.3m).

Lithofacies Sfr: The lithofacies can weather tan, dark grey, or rust in color and along fractures is buff to medium grey in color. It is characterized as a sandstone (S), ranging from lower very fine-grained to upper fine-grained (f), that is ripple cross-laminated (r). Sfr had an occurrence of $n=19$, with a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 74ft (22.56m). This deposit is predominantly quartz sandstone that can be very well-sorted and that is usually at least well-sorted, well-rounded, and has individual grains exhibiting high sphericity. It can be predominantly silica cemented or have a moderate amount of calcite cement. There is both symmetrical and asymmetrical ripple cross-lamination. In places, the bedding is flaser in nature with mud partings. Some post-depositional artifacts are burrows, trails, and syneresis lines.

This lithofacies is the response to migrating ripple scale bed forms, in the lower flow regime (Harms et al., 1975). Both unidirectional and bidirectional currents were present based on asymmetrical and symmetrical ripple cross-laminated intervals, and herringbone cross-lamination was noticed in both outcrop and core. Waxing and waning of the currents can be interpreted from the deposits based on the mud partings. Salinity may have also fluctuated along with the intensity of the current based on the syneresis lines.

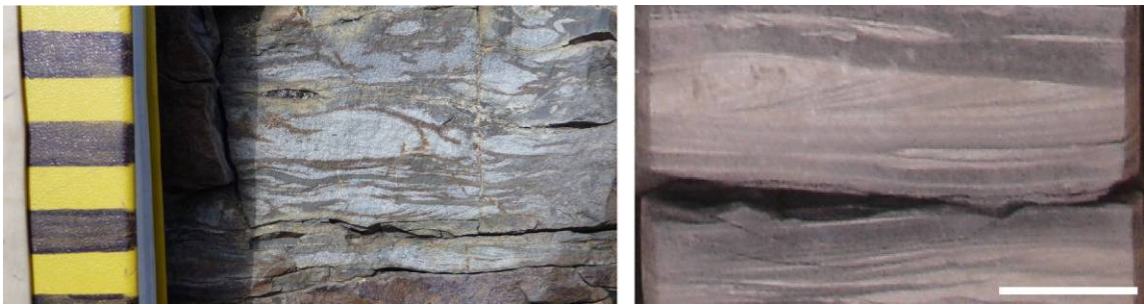


Figure 24: Lithofacies Sfr, example photos of outcrop and described core. The photo on the left is of the Swift Formation, Sandstone Member at SGHFS (293ft, 89.3m) (scale bars on field book are 1cm, 0.4in). The right photo is of the Swift Formation, Sandstone Member from Core R371 (3228ft, 984m) (scale bar is 1in, 2.5cm).

Lithofacies Sfs: The lithofacies is characterized as a sandstone (S), ranging from lower very fine-grained to upper fine-grained (f), and structureless (s). Sfs had an occurrence of n=37, a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 26ft (7.9m). The deposit can be well-sorted to very well-sorted, with horizontal and vertical burrows, and fossils and fossil fragments may be present in part. It is normally quartz dominated and can be light grey to off white to tan in color in outcrop. Based on some of the intervals preserving burrows it is interpreted that bioturbation had a strong influence on the structureless nature of this lithofacies.

Another influence logically could be rapid deposition based on the vertical succession of lithofacies found in some of the intervals, leading to an interpretation of an overall waning flow.



Figure 25: Lithofacies Sfs, example photos from described cores only. The left photo is of the Piper Formation, Bowes Member in Core R371 (3537ft, 1078m) (scale bar is 1in, 2.5cm). Regardless of the low resolution nature of photo, it does show the lack of apparent structure. The photo on the right is of the Swift Formation, Sandstone Member in Core S575 (3370ft, 1027.2m) (scale bar is 1in, 2.5cm). Note the transition at the top into the overlying ripple cross-laminated lithofacies (Sfr).

Lithofacies Sfhs: This lithofacies was only noted in the Siltstone Member of the Sawtooth Formation at outcrops SRCFS and SWRFS. It weathers buff-grey, yellowish-grey in part, and fractures dark grey. This lithofacies is characterized as a sandstone (S), ranging from lower very fine-grained to upper fine-grained (f), that is hummocky and swaley cross-stratified (hs). Sfhs had an occurrence of $n=2$, a minimum thickness of 1.5ft (0.46m), and a maximum thickness of 3.5ft (1.7m). The deposit is associated with fossils and fossil fragments. This lithofacies is in an interval that trends up from siltstone to very fine-grained sandstone and then reproduces this succession in reverse. The hummock and swaley cross-stratification is found in the sandstone. The process of formation for this sedimentary structure is most likely due to a storm induced lowering of wave base (below fair-weather wave base) (Harms et al., 1975).

This event caused an influx of coarser sediment to this environment; most likely during the storm where wave activity is greatest and then wanes (Collinson and Thompson, 1989 p. 104).

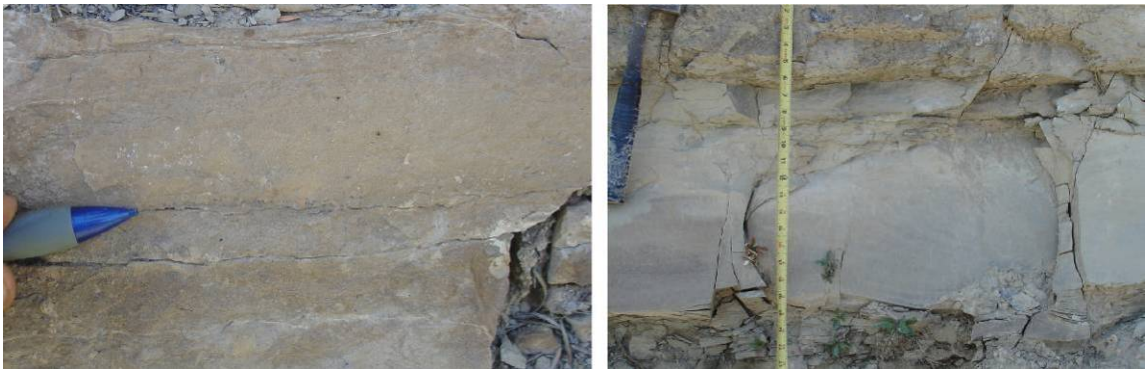


Figure 26: Lithofacies Sfh, example photos from outcrop. The photo on the left is of the Sawtooth Formation, Siltstone Member at SRCFS (27ft, 8.3m). Note the mechanical pencil for scale; it is pointing at the interval of fossil fragments at this locale. This interval corresponds to a similar/equivalent interval at SWRFS, where the fossils are intact or the fragments are much larger. The right photo is of the Sawtooth Formation, Siltstone Member at SWRFS (145ft, 44.2m).

Lithofacies Lpd: The lithofacies is characterized as a limestone (L), cross-bedded packstone (pd). Lpd had an occurrence of $n=4$, a minimum thickness of 4ft (1.23m), and a maximum thickness of 6.5ft (1.98m). It is grain-supported with carbonate mud and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The grains consist of carbonate grains, ooids, and quartz grains. There is both tabular and trough cross-bedding in outcrop; this lithofacies was applied to core intervals that exhibit said rock properties with larger scale inclined stratification. This lithofacies is the product of predominantly unidirectional, migrating dune bed forms, under lower flow regime conditions (Harms et al., 1975).

Based on truncation, grain orientation (in part), and variation in foreset orientation it appears there could have been a multidirectional and bidirectional current influence on the sediment.

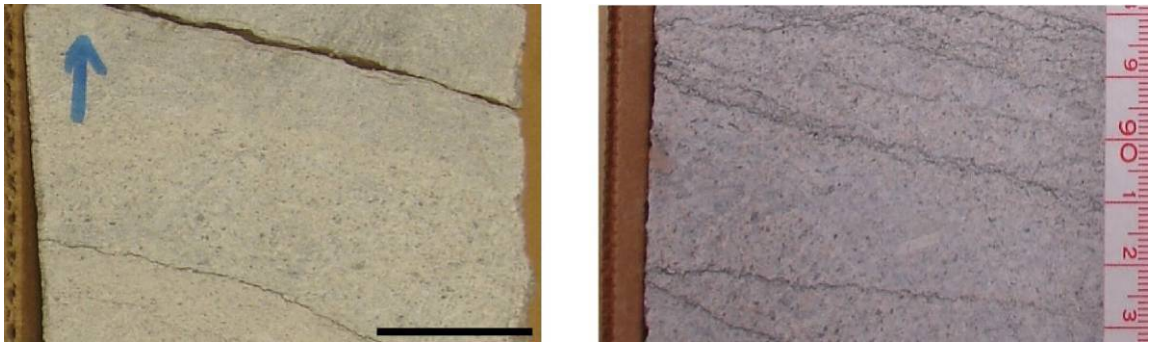


Figure 27: Lithofacies Lpd, example photos of described core. The photo on the left is of the Piper Formation, Bowes Member from Core C739 (3648ft, 1112m) (scale bar is 1in, 2.5cm). Foresets show dip to the right. The photo on the right is from the Piper Formation, Bowes Member from Core C739 (3663ft, 1116m). This interval is predominantly dipping similarly (right), however it does show variation in foreset direction.

Lithofacies Lpr: This lithofacies is characterized as a limestone (L), ripple cross-laminated packstone (pr). Lpr has an occurrence of $n=2$, with a minimum and maximum thickness of 1ft (0.31m). It is grain-supported with carbonate mud and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The grains consist of carbonate grains, ooids, and quartz grains. This lithofacies is the response to migrating ripple bed forms, in the lower flow regime (Harms et al., 1975).



Figure 28: Lithofacies Lpr, example photos of outcrop and core. The photo on the left is of the Piper Formation, Bowes Member at the BPMFS (75ft, 22.3m) (tape measure units are inches). The right photo is of the Piper Formation, Tampico Member from Core D083 (3314ft, 1010m) (scale bar is 1 in, 2.5cm).

Lithofacies Lpp: The lithofacies is characterized as a limestone (L), thin-bedded, with no apparent internal sedimentary structure, packstone (pp). Lpp had an occurrence of $n=22$, a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 12.5ft (3.81m). It is grain-supported with carbonate mud and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The grains consist of carbonate grains, ooids, and quartz grains, with fossils and fossil fragments in part. In some occurrences this lithofacies appears to be capped by mud cracks. In outcrop it can appear dark grey to black in color, and where fractured is black in color. The beds appear to be internally structureless and there is no apparent truncation to indicate erosion as a cause for the thin nature. Therefore it is likely that the individual sedimentation events were limited in volume and deposited rapidly. Based on the presence of mud cracks, desiccation occurred likely by local subaerial exposure of the unlithified aqueous sediment.



Figure 29: Lithofacies Lpp, example photos of outcrop and core. The left photo is of the Piper Formation, Bowes Member at SGHFS (48ft, 14.6m). Note this is in plan view focusing on the mud cracks that can be present. The photo on the right is of the Piper Formation, Bowes Member from Core S575 (3675ft to 3690ft, 1120m to 1124m). This photo shows the general thin bedded nature of this lithofacies, whether divided by other lithofacies or by subsequent sedimentation units.

Lithofacies IB 1: In outcrop this lithofacies weathers grey brown to brown in color, due to heavy oxidation, leading to an overall rust-color staining; fractured surfaces are grey in color. The mudstones appear a metallic grey-blue in color. This lithofacies is characterized as an interbedded (IB) deposit, consisting of lower very fine-grained to upper fine-grained sandstones interbedded with clay to medium-silt-rich mudstone. The (1) is based on its place in the four interbedded lithofacies, it being interpreted as being a response to the most energetic depositional setting, relative to the other four interbedded lithofacies. IB 1 had an occurrence of $n=9$, with a minimum thickness of 2ft (0.61m), and a maximum thickness of 32ft (9.75m). The bed thicknesses can vary from near equal to a more intercalated deposit, coupled with ripple cross-laminated sandstones; this can yield lenticular style bedding. Mud cracks and burrows were noticed in some of the occurrences of this lithofacies; found in the mudstone with the overlying sandstone filling the voids.

Based on the presence of mud cracks, desiccation occurred likely by local subaerial exposure of the unlithified aqueous sediment. This lithofacies is by definition a mixture of lithologies and sedimentary structures, due to fluctuating hydrodynamic conditions present at time of deposition. The laminae or beds that exhibit ripple cross-lamination are the response to migrating ripple bed forms, in the lower flow regime (Harms et al., 1975). The silt and clay fraction show no ripple cross-lamination, however there appears to be both lateral transport and suspension settling.



Figure 30: Lithofacies IB 1, example photos of outcrop and core. The left photo is of the Swift Formation, Sandstone Member at SRCFS (243ft, 74m) (scale bar is 1in, 2.5cm). The photo on the right is of the Swift Formation, Sandstone Member in Core C191 (2883ft, 878.7m).

Lithofacies IB 2: In outcrop this lithofacies can have black grey, dark grey, brown colors. The second interbedded (IB) lithofacies is characterized by lower very fine-grained to upper fine-grained sandstone interbedded with clay to medium-silt-dominated mudstone. The (2) is based on its place in the four interbedded lithofacies, it being interpreted as being a response to the second most energetic depositional setting, relative to the other four interbedded lithofacies. IB 2 had an occurrence of $n=8$, a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 10ft (3.05m). The bed thicknesses can vary from near equal to a more intercalated deposit.

Though no obvious ripple cross-lamination was noted, there is lenticular style bedding associated with this lithofacies; therefore it is presumed that in plan view there would be revealed ripple bedform morphology. Both vertical and horizontal burrows were noted. This lithofacies is by definition a mixture of lithologies and sedimentary structures, due to fluctuating hydrodynamic conditions present at time of deposition. The beds that exhibit, or are presumed to exhibit ripple cross-lamination are the response to migrating ripple bed forms, in the lower flow regime (Harms et al., 1975). The silt and clay fraction show no ripple cross-lamination, however there appears to be both lateral transport and some vertical suspension settling.



Figure 31: Lithofacies IB 2, example photos from core. The photo on the left is of the Piper Formation, Bowes Member in Core D083 (3253ft, 991.5m) (scale bar is 1in, 2.5cm). Note this example being from a mixed source, does contain some larger grains. The right photo is of the Swift Formation, Sandstone Member from Core D341 (1778ft, 541.9m) (scale bar is 1in, 2.5cm).

Lithofacies Lwk: This lithofacies is characterized as a limestone (L), thick-bedded wackestone (wk). Lwk had an occurrence of n=9, a minimum thickness of 1ft (0.31m), and a maximum thickness 7.5ft (2.29m). It is carbonate mud-supported with greater than 10% carbonate grains (0.03mm to 2mm, 0.001in to 0.08in) and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts.

The grain fraction is a mixture of carbonate grains and fossils, intact and fragmented, with *Gryphaea* being the dominant fossil. The lithofacies appears to have thicker beds compared to the other similar deposits (thin bed wackestones). This appears to be a product of rapid deposition from larger flows, more intense bioturbation, or longer periods of suspension settling.



Figure 32: Lithofacies Lwk, example photos of outcrop and core. The left photo is of the Piper Formation, Firemoon Member at BPMFS (18ft, 5.5m). The hammer, for scale, is at the base of this lithofacies. The photo on the right is of the Piper Formation, Firemoon Member in Core D083 (3289ft, m) (scale bar is 1in, 2.5cm).

Lithofacies Lwn: This lithofacies is characterized as a limestone (L), thin-bedded wackestone (wn). Lwn had an occurrence of $n=31$, a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 3ft (0.91m). It is carbonate mud-supported with greater than 10% carbonate grains (0.03mm to 2mm, 0.001in to 0.08in) and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The grain fraction is a mixture of carbonate grains consisting of carbonate mud fragments and fossils, intact and fragmented; with *Gryphaea* being the dominant fossil. Mud cracks can be noticed in some of the deposits of this lithofacies. Burrows were only noted in a few of the occurrences.

Based on the presence of mud cracks, desiccation occurred likely by local subaerial exposure of the unlithified aqueous sediment. Based on the floating nature of fossils, whole and fragmented, it could be likely the rapid deposition from small flows could have played a factor in the sedimentation of this lithofacies.



Figure 33: Lithofacies Lwn, example photos of outcrop and core. The photo on the left is of the Rierdon Formation at SGHFS (96ft, 29.3m). The multi-tool is approximately 4in (11cm). The right photo is of the Rierdon Formation in Core D083 (3217ft, 980m) (scale bar is 1in, 2.5cm).

Lithofacies Lwa: This lithofacies can appear light to medium grey in outcrop.

The lithofacies is characterized as a limestone (L), that is algal bound and thin-bedded, an algae derived boundstone that has the rock properties of a wackestone (wa). Lwa had an occurrence of $n=4$, a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 3ft (0.91m). It is carbonate mud-supported with greater than 10% carbonate grains (0.03mm to 2mm, 0.001in to 0.08in) and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The lithofacies consists of algal bound carbonate grains and mud, presumably precipitation of carbonate mud. “Internal clasts” appear to be a product of in situ preferential deformation of differentially lithified laminae. Howe and Goldman (1925) did analysis on samples collected from this deposit and the surrounding area; they designated the algae as *Lithothamnium ellisianum*.



Figure 34: Lithofacies Lwa, example photos from outcrop. Photos are of the Piper Formation, Bowes Member at BPMFS (71ft, 21.6m). Right photo is a close up of the left photo. This is the same unit of which Howe and Goldman (1925) did analysis to confirm the algal nature of this specific interval.

Lithofacies Msr: This deposit can be various colors in outcrop. This lithofacies is characterized as a mudstone (M) that consists of coarse-silt to sand-rich mudstone (sr). Msr had an occurrence of $n=10$, a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 26ft (7.93m). It is common in places for this lithofacies to be burrowed, fossiliferous, and can be micaceous and calcareous. Based on the grain size, it is interpreted that this lithofacies is primarily a response to suspension settling and weak traction currents. Bioturbation did play a role, though there were no intervals where the laminae were completely reworked.



Figure 35: Lithofacies Msr, example photos from outcrop and core. The photo on the left is of the Sawtooth Formation, Siltstone Member at SRCFS (30ft to 45ft, 9m to 13.7m) (scale bar is 5ft, 1.5m). The right photo is of the Swift Formation, Sandstone Member in Core C191 (2891ft, 881.2m) (scale bar is 1in, 2.5cm).

Lithofacies IB 3: This lithofacies can appear dark grey-brown in outcrop. The third interbedded (IB) lithofacies is characterized by coarse-silt interbedded with clay to medium-silt-rich mudstone. The (3) is based on its place in the four interbedded lithofacies, it being interpreted as being a response to the third most energetic depositional setting, relative to the other four interbedded lithofacies. IB 3 had an occurrence of $n=9$, a minimum thickness of 1ft (0.31m) and a maximum thickness of 5.5ft (1.68m). The bed thicknesses can vary from near equal to a more intercalated deposit. This lithofacies is by definition a mixture of lithologies and sedimentary structures, due to fluctuating hydrodynamic conditions present at time of deposition. Based on the grain size and orientation of the lamina, the likely process would be suspension settling and weak traction currents for the deposition of this lithofacies.



Figure 36: Lithofacies IB 3 example photos from outcrop and core. The left photo is of the Sawtooth Formation, Siltstone Member at SWRFS (144ft, 43.9m) (tape measure for scale is in inches). The photo on the right is of the Swift Formation, Sandstone Member (2885ft, 879m) (scale bar is 1in, 2.5cm).

Lithofacies IB 4: In outcrop this lithofacies weathers dark olive-grey to grey. The fourth interbedded (IB) lithofacies is characterized by coarse-silt to medium-silt-rich mudstone interbedded with clay to medium-silt-dominated mudstone.

The (4) is based on its place in the four interbedded lithofacies, it being interpreted as being a response to the fourth most energetic depositional setting, relative to the other four interbedded lithofacies. IB 4 had an occurrence of $n=3$, and a minimum thickness of 3.5ft (1.07m), and a maximum thickness of 13ft (3.96m). The bed thicknesses can vary from near equal to a more intercalated deposit. In a few isolated occasions, symmetric crestline, ripple bed form morphology were noted, though no apparent ripple cross-lamination was noted. This lithofacies is by definition a mixture of lithologies and sedimentary structures, due to fluctuating hydrodynamic conditions present at time of deposition. Based on the grain size and orientation of the lamina, the likely process would be suspension settling and weak traction currents for the deposition of this lithofacies; probable dominate influence being a periodic change in water depth.



Figure 37: Lithofacies IB 4, example photos of outcrop. Both photos show the Swift Formation, Sandstone Member at SWRFS (~392ft, 119.5m). The rock hammer, for scale, is resting on lithofacies Cgp, which is encased in the IB 4 lithofacies.

Lithofacies Mcr: This lithofacies is characterized as a mudstone (M) that consists of clay to medium-silt-rich mudstone (cr). Mcr had an occurrence of $n=16$, a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 7ft (2.1m). It is common in places for this deposit to be fossiliferous and is predominantly very thin-bedded.

Based on bedding, grain size, and fossil orientation (concave up), there appears to be no signs of lateral transport. The likely process for sedimentation of this lithofacies would have been suspension settling.



Figure 38: Lithofacies Mcr, example photos of outcrop and core. The left photo is of the Sawtooth Formation, Shale Member at SRCFS (10ft, 3m). The hammer and finger, marking a very thin pyritic sandstone found near the top of the lithofacies in this horizon. The photo on the right is of the Sawtooth Formation, Shale Member in Core R609 (1975ft, 602m) (scale bar is 1in, 2.5cm).

Lithofacies Mcd: In outcrop this lithofacies can appear medium grey, green-grey, dark green-grey. This lithofacies is characterized as a mudstone (M) that consists of clay to medium-siltstone-dominated mudstone (cd). Mcd had an occurrence of n=96, with a minimum thickness of 0.5ft (0.15m), and a maximum thickness of 44.5ft (13.56m). This deposit is predominantly very thin-bedded and shows no signs of lateral transport. It was found in outcrop to have large variations in the amount of calcite. The likely process for sedimentation of this lithofacies would have been suspension settling.



Figure 39: Lithofacies Mcd, example photos of outcrop and core. The photo on the left is of the Piper Formation, Firemoon Member at BPMFS (23ft, 7m). This photo is showing the Mcd lithofacies lying between two deposits of lithofacies Lm. The right photo is of the Rierdon Formation in Core S575 (3644ft, 1111m) (scale bar is 1 in, 2.5cm). The fissile habit is very common in this lithofacies.

Lithofacies Lm: This lithofacies weathers to a light grey in outcrop and usually fractures dark grey to black. The lithofacies is characterized as a limestone (L), mudstone (m). Lm had an occurrence of n=43, a minimum thickness of 0.5ft (0.15m) and a maximum thickness of 14ft (4.27m). It is carbonate mud-supported with less than 10% carbonate grains (0.03mm to 2mm, 0.001in to 0.08in) and consists of fewer than 10% clasts of 2mm (0.08in) or larger carbonate clasts. The likely process for sedimentation of this lithofacies would have been suspension settling.



Figure 40: Lithofacies Lm, example photos of outcrop and core. The left photo is of the Piper Formation, Firemoon Member at BPMFS (~23ft, 7m). The tape measure lies at the top of the lithofacies in the photo. The photo on the right is of the Piper Formation, Firemoon Member in Core D083 (3277ft, 999m) (the scale bar is 1 in, 2.5cm). Note the oil staining on the fracture plane; however no oil was present in non-fracture-porosity.

Lithofacies Association:

This project defined 26 lithofacies for the Ellis Group in north-central Montana.

The lithofacies were then grouped into six lithofacies associations based on mutual occurrence (Figure 41). The lithofacies associations are interpreted to be related by similarity in hydrodynamic setting based on the inherent hydrodynamic indicators used in assembling the lithofacies, e.g. grain size, grain to mud proportions, sedimentary structures, and when available fossils and trace fossils. That work generated depositionally similar lithofacies associations that allow an understanding of the depositional systems of the Jurassic Ellis Group. See Appendix A for more data on the distribution of lithofacies through lithofacies associations.

FA1: Lithofacies association 1 (FA1) consists of lithofacies Ccb and Cgp. FA1 is predominantly clasts larger than sand, with high clast to mud proportions with no noticeable sedimentary structures (in rare occasions clasts are imbricated).

Many of the occurrences are subsequent to a surface of erosion. These deposits appear to be products of the highest hydrodynamic setting based on said properties.

Lithofacies Ccb and a few occurrences of Cgp are interpreted to be products of sediment gravity flows (Middleton and Hampton, 1976; Nardin et al., 1979). The majority of the Cgp lithofacies is associated with reworking by wave action. It is common for FA1 to be immediately juxtaposed to a significant stratigraphic surface as in a regional unconformity or a non-walthesian shift in lithofacies. There are occurrences of borings at the regional unconformity below Cgp that would be part of the *Trypanites* ichnofacies association.

FA2: Lithofacies association 2 (FA2) consists of lithofacies Lfs, Lgd, Lgs, Scd, Smd, Sfp, Sfd, and IB 1. FA2 is largely comprised of particles ranging from mud to pebble; however, it is predominantly in the upper range of sand. The grain to mud proportion is primarily very low in mud, with the exception of IB 1 (an interbedded lithofacies) though the sand beds are very low in mud fraction. The sedimentary structures range from structureless, ripple cross-laminated, cross-bedded, to plane parallel lamination.

The dominant sedimentary process is a unidirectional current, waning from a surface of erosion, or indicating a waxing and waning flow. It is apparent in outcrop, lithofacies Lfs, Scd, and Smd, are confined deposits that are associated with a localized channelized deposit. Those channelized deposits are interpreted as either coastal or tidal in nature based on vertical facies relationships (sensu Van Wagoner et al., 1990).

Lithofacies Sfp is plan parallel laminated and is interpreted as foreshore at BPMFS based on vertical lithofacies relationship (sensu Van Wagoner et al., 1990). Also, at that field site mud cracks are found in the mud partings in the IB 1 lithofacies. The properties of this association based on both, responses and interpreted processes, point to a shallow marine/coastal environment of deposition (sensu McCubbin, 1981, p. 257-258, 266; Shinn, 1983, p. 174-178, 191-195, 208-209; Bridge, 2006). In particular, areas associated with the depositional shoreline break, i.e. coastal plain, tidal flat, and foreshore to upper shoreface (sensu Van Wagoner et al., 1990).

FA3: Lithofacies association 3 (FA3) is comprised of lithofacies Sms, Sfr, Lpd, Lpr, Lpp, Lwk, Lwn, and Lwa. FA3 is predominantly composed of particle sizes from coarse silt to medium-grain. The grain to mud proportions can range from sand-dominated to mud-dominated, subsequently the deposits can be grain or mud-supported. Sedimentary structures range from structureless, ripple cross-laminated, cross-bedded. Much of the structureless deposits appear to be internal to varying scales of stratification.

Sedimentary processes likely for these deposits appear to be unidirectional flows, with occasional bidirectional current influence in the case of symmetrical ripple bed forms. Rapid deposition and or bioturbation are viable processes for the other lithofacies that appear structureless with no grading and associated burrowing. These attributes point to environments of deposition that have fluctuating current directions and intensities (sensu Dalrymple, et al., 1978; Shinn, 1983, p. 208-209).

Intertidal to subtidal to middle shoreface would be the primary environments of deposition for these properties (*sensu* McCubbin, 1981, p. 257-258, 266; Shinn, 1983, p. 208-209; Van Wagoner et al., 1990).

FA4: Lithofacies association 4 (FA4) consists of lithofacies Sfs, IB 1, IB 2, Lwk, and Lwn. FA4 ranges in grain size from mud to fine-grained sand. The grain to mud fraction is predominantly mud. Sedimentary structures range from structureless to ripple cross-laminated flaser and lenticular bedding. Much of the structureless deposits appear to be internal to varying scales of stratification.

The sedimentary responses in this association have fluctuating hydrodynamic conditions in common. Waxing and waning of depositional energy is apparent in the interbedded and structureless deposits. There are both vertical and horizontal burrows in all of the lithofacies. Based on the similar properties of the lithofacies that comprise this lithofacies, it is likely the environment of deposition would be lower shoreface or down slope of a reef where there were periods of fluctuating fair-weather wave base and possibly influence by storms, causing an abnormal change in wave base and sediment flux (*sensu* McCubbin, 1981, p. 257-258, 266; Van Wagoner et al., 1990; Clifton, 2006).

FA5: Lithofacies association 5 (FA5) is comprised of lithofacies Sfhs, IB 1, IB 2, IB 3, IB 4, and Msr. FA5 ranges in grain size from mud to fine-grained sand, predominantly in the coarse silt to very fine-grained area of the spectrum. There are hummocky-swaley cross-stratified deposits, some ripple cross-laminated lenticular and flaser deposits, and structureless deposits.

This association contains all of the interbedded lithofacies, indicating a depositional setting where fluctuating hydrodynamic conditions dominate. There is also the storm deposit of the hummocky-swaley cross-stratified lithofacies, and then the silt to sand-rich mudstone. Vertical and horizontal burrows are common. The properties of this lithofacies association all can be found in the likely environment of deposition of the offshore transition zone and occasionally lower shoreface (*sensu* Clifton, 2006; Dumas and Arnott, 2006).

FA6: Lithofacies association 6 (FA6) consists of lithofacies Lwk, Lwn, Mcr, Mcd, and Lm. The lithofacies in this association are dominated by mud to silt fraction in particle size and composition. This grouping is interpreted as the muddiest, whether it be argillic or carbonate derived.

There are relatively no sedimentary structures associated with these deposits that show any sign of a lateral component of movement. Suspension settling is the primary interpreted sedimentary process for these muddy deposits. This association is interpreted to be the lowest energy hydrodynamic depositional setting. Based on these properties it is interpreted that these pelagic deposits (Scholle, et al., 1983, p. 620) would most likely be found in the offshore in following this classification scheme (*sensu* Clifton, 2006).

-  FA1 - Lithofacies association 1; consisting of lithofacies Ccb and Cgp. In most occurrences is interpreted as a lag deposit or sediment gravity flow above a surface of erosion. This association did not appear to be restricted to a environment of deposition.
-  FA2 - Lithofacies association 2; consisting of lithofacies Lfs, Lgd, Lgs, Scd, Smd, Sfp, Sfd, and IB 1. The interpreted environment of deposition is shallow marine to coastal, proximal to the depositional shoreline break.
-  FA3 - Lithofacies association 3; consisting of lithofacies Sms, Sfr, Lpd, Lpr, Lpp, Lwk, Lwn, and Lwa. The interpreted environments of deposition are tidal to subtidal down to middle shoreface.
-  FA4 - Lithofacies association 4; consisting of lithofacies Sfs, IB 1, IB 2, Lwk, and Lwn. The interpreted environments of deposition are lower shoreface or outboard of base of reef.
-  FA5 - Lithofacies association 5; consisting of lithofacies Sfhs, IB 1, IB 2, IB 3, IB 4, and Msr. The interpreted environments of deposition are lower shoreface to offshore transition zone.
-  FA6 - Lithofacies association 6; consisting of lithofacies Lwk, Lwn, Mcr, Mcd, and Lm. The interpreted environments of deposition are offshore below both fair-weather and storm wave base.

Figure 41: Lithofacies associations. This figure is a summary of the above writings that layout the basis for the lithofacies associations.

CHAPTER 5 - STRATIGRAPHIC ANALYSIS

A fundamental component to deciphering the geologic relationships responsible for “Belt Island” was establishing a temporally significant stratigraphic architecture of the Ellis Group. If there were a large structural feature during the deposition of the Ellis Group it would have had an influence on the Ellis Group’s architecture. This influence would be expressed in vertically thickening and thinning of stratigraphic intervals, being a direct response to accommodation induced by the structural undulation of the paleotectonic features of the area.

To investigate the influence of a large feature on the stratigraphic architecture of the Ellis Group a stratigraphic framework was assembled from multiple forms of data, multiple methods of stratigraphy, and a considerable amount of work from the literature search. This stratigraphic framework based on preexisting lithostratigraphy, biostratigraphy, and regional unconformities integrated with the outcrops, cores, and geophysical well logs, makes the foundation for a chronostratigraphically significant framework. This was the foundation for constructing a high-resolution sequence stratigraphic framework over the project area.

Regional Unconformities

The importance of unconformities to stratigraphy has stood through time. From early beginnings as horizons of lithologic differentiation for lithostratigraphy, to the development of sequence stratigraphy as surfaces for differentiating genetic packages, “they are essential as a framework of reference...” (Wheeler, 1959, p. 699).

Regardless of “datum variance” unconformities are important to the dimensional configuration of a stratigraphic framework. There are numerous regional scale unconformities that exist within and far beyond the boundaries of this project area. Pipiringos and O’Sullivan (1978) compiled a significant amount of previous literature into a very useful work of literature that this project utilized. The regional unconformities from that work that are applicable to this project are the J-2, J-3, J-4, and J-5. It should be noted that the J-3 was not mentioned in said work within the project area, however there is discussion of it in the surrounding area. The J-2 unconformity is the boundary between the base of the Ellis Group and Mississippian strata as a total vacuity within the project area. This unconformity represents the base of the Middle to Late Bajocian Stage. The J-2 coincides with the base of the Zuni Sequence as defined by Sloss (1963). That superposition puts the Zuni Sequence in contact with the Kaskaskia Sequence with no material representation of the Absaroka Sequence within the project area (Sloss, 1963). The J-4 unconformity separates the Rierdon Formation from the Swift Formation, this being internal to the Late Callovian Stage. The J-5 unconformity divides the Swift Formation from the subsequent Morrison Formation. This surface is the division of the Jurassic, from marine to terrestrial deposits. There is disagreement in the literature about this contact being conformable or unconformable, apparently a paraconformity. Based on this research, the bounding nature of this surface is relative to the specific location.

This research is not implying an isochronous value to unconformities, in this project or in general, therefore in agreement with the discussion put forth by Wheeler and Beesley (1948). With that said, based on their regional extent compared to the size of the project area, the diachronous magnitude is deemed second to the chronologic resolution provided by the biostratigraphy. Therefore, these regional scale surfaces more than adequately serve as the chronologically significant sequence boundaries for the project. Supported by the regional work on the unconformities and biostratigraphy, and the lithofacies characterization by this project, these surfaces are the backbone to the sequence stratigraphic framework. This framework is shown in Figure 42.

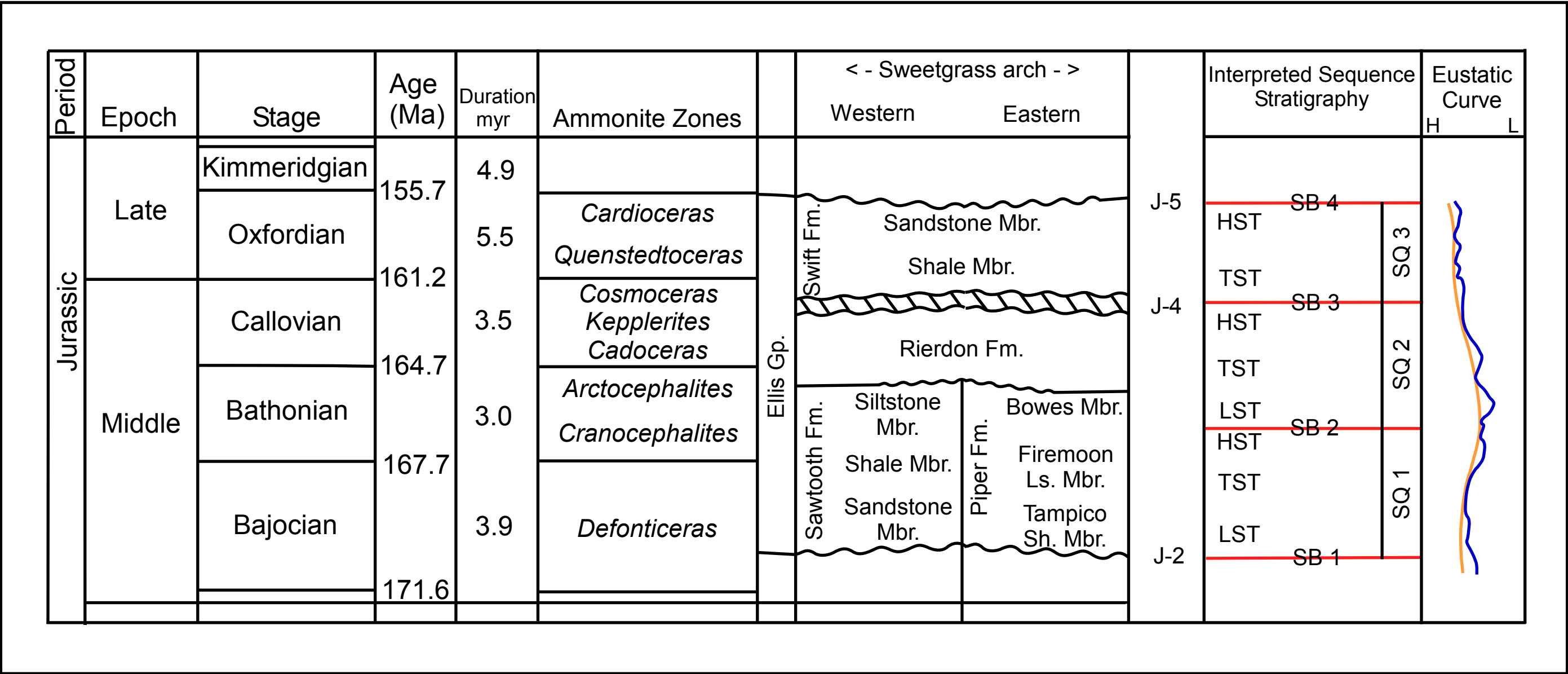


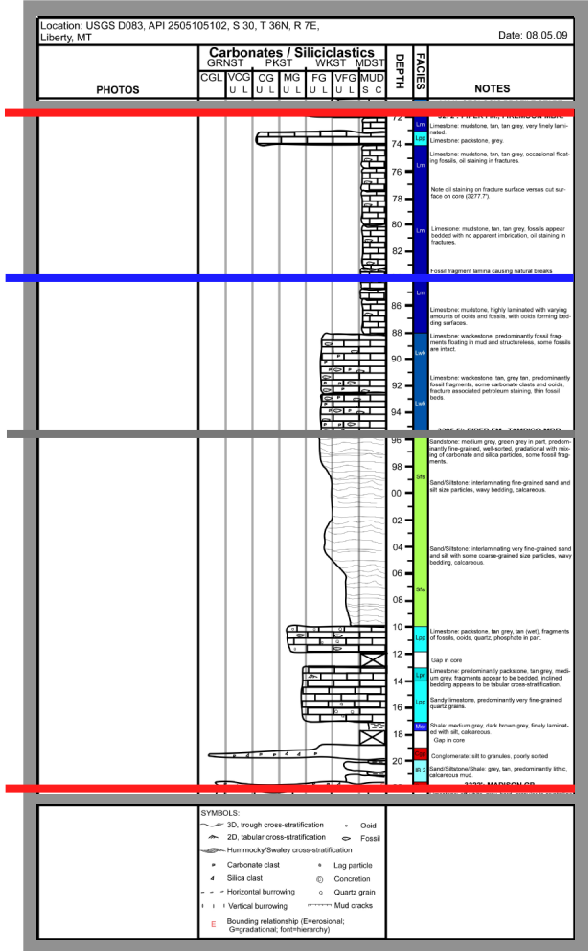
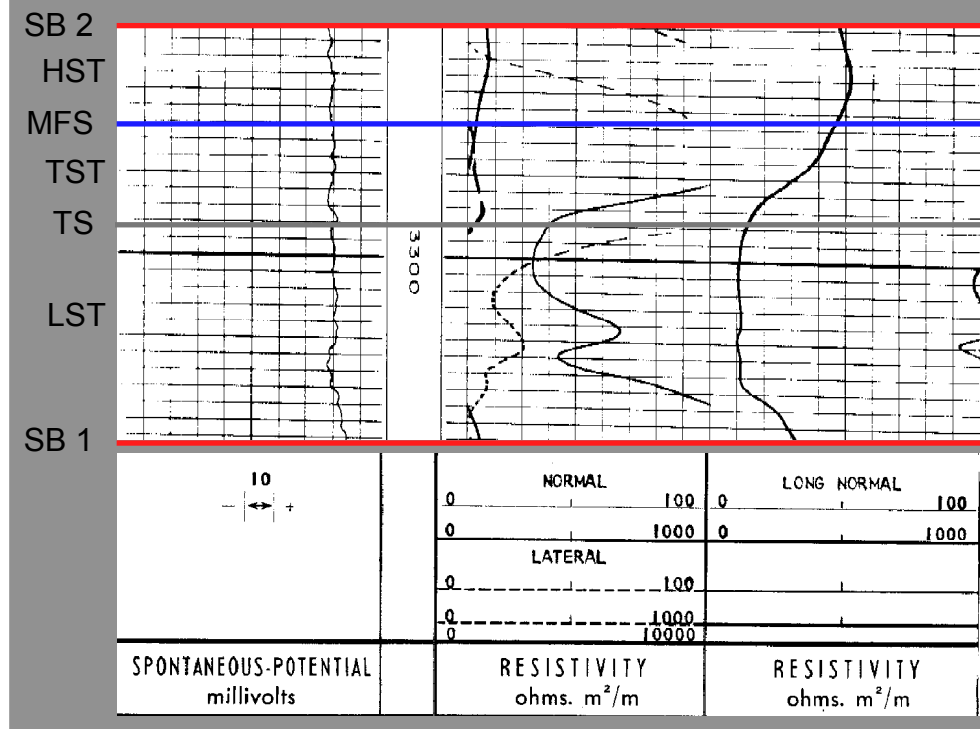
Figure 42: Stratigraphic column for the project incorporating: chronological intervals, biostratigraphy, lithostratigraphy, regional unconformities, and interpreted sequence stratigraphy. Note the corresponding lithostratigraphy of the Ellis Group to the regional unconformities as put forth by Pipiringos and O’Sullivan (1978). Additionally, the interpreted sequence stratigraphy with the correlation between lithostratigraphic members and formations to the sequences and systems tracts. The red lines are sequence boundaries (SB); the sequences are labeled as SQ; the systems tracts are labeled as lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST). The eustatic sea level curve is from Haq et al., 1989 (the orange line is long-term and the blue is short term cyclicality).

Sequence Stratigraphic Framework

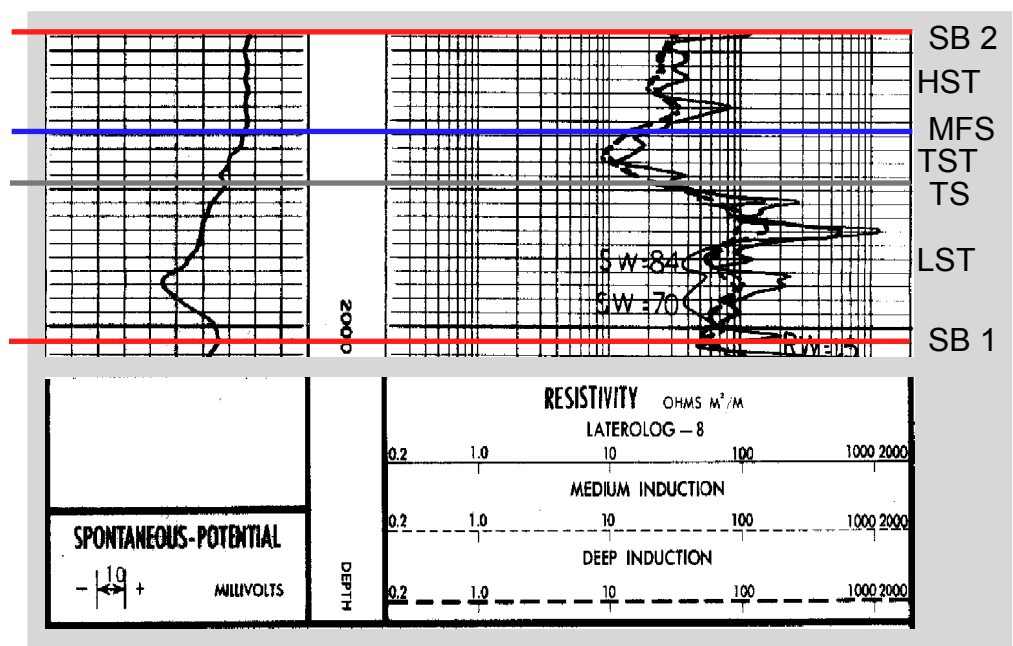
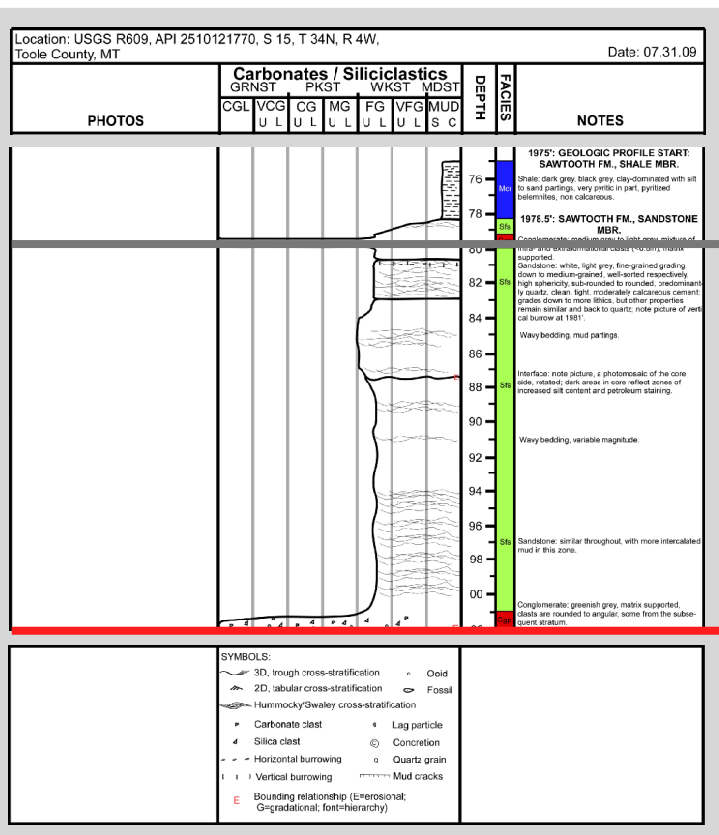
As stated previously, an objective of this project was to generate a high-resolution sequence stratigraphic framework (sensu Van Wagoner et al., 1990). This was accomplished through integration of outcrops, cores, and geophysical well logs utilizing the pre-existing lithostratigraphy, biostratigraphy, and regional unconformities (Figures 42-48). Together this synthesis of data and methods allow for the chronostratigraphic constraints needed to investigate and elucidate “Belt Island”. Within this sequence stratigraphic framework the stratigraphic architecture and facies differentiation show, not only where, but when “Belt Island” was present and influencing Middle to Late Jurassic deposition and erosion. Furthermore, this sequence stratigraphic framework allows for the effect of a large local feature on the sedimentology and stratigraphy of the Ellis Group to be understood within a global context. That is to say, the interplay of local tectonics and eustasy as one forcing function dominates over the other; as can be noted in Figure 42. Chapter 6 provides the synthesis on the local and regional tectonics in place during the Middle to Late Jurassic. Chapter 7 presents in greater detail the sequence stratigraphy in application to this project encompassing the lithofacies from Chapter 4 for a fully incorporated sequence stratigraphic framework that is coupled with the tectonics in and around the project area for a fully integrated geologic framework.

Sequence One (SQ 1) - Eastern

Figures showing the geologic profile for described core D083 and the associated log suite for the well over the sequence one interval in said borehole. The geophysical well log shows the complete sequence as seen in the area as well as in this case, the entire sequence was cored in the same said well. The geologic profile shows the full sequence from the SB 1 to SB 2. This is an example for the eastern slope of the Sweetgrass arch. Note the ability to calibrate the important stratigraphic surfaces was fairly easy, even with older raster data. However, the log resolution is not on par with the cores to completely calibrate the individual lithofacies. This raster image in particular is a good example of the limits of this project where the only real differentiation in lithofacies is the difference between carbonates and siliciclastics.



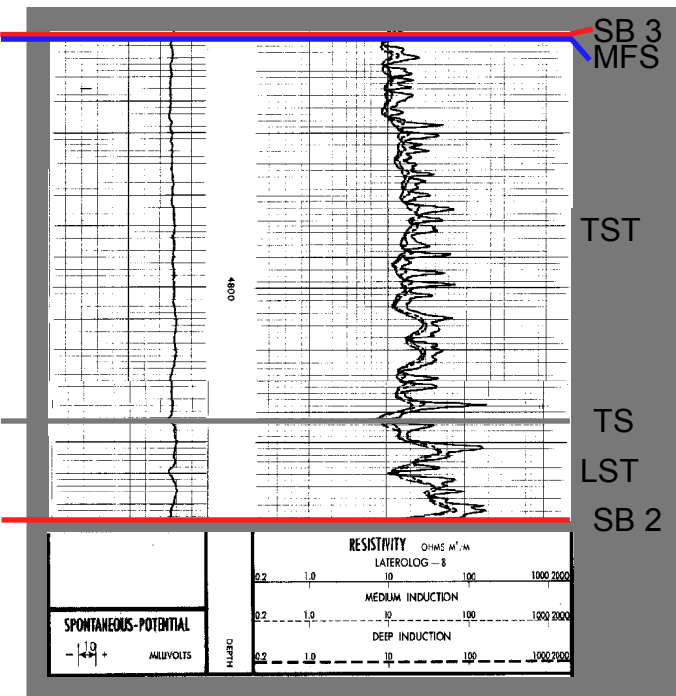
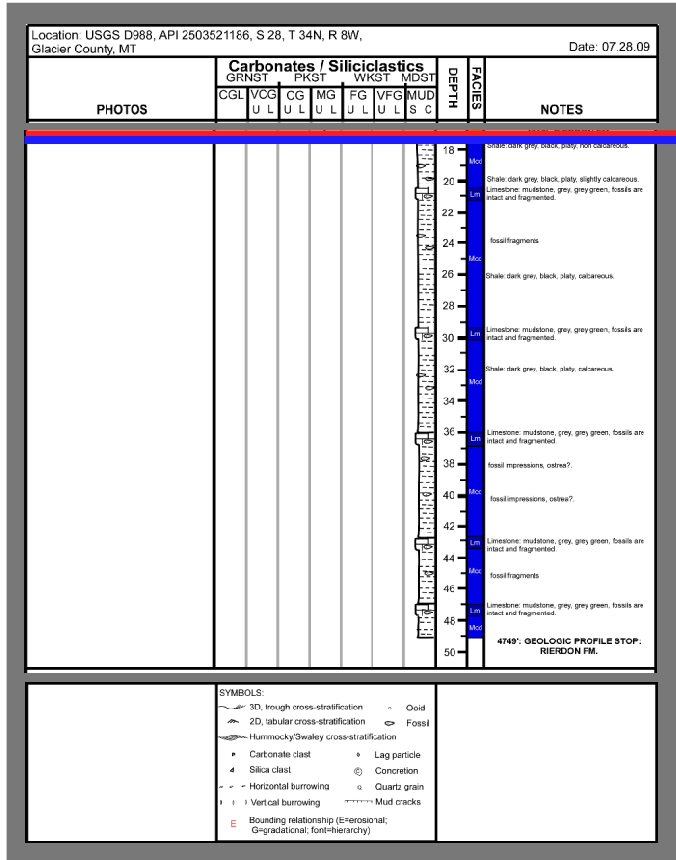
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Sequence One (SQ 1) - Western

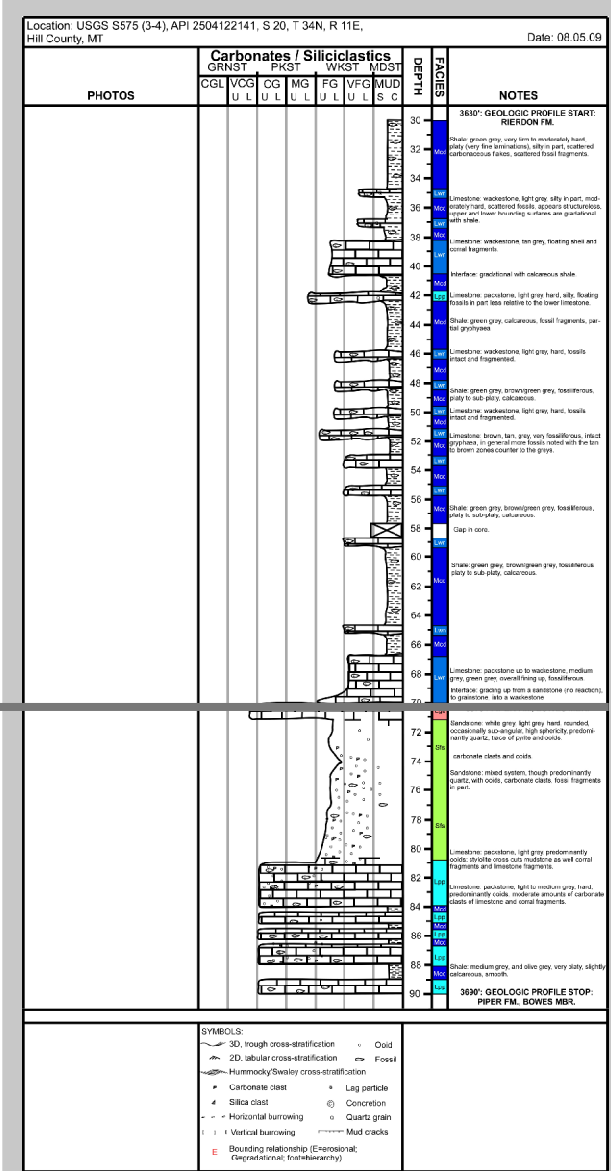
Figures showing the geologic profile for described core R609 and the associated log suite for the well over the sequence one interval in said borehole. The geophysical well log shows the complete sequence as seen in the area, however there was no full core description on the western slope of the Sweetgrass arch. The geologic profile shows mostly the LST and the lower portion of the TST for this sequence. Note the ability to calibrate the important stratigraphic surfaces was fairly easy, even with older raster data. However, the log resolution is not on par with the cores to completely calibrate the individual lithofacies. It was possible to correlate general trend variations in the lithofacies.

Figure 43: Application of the sequence stratigraphic framework to the Sequence One interval. See insets for greater description.



Sequence Two (SQ 2) - Western

Figures showing the geologic profile for described core D988 and the associated log suite for the well over the sequence two interval in said borehole. The geophysical well log shows the complete sequence as seen in the area, however in the core only the upper portion of the sequence is represented. This is an example for the western slope of the Sweetgrass arch. There is a noticeable difference in log response between the two logs/sides of the arch.



Sequence Two (SQ 2) - Eastern

Figures showing the geologic profile for described core S575 and the associated log suite for the well over the sequence two interval in said borehole. The geophysical well log shows the complete sequence as seen in the area, however there was no full core description on the eastern slope of the Sweetgrass arch. The geologic profile shows most of the LST and TST for this sequence. Note the ability to calibrate the important stratigraphic surfaces was fairly easy, even with older raster data. However, the log resolution is not on par with the cores to completely calibrate the individual lithofacies. It was possible to correlate general trend variations in the lithofacies. As with some of other calibrations, the greatest difference is between the carbonated dominated versus siliciclastic dominated intervals.

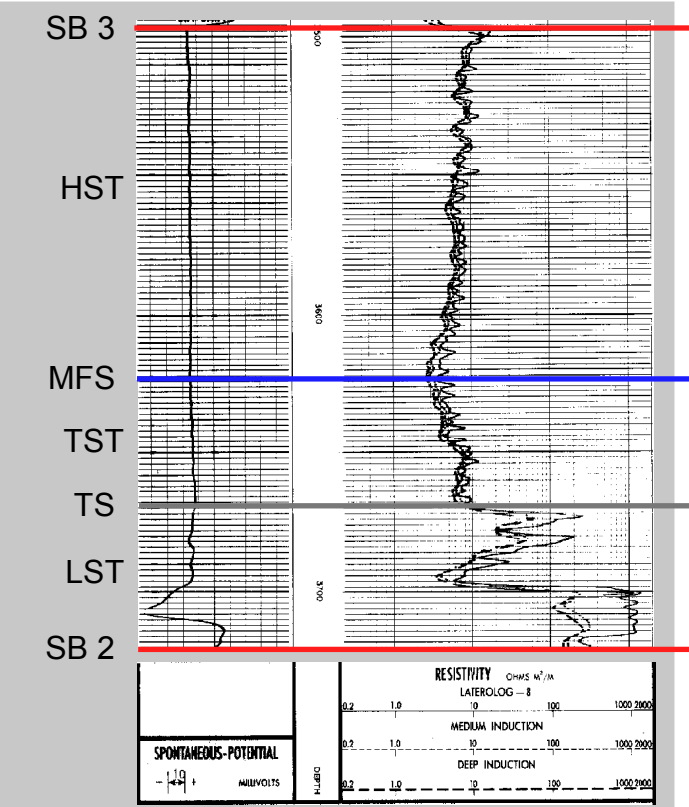


Figure 44: Application of the sequence stratigraphic framework to the Sequence Two interval. See insets for greater description.

Figure 45: Application of the sequence stratigraphic framework to the Sequence Three interval. See insets for greater description.

Assembling the high-resolution chronostratigraphically significant framework began from the lithofacies up. Utilizing the lithofacies and lithofacies associations, one could determine significant, and just as important, less significant (hierarchically speaking) basinward shifts in depositional environments. Integrating the lithofacies, basic petrophysical calibrations, and the previous stratigraphic work, made it possible to expand the sequence stratigraphic framework throughout the project area to the multiple data sources as noted in Figures 43, 44, and 45. Without the sequence stratigraphic framework, it would be impossible to compare the differentiation in coeval lithofacies across the project area. Which is important and the author believes that Figures 43, 44, and 45 show that very well.

Comparison of the coeval lithofacies allowed for interpretation and understanding of the stratigraphic architecture. In analyzing the lithofacies relationships, both vertical and lateral, they allowed for a more complete understanding of the bounding relationships of separate stratigraphic zones. In determining the likely environments of deposition of a genetically related package of lithofacies one can find agreement with the stratal stacking patterns. This aided in understanding that most importantly the Ellis Group was onlapping onto a paleostructural high and not downlapping onto the basin floor; an important notion as without context, non-deposition could not be explained either way. In particular Figures 47, 48, and cross section EE' (Appendix A) serve to validate this concept. Furthermore, the lithofacies support the concept of separating out parasequences and organizing those genetically related rock packages into systems tracts, further supporting the stratal stacking patterns.

This framework, from the lithofacies up to the regional unconformities, puts the temporal constraints on the “Belt Island” feature that was needed to understand it.

The project generated numerous cross sections. However, the project limited the ones that revealed the story of “Belt Island” best to this paper, in particular Figures 47 and 48 (see also Appendix A). The stacking patterns of the systems tracts and sequences in relation to the “Belt Island” feature with can be thought of as the black pre-Jurassic strata (for all real purposes the developing peripheral bulge). These cross sections show the growth of the structure through time, i.e. by sequence (most obvious in EE’). Furthermore, they support the concept of changing sediment volume around the project area being a direct, and significant, relationship between stratal patterns and lithofacies.

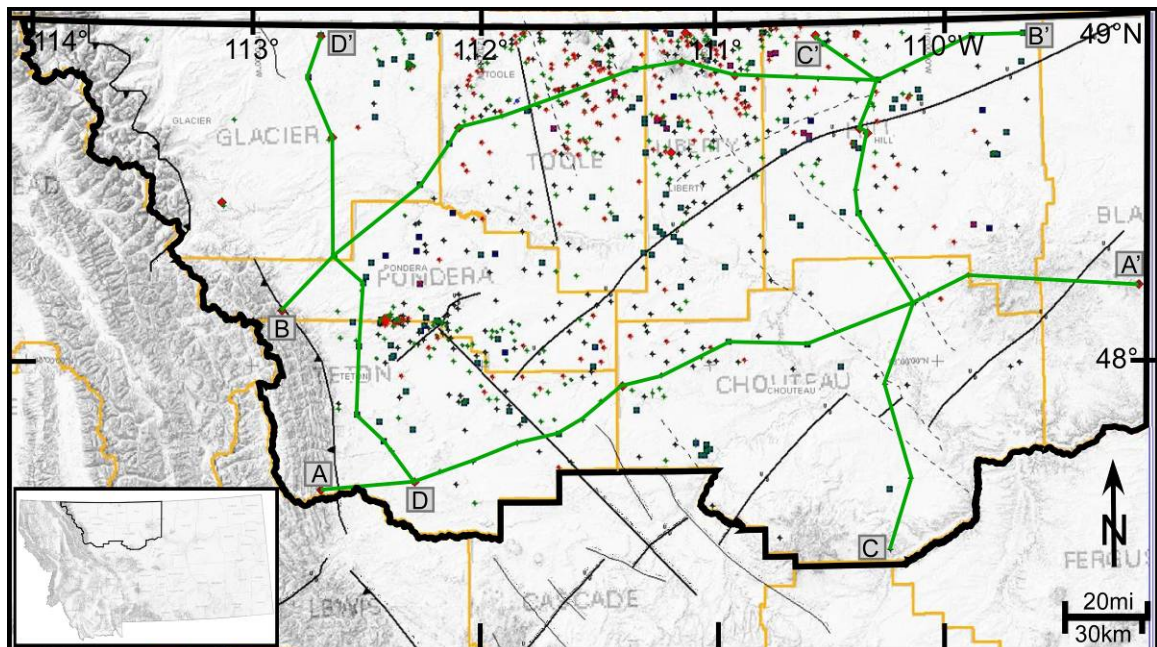


Figure 46: Base map for final four cross sections in Figures 47 and 48. This map shows the placement of the final four cross sections relative to the project area and one another. The order of the cross sections are such that the first two (AA' and BB') are to be thought of as being viewed from the south; and (CC' and DD') as being viewed from the east. Therefore, in two-dimensional projection the “front” cross sections end up at the bottom of the page.

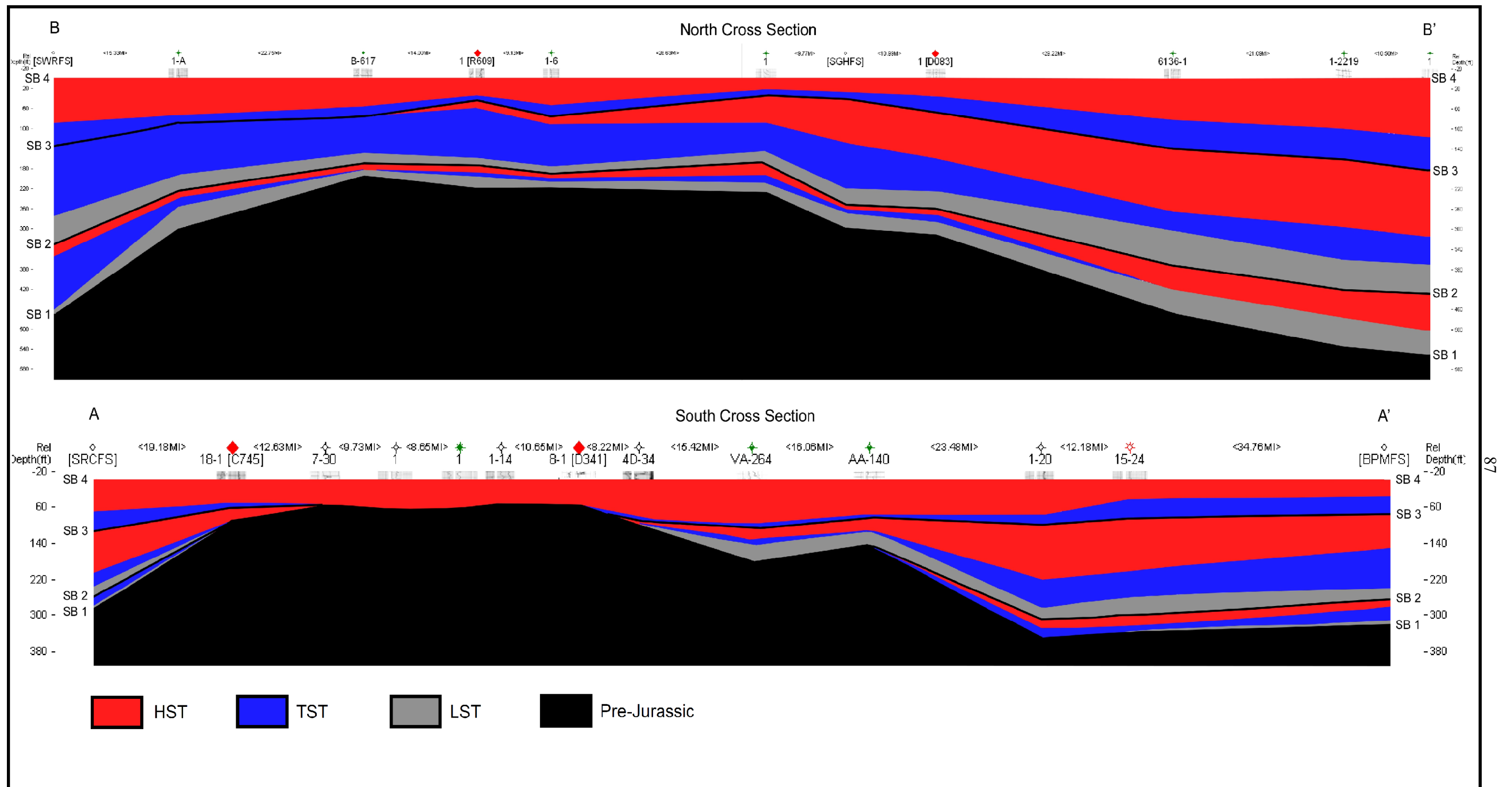


Figure 47: AA' and BB' cross sections. See Figure 46 for reference map. These cross sections show the cross sectional vertical profile of the Ellis Group partitioned into sequences and systems tracts. The dynamics of the general stratral stacking patterns can be noticed across the project area and in relation to the developing peripheral bulge. In particular, notice on the west side, in both AA' and BB', the HST of Sequence Two pinches out to the north. However, in Sequence One the HST pinches out to the south.

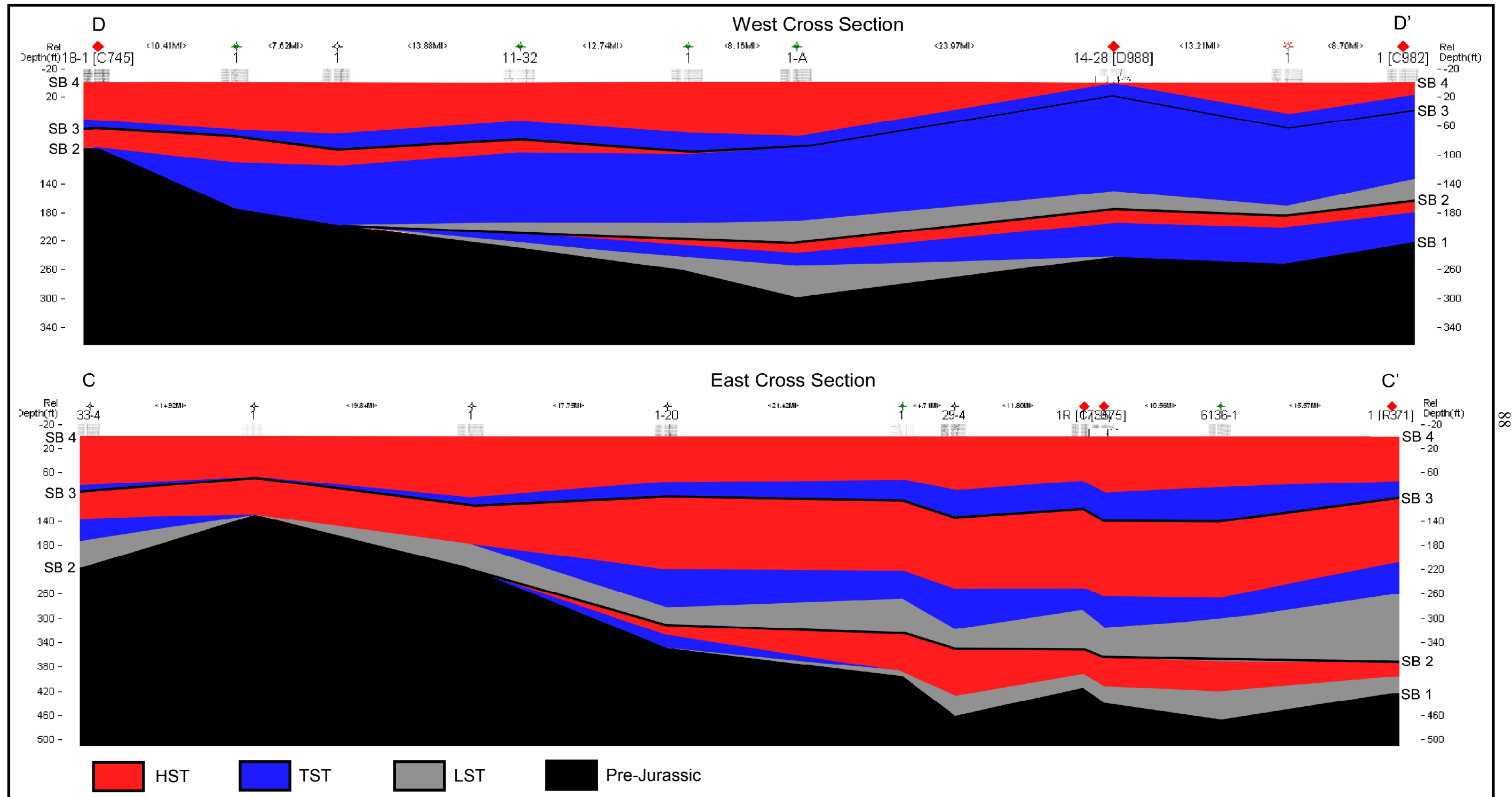


Figure 48: CC' and DD' cross sections. See Figure 46 for reference map. These cross sections show the cross sectional vertical profile of the Ellis Group partitioned into sequences and systems tracts. The dynamics of the general stratal stacking patterns can be noticed across the project area and in relation to the developing peripheral bulge. In particular, notice on the west side (DD'), as discussed in Figure 47, the HST of Sequence Two pinches out to the north. However, in Sequence One the HST pinches out to the south. The other difference made apparent by these cross sections is the presence and or thickness differences between the west side (foredeep area) and east side (back-bulge area) of the developing peripheral bulge, more importantly which type of systems tracts dominates.

CHAPTER 6 – TECTONICS

This chapter focuses on the paleotectonics and tectonics, events, and features that are deemed pertinent to the project area and the development of “Belt Island”. In progressing through these particular facets of the argument, the chapter interprets “Belt Island” in a modern tectonic context.

Sweetgrass Arch

There is presently a positive structure in the general paleogeographic area that “Belt Island” occupied, known as the Sweetgrass arch, first described by Stebinger (1916). The Sweetgrass arch in Montana is comprised of two main features, the South arch and the Kevin-Sunburst dome (Cobban, 1945). The South arch, once called “teton anticline” by Collier (1930), extends northwesterly from the Little Belt Mountains to the Pendroy fault zone (Cobban, 1945). Kevin-Sunburst dome is centered in the general area of the southwest quarter of Township 34N, Range 1W (Cobban, 1945). North into Canada the Sweetgrass arch is comprised of the Bow Island arch also known as the North arch.

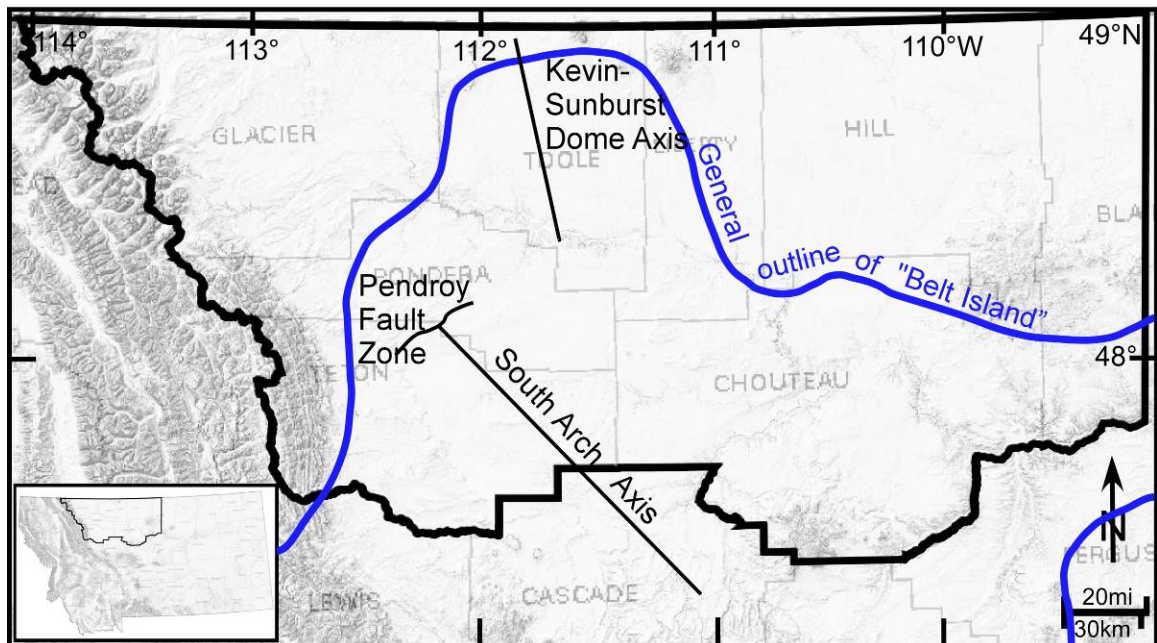


Figure 49: Sweetgrass arch and “Belt Island”. The South arch and Kevin-Sunburst dome make up the greater Sweetgrass arch in Montana; north into Canada, other features are present. The South arch has a downward trajectory to the northeast-trending Pendroy fault zone, where the Sweetgrass arch general axis steps northeast to join the Kevin-Sunburst dome axis.

Theories on origin of this tectonic feature have been postulated for some time, the first beginning with Clark (1923). “The folding [the Sweetgrass arch] involved was probably induced by lateral pressure exerted during the Rocky Mountain uplift which resulted in the over-thrust faults of the Front Range” (Clark, 1923, p. 271). Clark (1923) continues hypothesizing with less than accurate possibilities due to conflict of timing, however this is impressively insightful considering the time of this before the thought of plate tectonics and foreland basin models. Michener (1934, p. 45) proposed a more dynamic sequence of diastrophism, “initial folding of the arch was probably produced by vertical stresses. The final folding was controlled by stresses which were vertical in action, but which were the result of the progressive resolution of horizontal diastrophic stresses from the west”.

Interestingly Michener (1934) notes the importance of using stratigraphy to get at timing of the tectonism, more so he proposes a dynamic tectonism that persisted from the Jurassic to the Middle Cretaceous. This concept is fundamental to this research in establishing a chronostratigraphically significant framework to constrain the temporal and spatial equivocation of the large tectonic feature of the Mesozoic. This theme of tying the modern day feature (Sweetgrass arch) to the equivalent paleogeographic area that exhibits signs of tectonism continue in the literature up to and beyond the inception of “Belt Island”. Cobban (1945) discussed in detail the multiple components of the arch being active during different ages of the Middle to Late Jurassic. It appeared that the work of Imlay et al. (1948) should have drawn a distinction between the modern day feature (Sweetgrass arch) and the feature that was present during the Jurassic (“Belt Island”). However, after the inception of the “Belt Island” concept, the lines though defined were not adhered to. The misnomers in the subsequent literature are not inconceivable, with the overlap that can be seen in Figure 49, and the trend in literature that preceded the inception of “Belt Island”. Tovell (1958) does an exceptional job in laying out a majority of the previous work on the Sweetgrass arch and partially illuminates the overlap in nomenclature. In the author’s opinion, Lorenz (1982) is a summation of what the Sweetgrass arch is and appears to be the most modern and substantiated tectonic explanation. Lorenz (1982) addresses the lateral compressive force theories mentioned above; these forces may explain the smaller scale deformation features noted on the arch, but cannot account for a lithospheric flexure of this magnitude.

The Sweetgrass arch is a product of multiple periods of deformation and early on the forces exceeded the elastic limits of the lithosphere, thereby making a preexisting zone of weakness that the subsequent periods of deformation would exploit (Lorenz, 1982). This effect thereby caused the arch (peripheral bulge) to remain laterally locked in place though undergo upward deflection due to the easterly migrating thrust belt. It is understood that the Sweetgrass arch is of a polygenetic origin, as it is known today, evolving from the Proterozoic to present day. It seems appropriate to cite Mudge's comment for a segue into the next section, "all features of the Sweetgrass Arch involve the Precambrian crystalline basement" (1982, p. 91).

Great Falls Tectonic Zone

A key tectonic element that is present in and beyond north-central Montana is the Great Falls tectonic zone. This geologic zone is characterized by recurrent movement from the Paleoproterozoic to present day. O'Neill and Lopez defined the Great Falls tectonic zone (GFTZ) as "a belt of diverse northeast-trending geologic features that can be traced from the Idaho batholith in the Cordilleran miogeocline, across thrust-belt structures and basement rocks of west-central and southwestern Montana, through cratonic rocks of central Montana, and into southwestern-most Saskatchewan, Canada" (1985, p. 437). O'Neill and Lopez (1985) are credited with naming this geologic zone; however, it is acknowledged that Alpha (1956) first recognized this trend of tectonism.

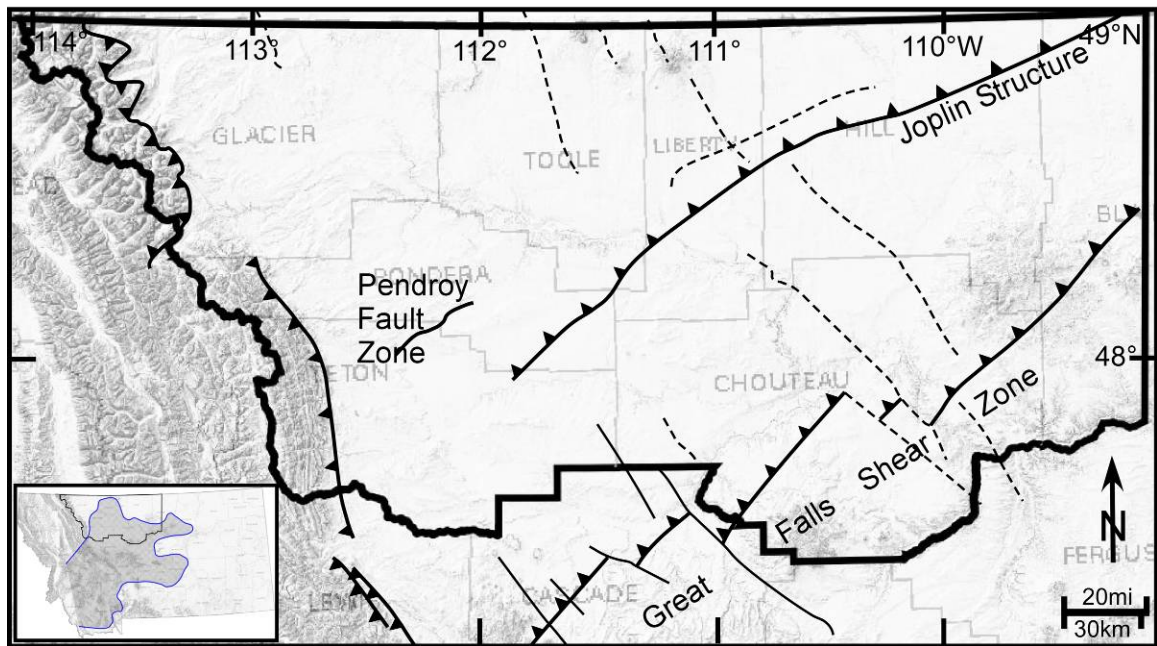


Figure 50: The project area and northeast-trending features. The Great Falls tectonic zone is made up of named and many unnamed northeast-trending features in and beyond the project area. Some of these tectonic features appear to indicate syndepositional movement with the Ellis Group (discussed further in Chapter 7).

Theory of origin began with the GFTZ being related to, and possibly a product of, accretion of the Medicine Hat block and the Wyoming craton during the Trans-Montana Orogeny (O'Neill and Lopez, 1985) (Figures 5, 6, and 50). In support of this are the similarities between the GFTZ and the Churchill-Superior collisional boundary, such as northeast-trending faults, shear zones, and marked topographic lineaments, pronounced linear magnetic and gravity anomalies, igneous intrusions, and fault-controlled depositional patterns and mineralization (O'Neill and Lopez, 1985). It is important to note the comment on "fault controlled depositional patterns" as this was revealed in the analysis of the Ellis Group in isochore-thicks that directly correlate to major lineaments (discussed further in Chapter 7). Syndepositional movement is important for two reasons. First, it indicates tectonic activity during the Middle to Late Jurassic.

Second, it supports the theory of a large feature influencing lithofacies distribution and the stratigraphic framework of the Ellis Group.

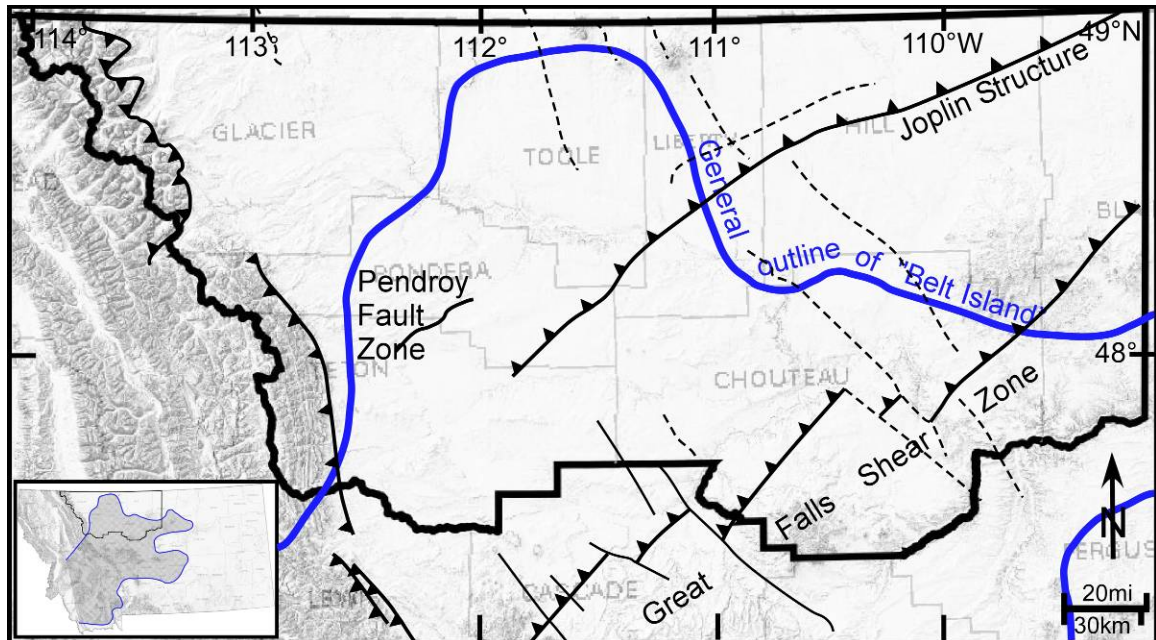


Figure 51: Great Falls tectonic zone and “Belt Island”. This figure shows the general outline of “Belt Island” and the main tectonic features of the GFTZ. Important is the deviation to the east of the outline over the general areas of the Big Snowy, Little Belt, and Big Belt uplifts as described by Imlay et al. (1948); which is over the Great Falls Shear Zone of the GFTZ.

There are certainly other notable papers on the GFTZ (O’Neill, 1998; Boerner et al., 1998; Mueller et al., 2002; Jorgensen, 2004; Sims et al., 2004; and Probst et al., 2008) that debate the exact nature, origin, and timing of origination of the tectonic zone.

However, they quickly go beyond the scope of this project and the role of the GFTZ as a tectonic feature in the explanation of “Belt Island”. There is a general agreement of the tectonic zone originating in the Paleoproterozoic, having an effect on accommodation in the Mesoproterozoic, and recurrent tectonic activity throughout the Phanerozoic.

Important to this project, is the apparent correlation of the stratigraphic architecture of the Ellis Group, in part, being controlled by primary tectonic features of the GFTZ.

Western North American Cordillera

The Western North American Cordillera extends a great distance from the southwestern United States to the Beaufort Sea, comprised of many different mountain systems. It is the product of effectively westward and northwestward migration of the North American Plate, particularly during the Mesozoic. Lithologically it is comprised of accreted terrain and folded and thrust sedimentary rocks during the collision of the Farallon and North American Plates. Far beyond the scope of this project at that scale, therefore it is important to focus into the area of the cordillera that is pertinent. Specifically, the western boundary of the project area is the disturbed belt (Mudge, 1970a) which is immediately juxtaposed to the previously discussed Sweetgrass arch, the “Belt Island” feature, and the Great Falls tectonic zone. It is this notion of the Western North American Cordillera being active during and occupying the same paleogeographic area as the “Belt Island” feature that is so critical in understanding the tectonic reasons for that feature.

The topic of timing, that is the onset of the development of a foreland basin system in the region of the project area related to the Western North America Cordilleran Orogeny. The Orogeny can be thought of being composed of other geographical and temporally restricted orogenies, e.g. Nevadan Orogeny, Columbian Orogeny, Sevier Orogeny, and the Laramide Orogeny in chronologic order. The Nevadan and Columbian Orogenies do overlap temporally but effect geographically different areas.

The focus here is evidence, which supports the theory that during the Nevadan Orogeny there was tectonic activity in the paleogeographic area of the project area in the form of lithospheric flexure due to the compression and crustal loading of the greater Western North America Cordilleran Orogeny. Multiple authors have purported and presented evidence that tectonic activity in the Middle to Late Jurassic was related to the Western North America Cordilleran Orogeny (Peterson, 1957; Mudge, 1970a, 1970b; Scholten, 1970; Kauffman, 1977; Suttner et al., 1981; Mudge, 1982; Brenner and Peterson, 1994; Dolson and Piombino, 1994; DeCelles, 2004; Parcell and Williams, 2005; Ward and Sears, 2007; Fuentes, DeCelles, and Gehrels, 2009). Suttner et al. (1981, p. 97), states, “...within the foreland basin, the [“Belt Island”] influenced both the thickness and composition of the basin fill...” pertaining to the Ellis Group. Additionally, they state the correlation between “Belt Island”, basement controlled faulting, and the net result of this tectonism controlling the stratigraphic architecture of the Ellis Group, in particular the Swift Formation (Suttner et al., 1981).

Some of the more modern evidence is presented by DeCelles (2004) with apatite/zircon fission track dating, $^{40}\text{Ar} - ^{39}\text{Ar}$, and K – Ar dating. These data coming from multiple sites along the cordillera, one in particular came from the northwest region of the research project area. Very similar data is used in a later paper (Fuentes, DeCelles, and Gehrels, 2009) that shows strong supporting evidence, through provenance analysis, the onset and influence of the Western North America Cordilleran Orogeny during the deposition of the Ellis Group; therefore showing the migration of primary source regions.

A preponderance of the evidence indicates the direct influence of the Western North America Cordilleran Orogeny on the paleogeographic area that was “Belt Island”.

Remarks

The work shows that there are locally some great discrepancies in the paleogeography of “Belt Island”, however on a regional scale there is some considerable agreement. This general area of “Belt Island” strongly corresponds with the tectonic features discussed. The evidence that supports these features is strong and valid to explain “Belt Island” in a modern tectonic context as a paleogeographic area where sedimentology and stratigraphy of the Ellis Group was noticeably affected due to the regional tectonic activity. The sediment provenance analysis strongly suggests the onset of the Western North America Cordilleran Orogeny during the Middle Jurassic and affecting the sediment sourcing and routing of the rocks comprising the Ellis Group. The work on the Sweetgrass arch supports this theory in the expected result of crustal loading from the west to cause lithospheric flexure in the foreland area. The behavior of the Sweetgrass arch as a peripheral bulge is non-ideal due to the preexisting crustal weakness due to previous deformational events exceeding the elastic limits of the lithosphere. Deformational events, or in a less punctualistic vernacular, ongoing tectonism in the region is explained by the Great Falls tectonic zone. Recurrent movement from the Paleoproterozoic to the modern day defines this zone. This movement is supported by evidence of lithofacies differentiation and dynamic stratigraphy of the Ellis Group associated with large scale features of the GFTZ.

It is these data sources that support the conclusion that “Belt Island” is a result of local tectonics on the sedimentary rocks of the Ellis Group. The term “Belt Island” is a paleogeographic area, from Bajocian to Oxfordian time, where concurrent sea level fluctuations interacted with syntectonic forces due to lithospheric flexure, differentially exploiting preexisting crustal weaknesses, to cause differential deposition/preservation of the Ellis Group.

CHAPTER 7 – GEOLOGIC FRAMEWORK

The Geologic Framework is a figure rich chapter showing the multiscale and multidimensional integration of data, used in this project, displayed in maps. The geologic framework shows, through the use of structure maps, isochore maps, and cross sections the paleotectonic setting during the Middle to Late Jurassic. The structure maps are based on important stratigraphic surfaces that served to construct the sequence stratigraphic framework. The isochore maps show these same surfaces adding a chronostratigraphic constraint to the lithofacies to define the systems tracts within the sequence stratigraphic framework. The oversized cross sections (Chapter 5 and Appendix A) show the stratigraphic architecture in the vertical component with respect to, and the effect of, a dynamic peripheral bulge. The tectonics chapter has laid out the structural platform for which this geologic framework can be understood in a modern tectonic context, a foreland basin setting.

Sequence One

Sequence One (SQ 1) is the first interval of deposition of the Ellis Group (see Figure 42). This interval is the stratigraphically thinnest of the three sequences but is composed of all three systems tracts. The infilling of inherited topography can be noted in the geologic profiles (Appendices A, B, and C), based on vertical and lateral facies relationships related to isolated or restricted deposits.

The direct influence on sediment routing due to syntectonic adjusted accommodation is very apparent with respect to the Joplin Structure (JS) in particular as noted in Figures 54, 58, 59, and cross sections CC' (Chapter 5) and EE' (Appendix A).

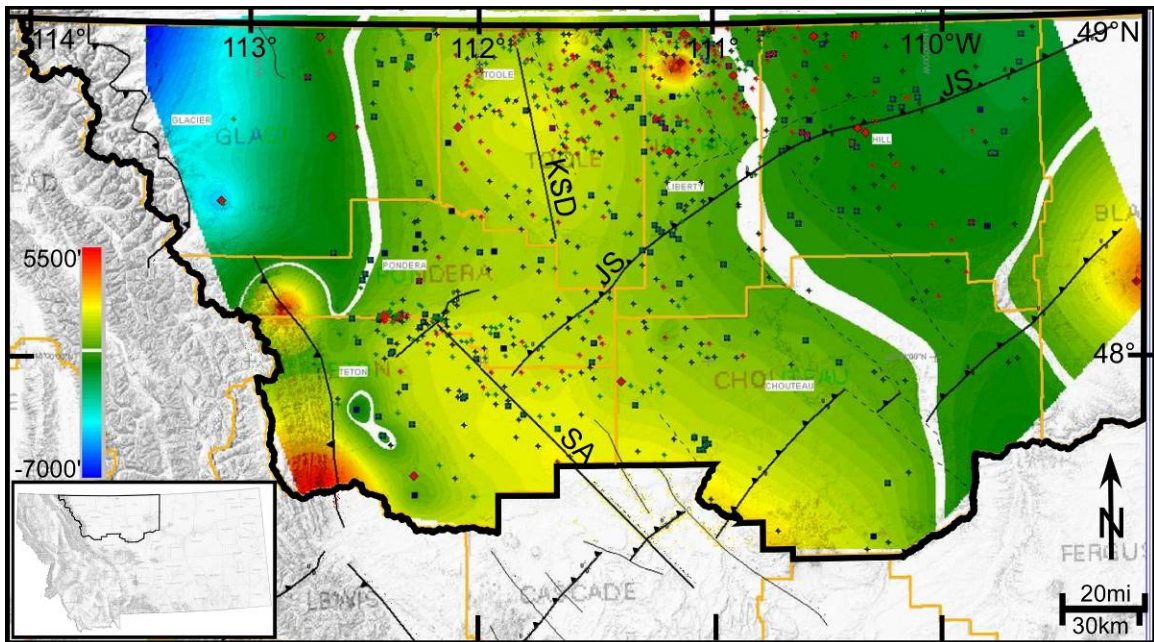


Figure 52: Surface structure map of SB 1. This surface is the J-2 regional unconformity and the top of the Mississippian strata. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

The structure contour maps (Figures 52 and 55), based on sequence stratigraphic boundaries, show with chronostratigraphic significance the dynamics of the peripheral bulge. The sea level contour interval was filled with white to stand out separate as a base line to make comparison between figures easier. That contour interval aides in comparing the peripheral bulge as a whole through time. Furthermore, noticing the subtle changes in contouring, one can see the changing expressions of the South arch (SA) and the Kevin-Sunburst dome (KSD) through time. The axes drawn on the map (more detail in Figures 49 and 50) are the present day axes.

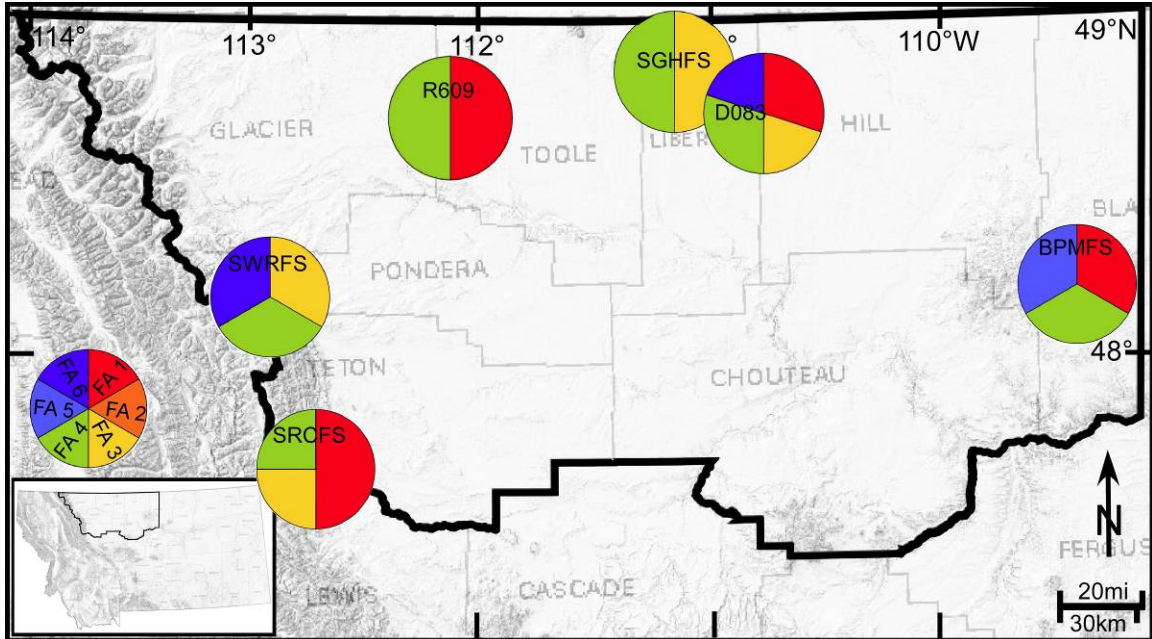


Figure 53: Distribution of lithofacies map of the LST of SQ 1. In general this map shows the LST to be dominated by the higher energy spectrum of lithofacies associations.

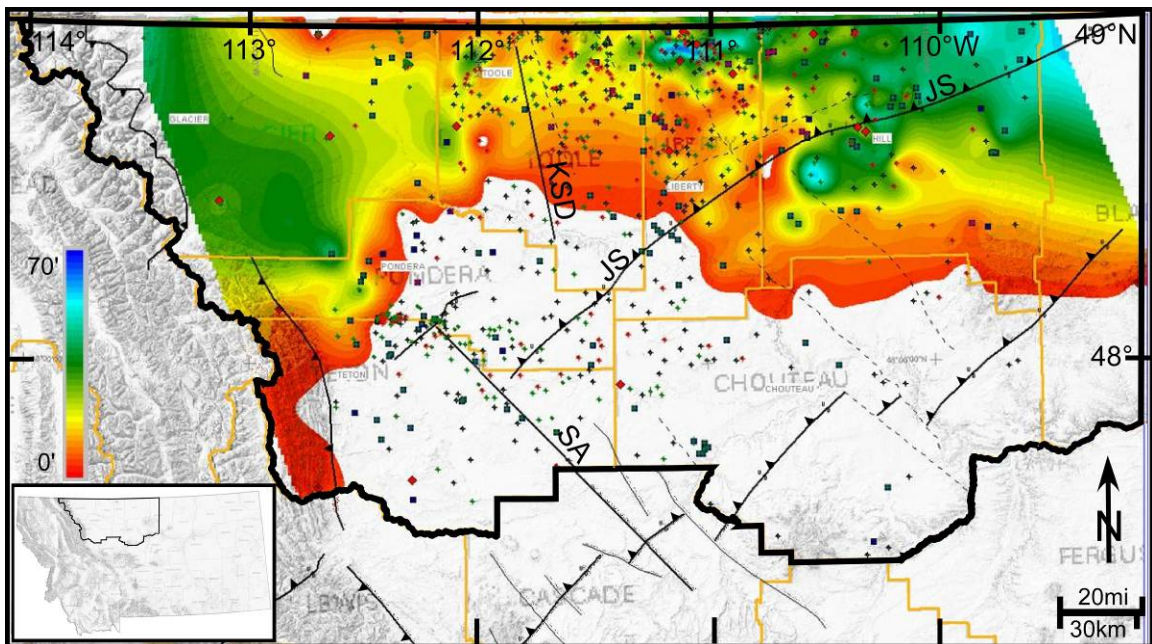


Figure 54: Isochore map of the LST of SQ 1. This map is of the LST, being the “basal members” as stated in Figure 42. This map shows the apparent thickness between SB 1 and the transgressive surface. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

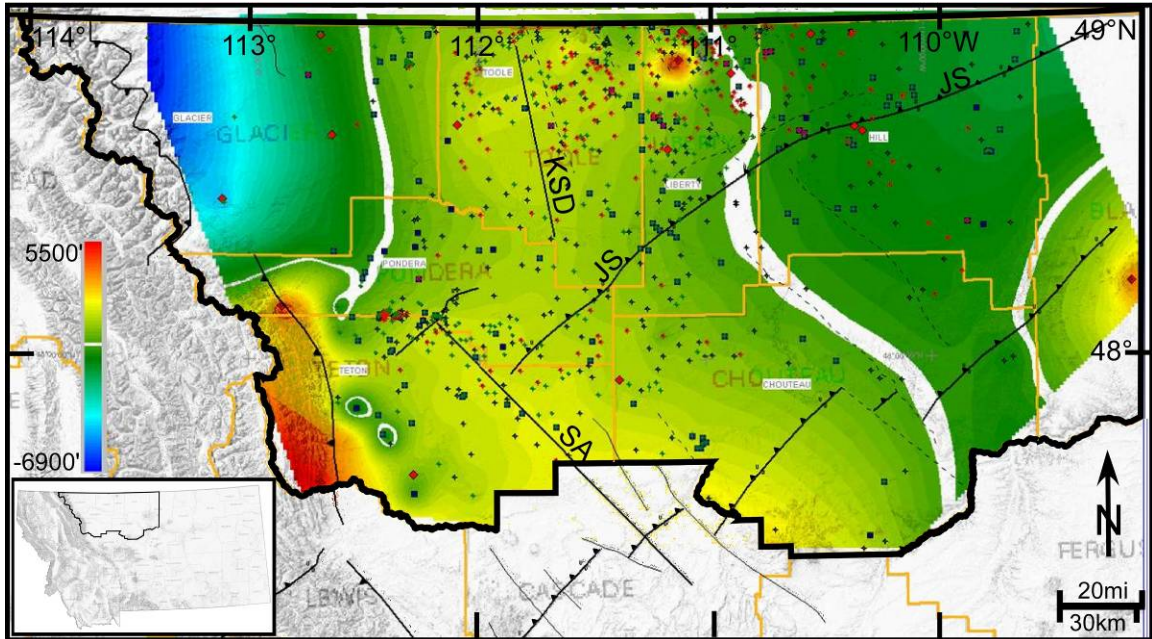


Figure 55: Surface structure map of the transgressive surface of SQ 1. Basal members, being the Sawtooth Formation, Sandstone Member and the coeval Piper Formation, Tampico Shale Member; together comprising the LST of SQ 1. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

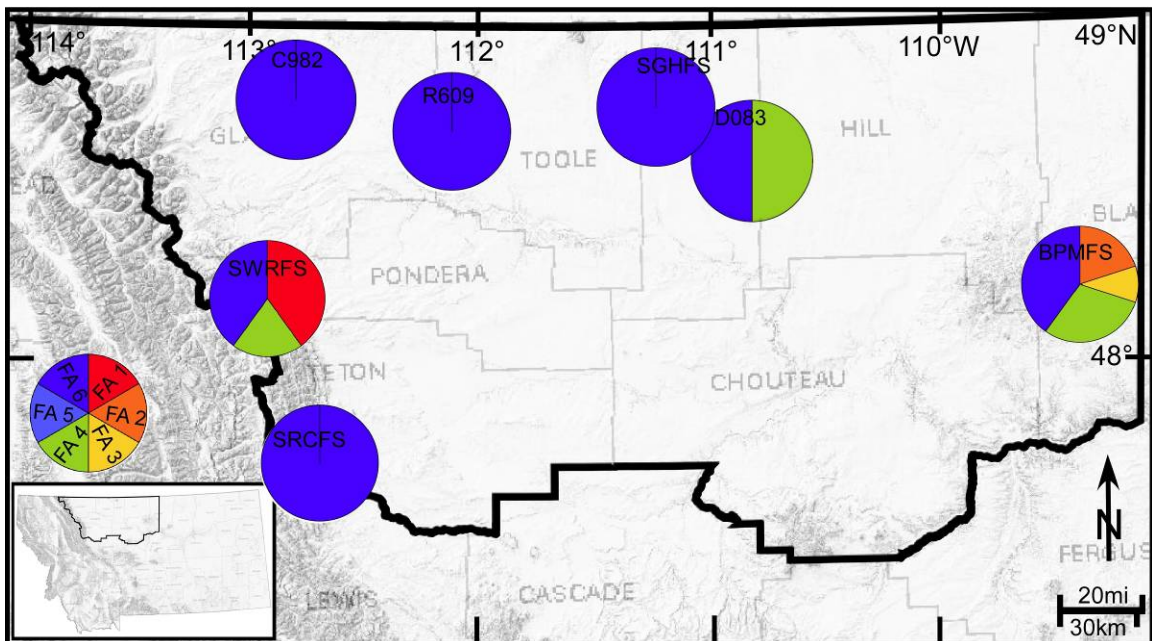


Figure 56: Distribution of lithofacies map of the TST of SQ 1. This map shows the TST to be dominated by the lower energy spectrum of lithofacies associations.

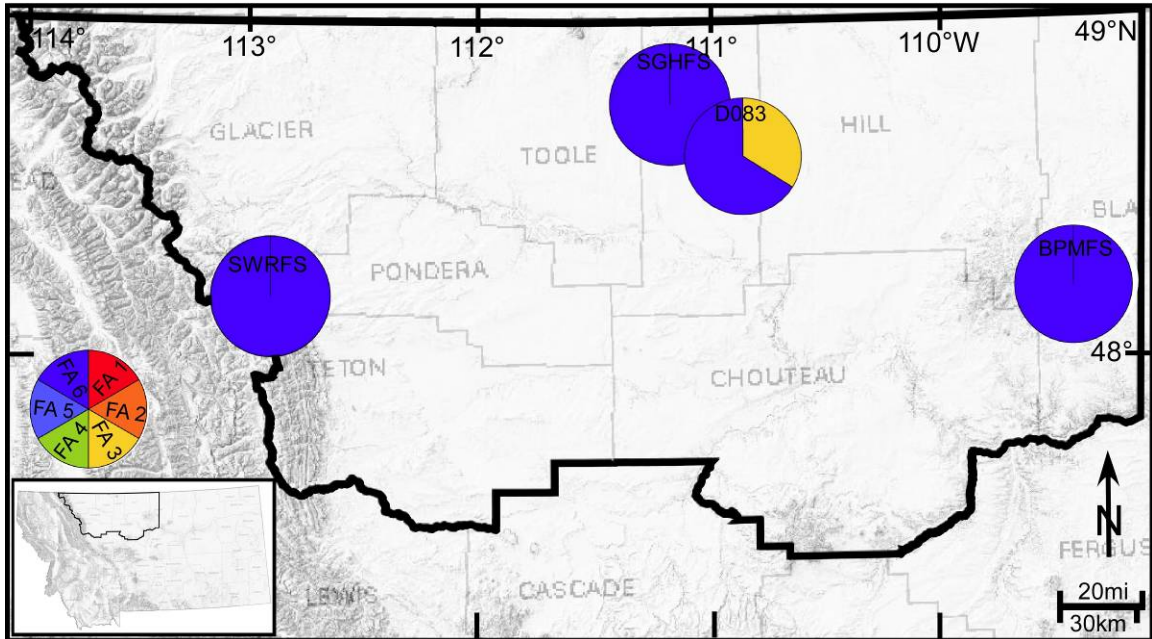


Figure 57: Distribution of lithofacies map of the HST of SQ 1. This map shows the HST to be dominated by the lowest energy spectrum of lithofacies associations.

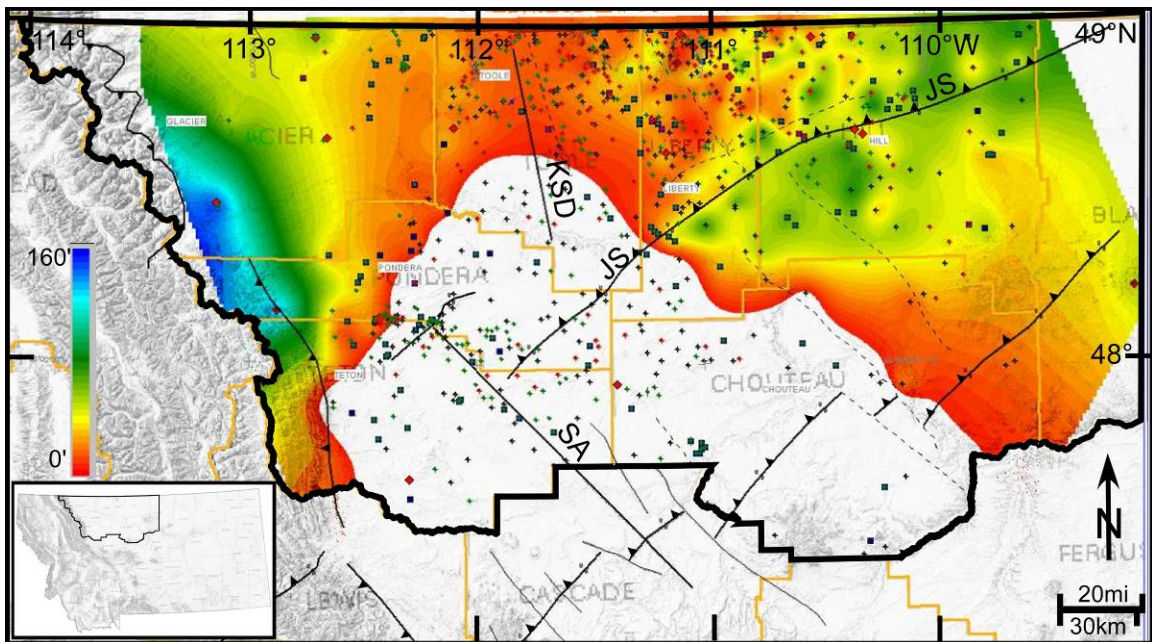


Figure 58: Isochore map of the TST and HST of SQ 1. This map is showing the apparent thickness of the Sawtooth Formation, Shale Member and Piper Formation, Firemoon Limestone Member that is the transgressive surface up to the top of SQ 1. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

The SQ 1 isochore maps (Figures 54, 58, and 59) show influence of lithospheric flexure on the sediment routing, deposition, and preservation of the Ellis Group. Furthermore, they show the areas of zero thickness that defined “Belt Island”, but equally as important are the very thin intervals over the Kevin-Sunburst dome area. The previous work that was only focused on the zero thickness areas was only seeing part of the story. The stratigraphic thinning over the Kevin-Sunburst dome area shows its structurally high setting during deposition of SQ 1 and supports a peripheral bulge instead of an isolated island. Reduced deposition and erosion can be as important to the whole story as non-deposition and erosion.

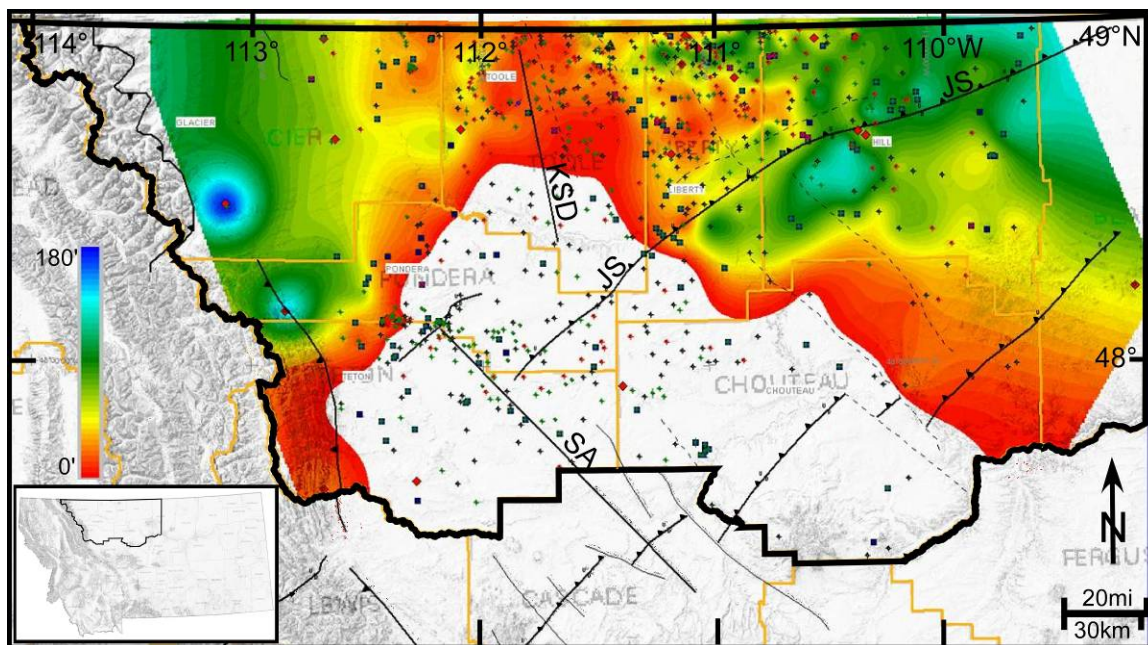


Figure 59: Isochore map of SQ 1. This is a map of the apparent thickness of the entire SQ 1. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Sequence Two

Sequence Two (SQ 2) begins on the SB 2 surface (Figure 42) this is shown in a surface contour map in Figure 60. There is a noticeable shift in the paleoaxis of the Kevin-Sunburst dome to the west. This is supported by the shift to the west in stratigraphic thinning as noted in Figure 62. These shifts are with respect to the positions at the closing of SQ 1. This strongly supports the concept of a dynamic peripheral bulge continuing further to the north beyond the zero thickness areas. By the end of the deposition of the LST, based on the interpreted transgressive surface (Figure 63) the axis appears to have migrated back to the east. Figure 63 is the first structure map of the series to show (note white contour interval) large scale change in the basin shape, this is supported in the comparison of Figures 62 and 66.

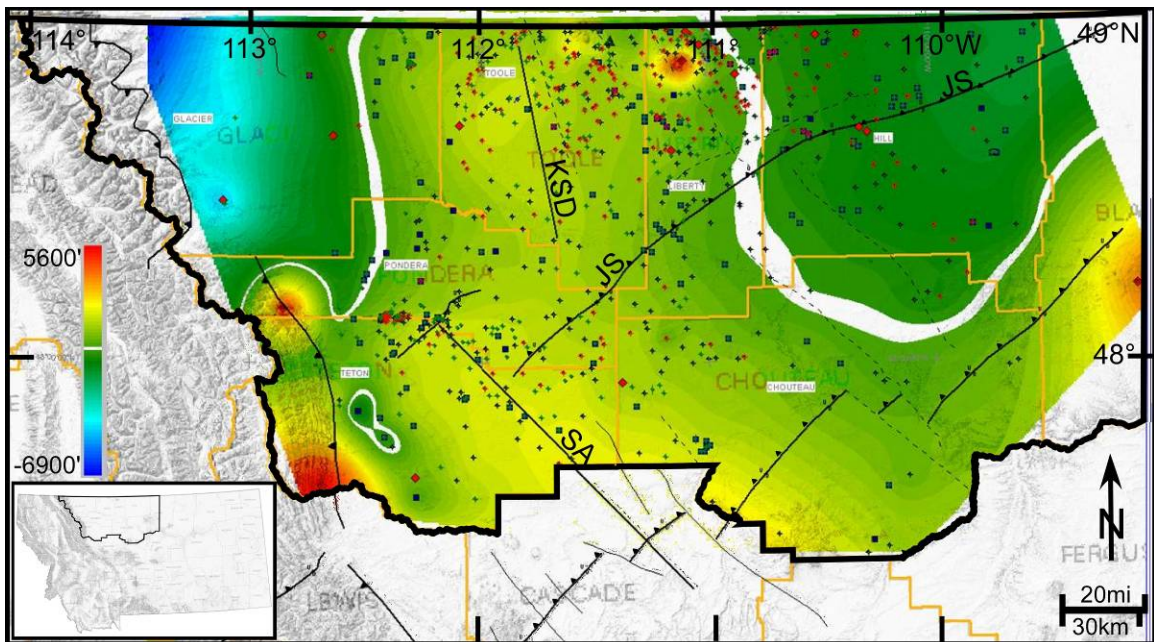


Figure 60: Surface structure map of SB 2. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

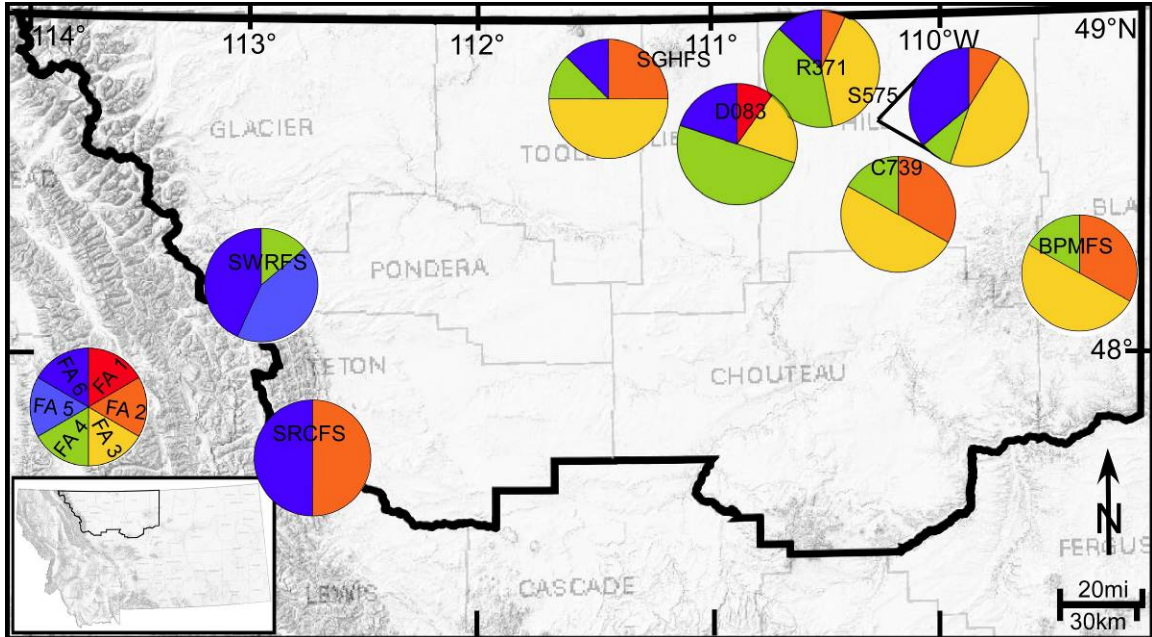


Figure 61: Distribution of lithofacies map of the LST of SQ 2. This map shows the LST to be dominated by the higher energy spectrum of lithofacies associations. Note the change in dominate lithofacies associations from the east side to the west side of the peripheral bulge.

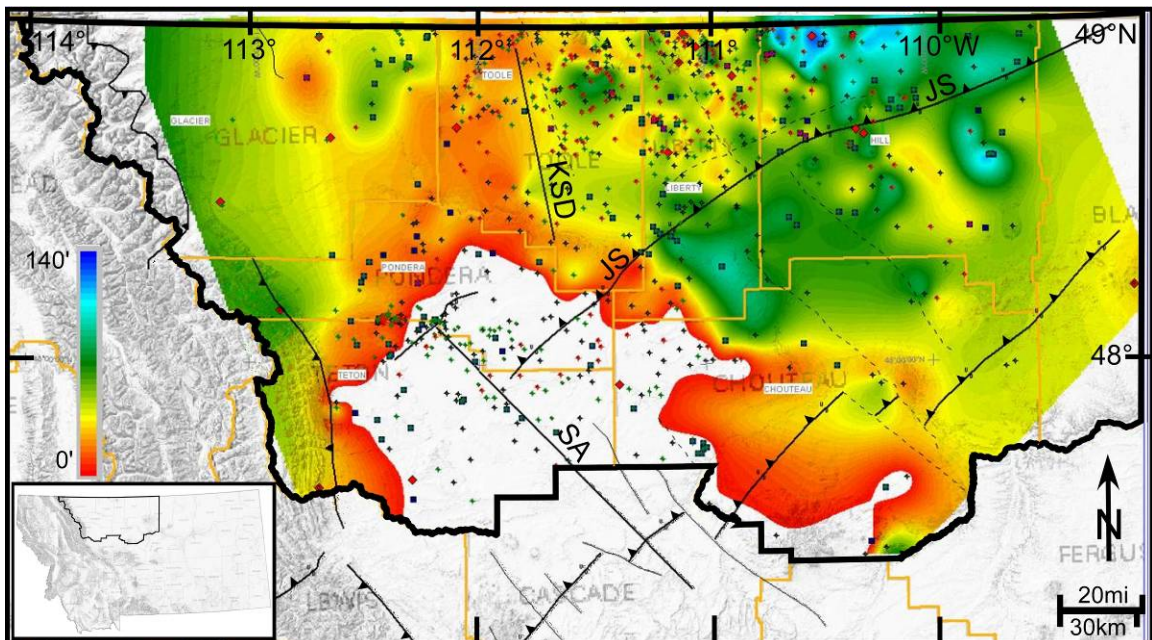


Figure 62: Isochore map of the LST of SQ 2. This is an apparent thickness map of the LST which is comprised of the Sawtooth Formation, Siltstone Member and the Piper Formation, Bowes Member. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

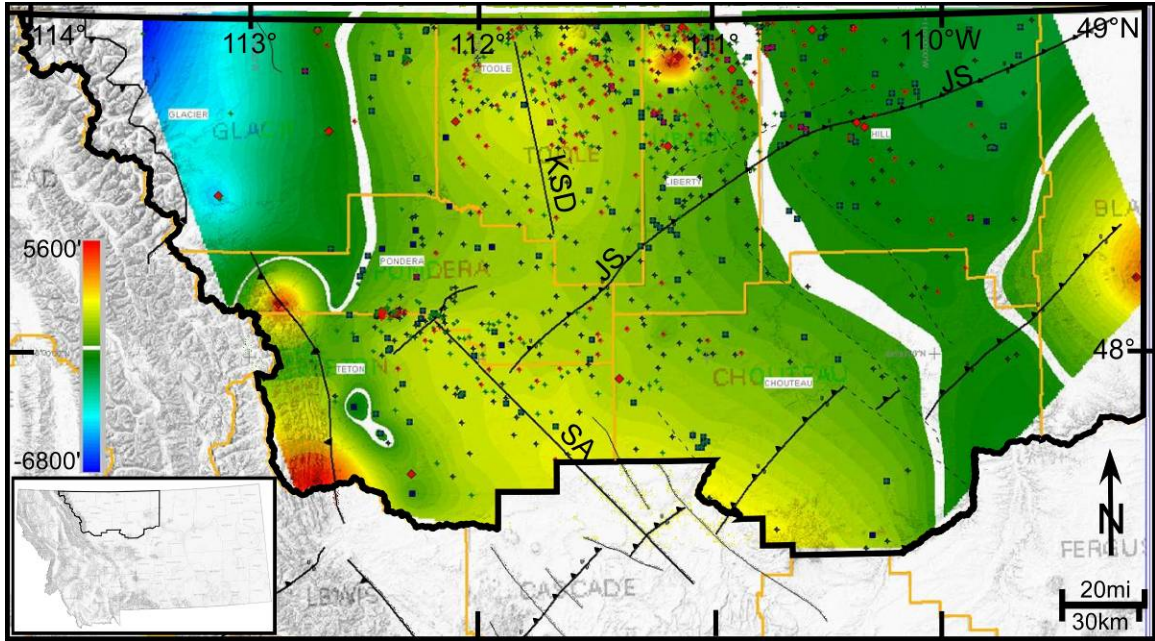


Figure 63: Surface structure map of the transgressive surface of SQ 2. This surface would be the lithostratigraphic top of the Sawtooth and Piper Formations. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Figure 62 shows increased deposition in the southern project area where non-deposition dominated in SQ 1. This further supports the adjustment in accommodation as described in the previous paragraph in reference to Figure 63. A basic principal, but important to supporting the concept of dynamic lithospheric response to crustal loading, to the west in this case. The Joplin Structure appears to be affecting sediment routing during deposition of the LST (Figure 62). The sediment infilling appears great enough in magnitude with respect to accommodation to be affected by the South arch, this was not noticed in SQ 1. Figure 66 shows the isochore for the TST and HST of SQ 2, this does agree with much of the previous work (Figure 10); although, this research shows deposits in the southern Chouteau County area.

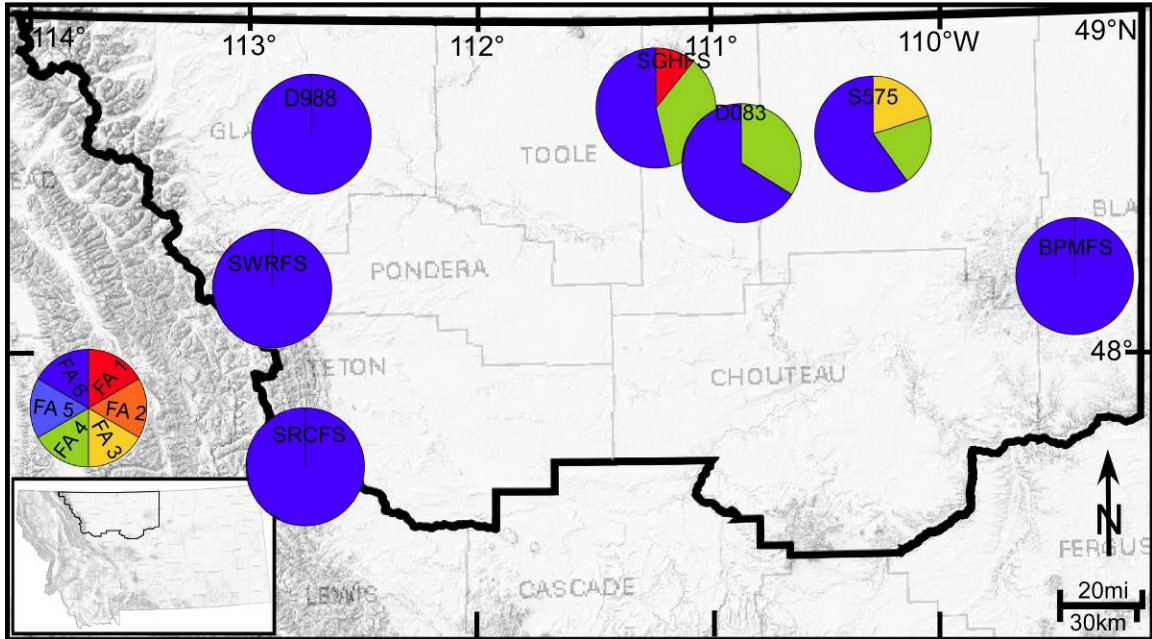


Figure 64: Distribution of lithofacies map of the TST of SQ 2. This map shows the TST to be dominated by the lower energy spectrum of lithofacies associations. Note the more median energy lithofacies associations over SGHFS, D083, and S575; they point to an area of locally shallower paleobathymetry during deposition, i.e. locally higher structure.

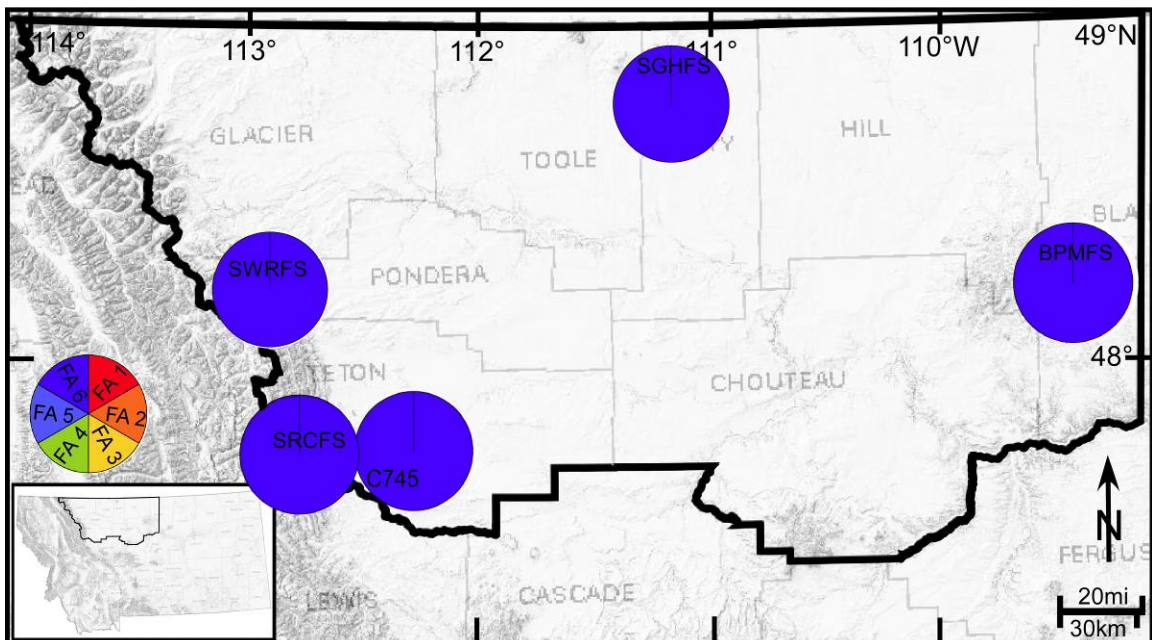


Figure 65: Distribution of lithofacies map of the HST of SQ 2. This map shows the HST to be dominated by the lowest energy spectrum of lithofacies associations.

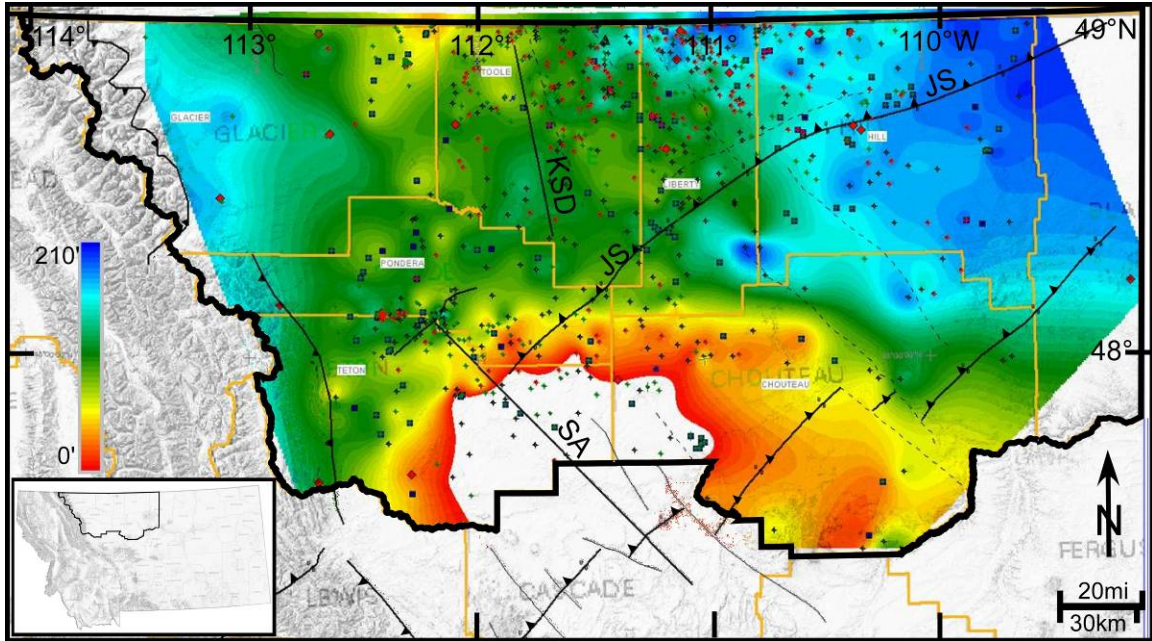


Figure 66: Isochore map of the TST and HST of SQ 2. This is an apparent thickness map of the TST which is comprised solely of the Rierdon Formation. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

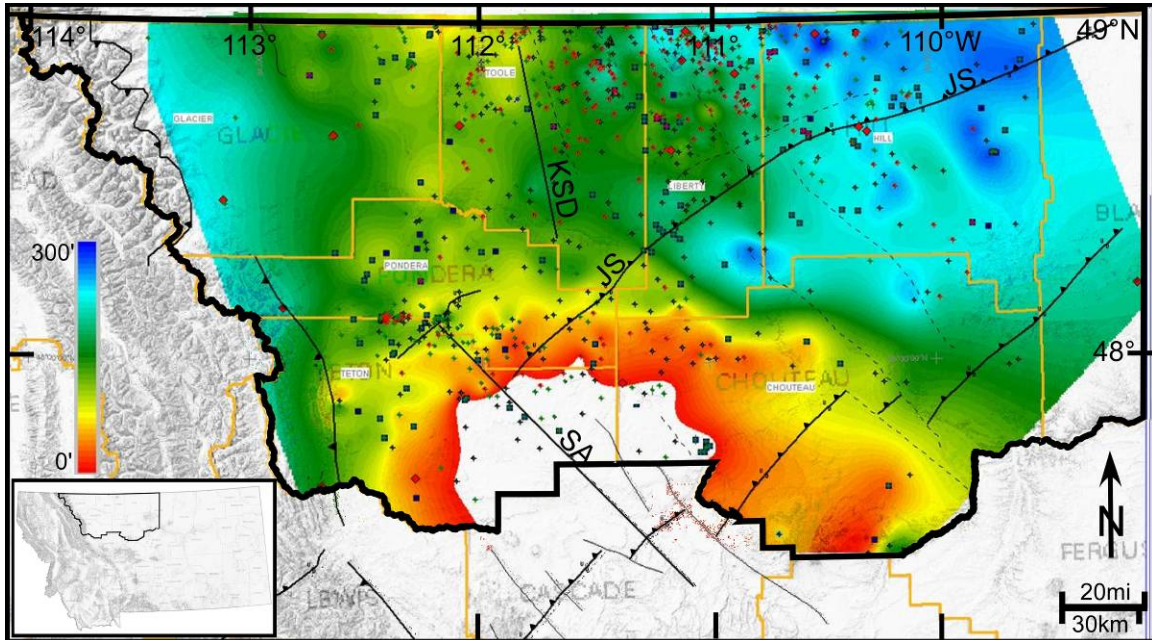


Figure 67: Isochore map of SQ 2. This is an apparent thickness map of the entire SQ 2. The isochore area that thins to zero over the South arch is interpreted as a combination of non-deposition and erosion (J-4). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Sequence Three

Sequence Three (SQ 3) is bounded by SB 3 and SB 4 (see Figure 42 for more details). SQ 3 was found to only be comprised of a TST and HST, with a transgressive surface of erosion above the SB 3 surface. It is probable there is presence of the LST beyond the project area. SB 3 is the same surface as the J-4 regional unconformity, as such, it is the longest hiatus within the three sequences. SB 4 is the equivalent surface as the J-5 regional unconformity and shows post-Ellis Group erosion as well as post-Jurassic erosion. The structure maps (Figures 68, 71, and 75) appear to show little structural change throughout SQ 3, supporting the concept of this sequence showing a quiescence of the vertical or lateral migration of the peripheral bulge as supported in cross sections (Figure 47 in Chapter 5, and EE' in Appendix A)

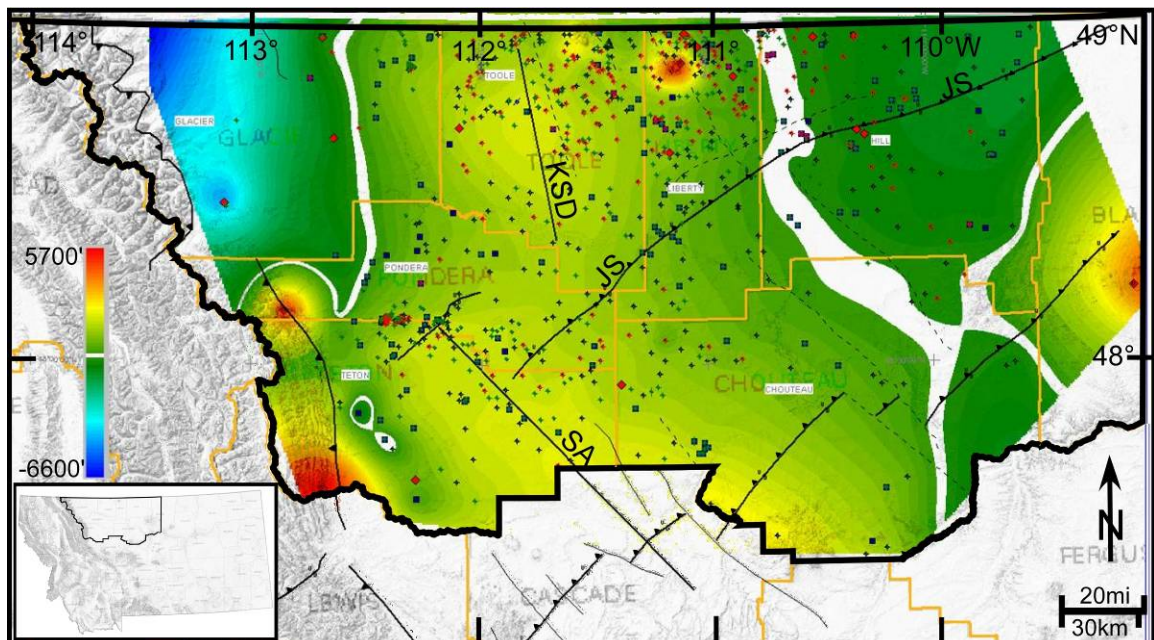


Figure 68: Surface structure map of SB 3. This surface is the J-4 regional unconformity that is also the top of the Rierdon Formation. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

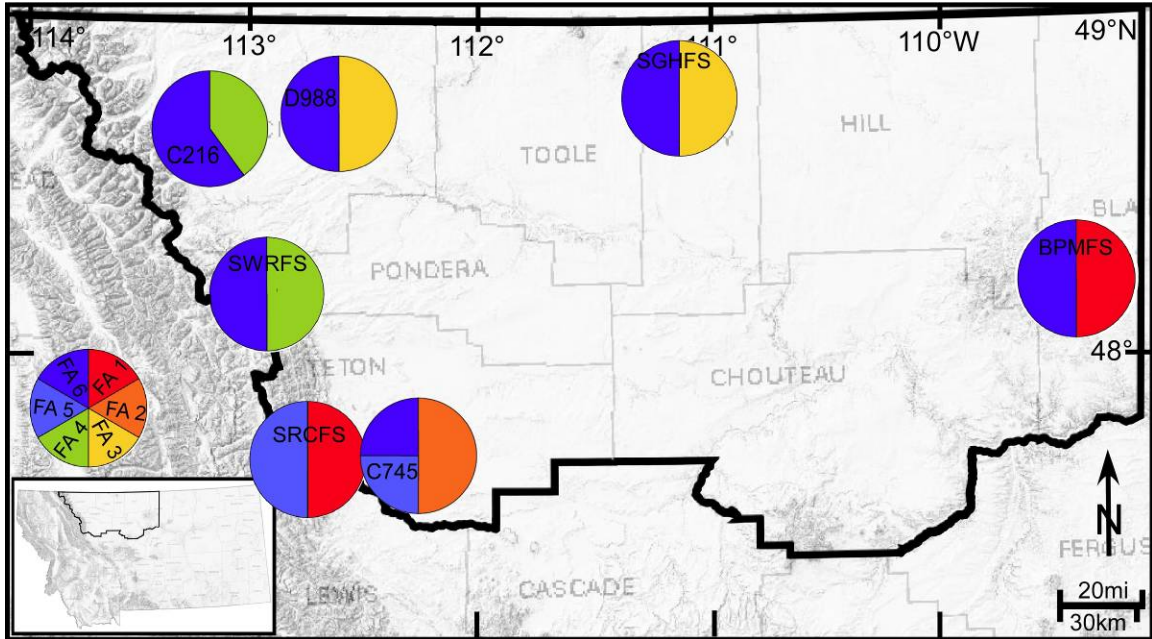


Figure 69: Distribution of lithofacies map of the TST of SQ 3. This map shows the TST to be dominated by the lower energy spectrum of lithofacies associations. Note the higher energy spectrum lithofacies associations compared to the other TSTs, this reflects the influence of the transgressive surface lag deposit being more significant.

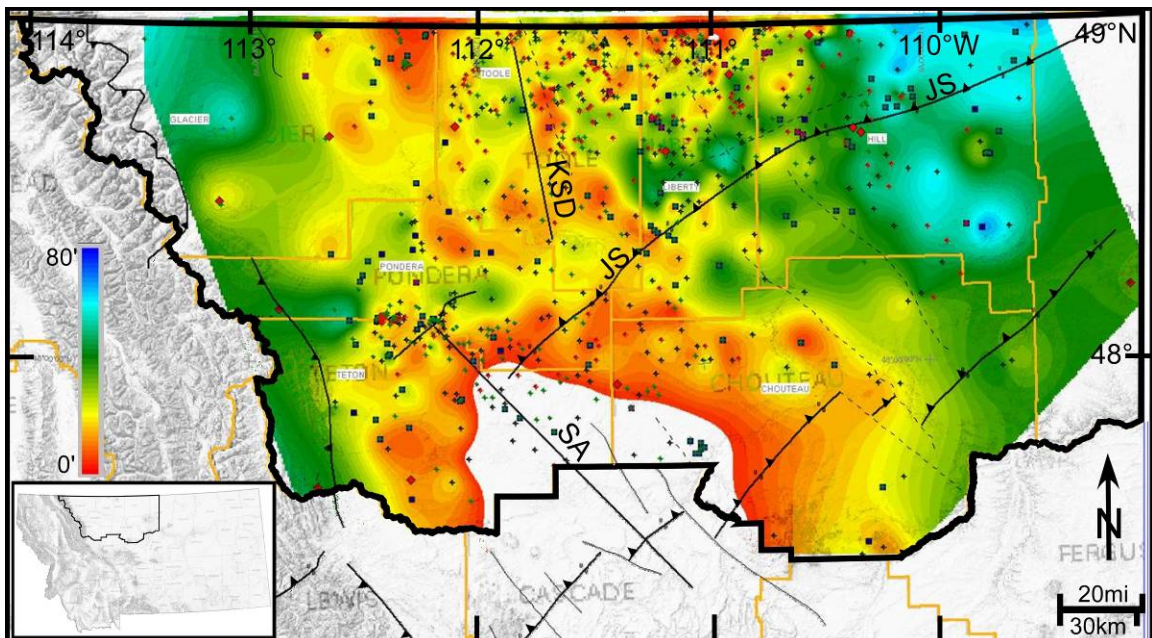


Figure 70: Isochore map of the TST of SQ 3. This is an apparent thickness map of the TST, being the Swift Formation, Shale Member. The isochore area that thins to zero over the South arch is interpreted as non-deposition based on stratigraphic architecture. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

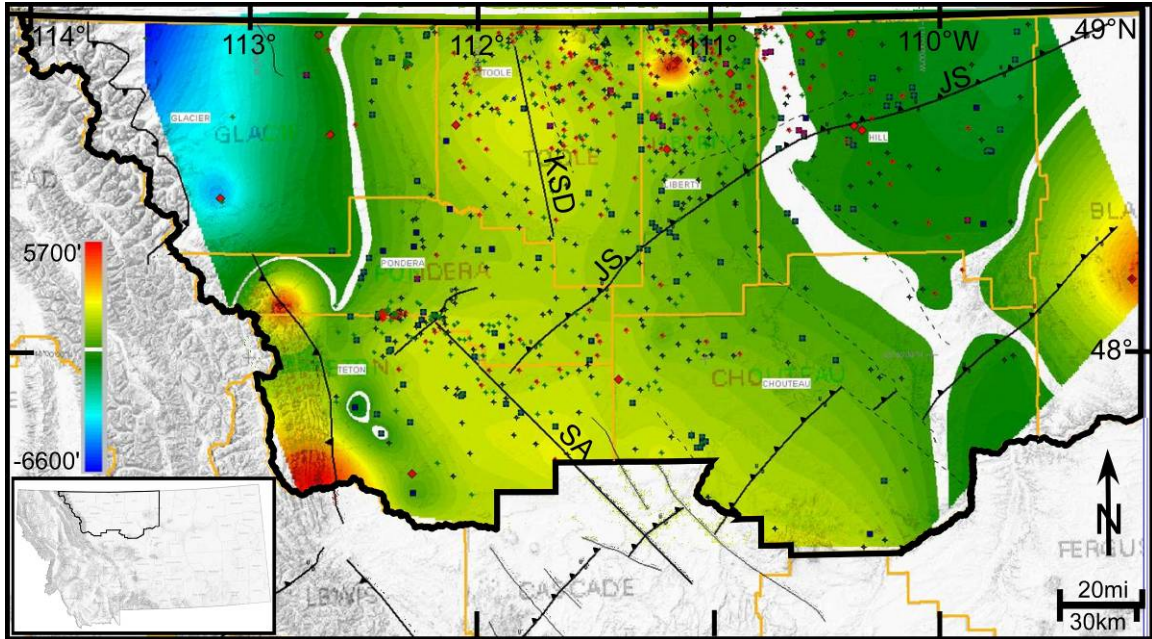


Figure 71: Surface structure map of the MFS of SQ 3. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

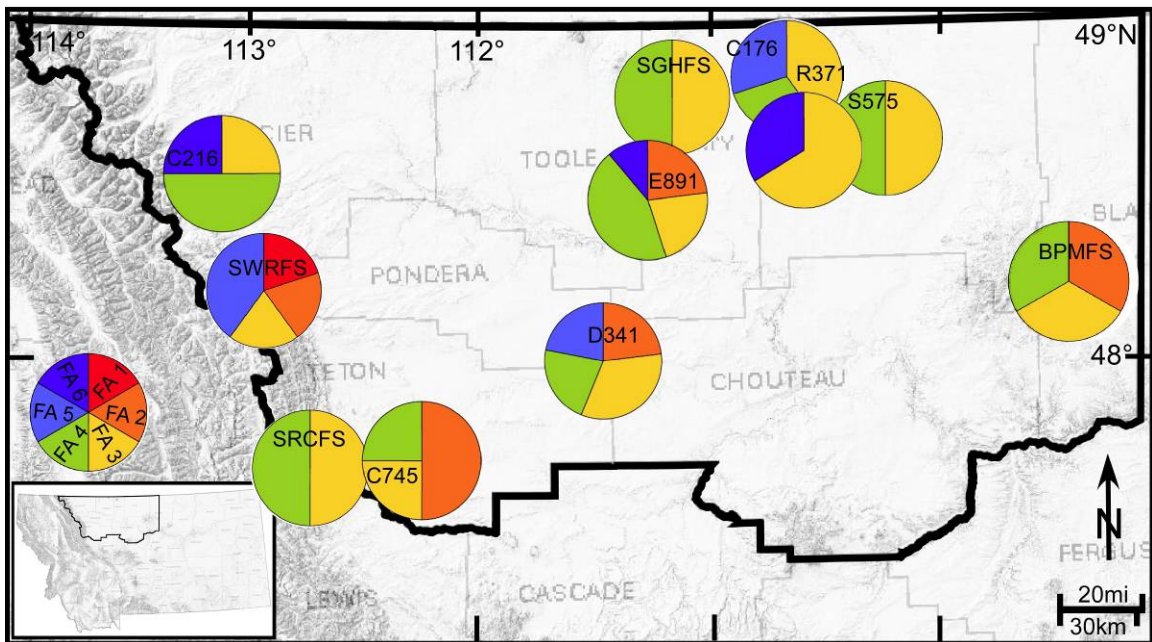


Figure 72: Distribution of lithofacies map of the HST of SQ 3. This map shows the HST to be dominated by the median energy spectrum of lithofacies associations.

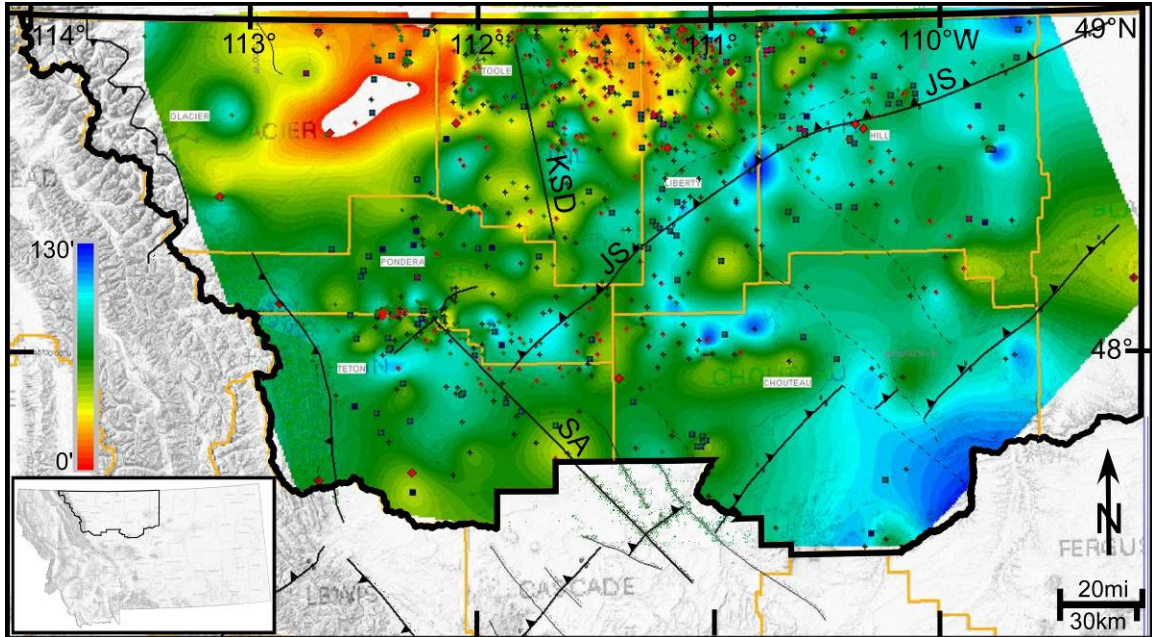


Figure 73: Isochore map of the HST of SQ 3. This is an apparent thickness map of the HST, being the Swift Formation, Sandstone Member. Note the very thin (red) to zero isochore areas (east and west flank of Kevin-Sunburst dome) are products of post-depositional erosion (J-5) related post-Jurassic incision (K-0). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Figure 70 shows the non-deposition of the TST over the southern end of the South arch area. This interpretation is based on the regional stratigraphic architecture of the TST, and its apparent thinning and onlapping nature. Said figure, shows the influence of the peripheral bulge on sedimentation and accommodation. There is a combination of non-deposition, reduced sedimentation, and erosion in said area; all processes support the notion of a paleotectonic high. Figure 73 shows the HST of SQ 3 and in general it appears to indicate relatively uniform deposition. The exceptions to this are local areas of thinning and thickening. The local thicks in the eastern area are interpreted to be mostly influenced by local faulting as determined by stratigraphic architecture compared to offset wells. The locally thinned areas on the western and eastern flanks of the Kevin-Sunburst dome are post-Ellis Group and post-Jurassic erosion.

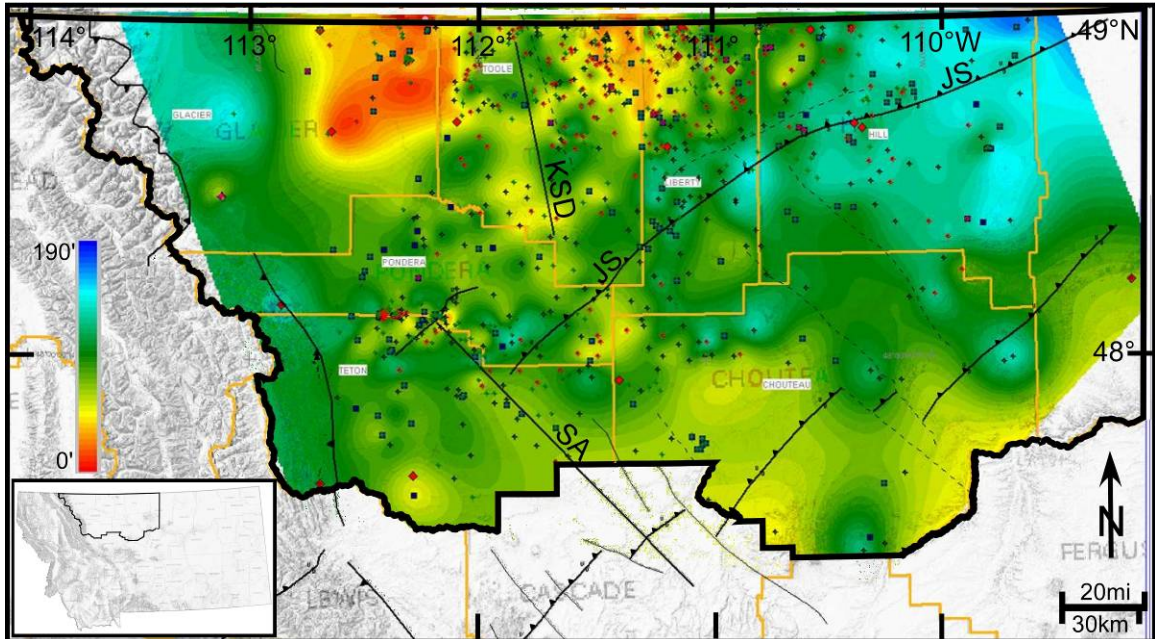


Figure 74: Isochore map of SQ 3. This is an apparent thickness map of the entire SQ 3. See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

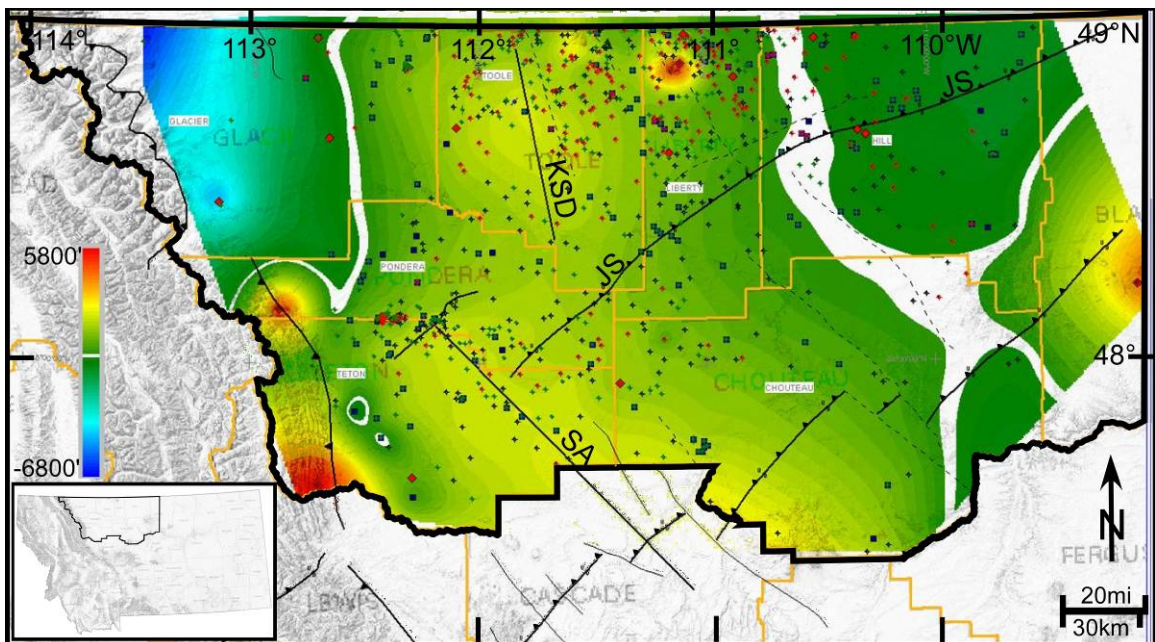


Figure 75: Surface structure map of SB 4. This surface is also the J-5 regional unconformity and the lithostratigraphic top of the Swift Formation. The white contoured interval is approximately sea level (elevation = 0'). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Applicability of Geologic Framework

It is important to understand, beyond the Significance of Research (see Introduction), the actual applicability of this work to real world applications concerning science and society. Currently there are concerns with rising Carbon Dioxide (CO₂) levels in the atmosphere that may have implications on society. It is important for science to understand how this problem fits into earth systems. Geology can play an important role in mitigating this rising problem. That is where the deliverables (e.g. Figure 76) of this research can assist in that endeavor.

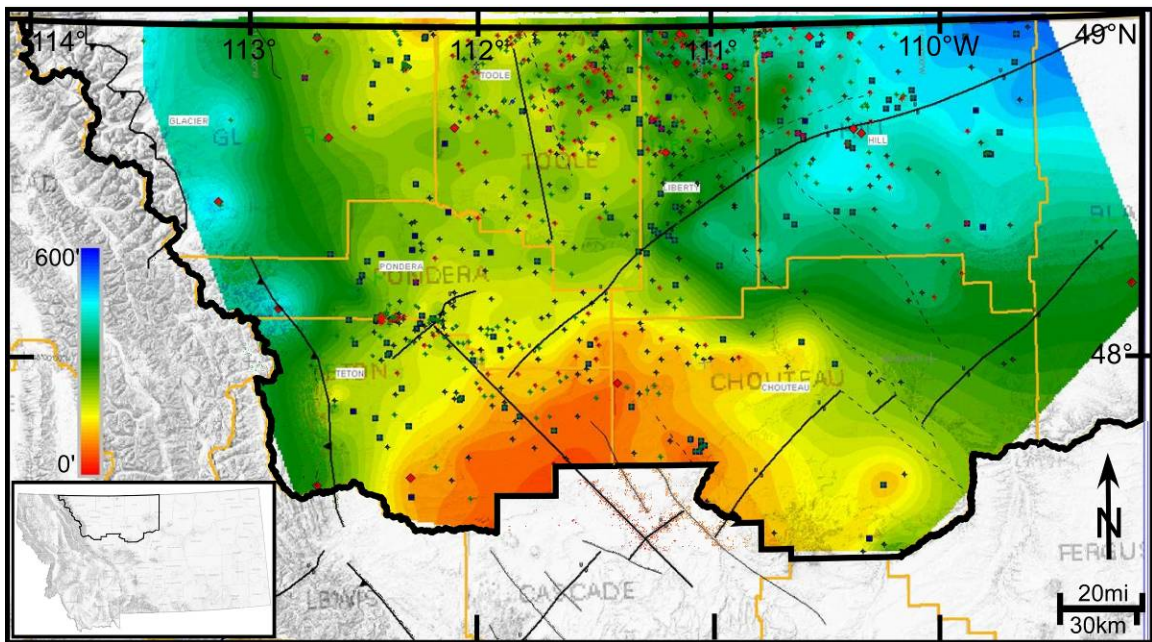


Figure 76: Isochore map the Ellis Group. This is an apparent thickness map of the entire Ellis Group. This map shows the lateral continuity of the Ellis Group over the project area, though there are intervals of thinning there is still lateral continuity. The importance of this continuity is important with respect to this geologic interval acting as a secondary seal for geologic carbon sequestration over Kevin-Sunburst dome (see Figure 77). See Figures 49 and 50 for more details on the tectonic features (axes and lineaments).

Currently the Big Sky Sequestration Partnership is doing research (Phase III) on the geologic sequestration of CO₂ in the large structure that is Kevin-Sunburst dome (e.g. Figures 49 and 77). The primary seal will be the Potlach Formation and the Ellis Group will play the role of secondary seal. Figure 77, illuminates the importance of knowing the lateral continuity of geologic intervals for regional seals, whether primary or secondary. In wanting to understand lateral continuity, brings about the need to understand that enigmatic “Belt Island” feature; that after all was defined as missing intervals of the Ellis Group. It would be hard for the Ellis Group to be a regional seal if in fact it is not present in areas. However, Figure 76 shows that the Ellis Group is in fact present over the entire project area, and in particular over the Kevin-Sunburst dome.

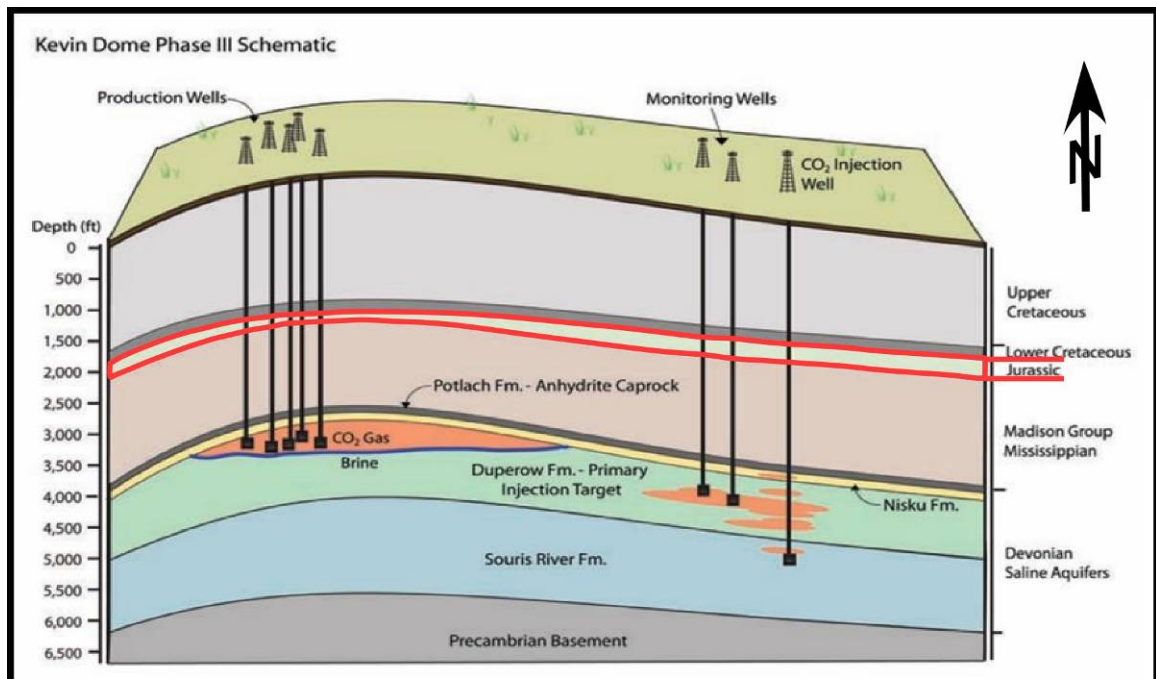


Figure 77: A schematic graphic of Kevin-Sunburst dome. Note the Jurassic Ellis Group is outlined in red in the figure. Modified from the N.E.T.L., 2010 Carbon Sequestration Atlas of the United States and Canada, p.45. Please see www.bigskyco2.org for more information on this project.

One might notice that the Ellis Group does in fact stratigraphically thin over the Kevin-Sunburst dome. This thinning of the Ellis Group is not a concern, due to the in depth lithofacies analysis performed by this research. Based on this research, it was determined that the lithologies (particular rock characteristics) that are still present over said structure are the primary sealing geologic intervals (i.e. clastic and carbonate mudstones) of the Ellis Group. Therefore, it can be determined from this research that the Ellis Group has all the properties to make it a regional secondary seal over the Kevin-Sunburst dome.

Remarks

This chapter shows the importance of the sequence stratigraphic framework to constrain the paleotectonic high of which a portion of was called “Belt Island”. From the lithofacies up to regional unconformities a depositionally and chronostratigraphically significant geologic framework was constructed. This framework aides in the understanding of the paleogeographic setting, as in the development of a foreland basin setting. Combining lithofacies, significant stratigraphic surfaces, and regional tectonics helps explain the enigmatic “Belt Island” in a modern geological context. In the context of sequence stratigraphy and a foreland basin setting, “Belt Island” was an effect of fluctuating eustatic sea level in conjunction with a dynamic peripheral bulge.

Through the integration of multiscale geological analysis, e.g, sedimentology, stratigraphy, and structure, a geologic framework was assembled in the project area. This chapter illuminates the importance of this geological analysis in providing answers to questions concerning geologic carbon sequestration in Kevin-Sunburst dome.

CHAPTER 8 – SUMMARY AND CONCLUSIONS

The distribution of lithofacies within this project area, do in fact support the notion or concept of an influential paleotectonic high. Based on the analysis from the outcrops and cores, there is direct evidence of changing paleotopography across the project area that directly corresponds with structure contour and isochore maps and further supported by cross sections. These distributions further support the notion of influence by the Great Falls tectonic zone on sediment routing and generation of accommodation. The lithofacies supported the interpretation of paleobathymetry, and sedimentary processes resulting in interpreted environments of deposition. These interpretations support the established sequence stratigraphic framework. The influence of the paleotectonic high is apparent on the marine setting and respective environments of deposition, particularly in SQ 1 and early on in SQ 2. However, there are no obvious indicators as to the influence later through SQ 2 and SQ 3. Nor, are there any strong indicators as to whether the high was a sediment source or not. To address this there might need to be a higher resolution sediment provenance analysis project performed, as such that would be beyond the scope of this current project.

The stratigraphic architecture defines so much of this project and provides the preponderance of evidence for the conclusions of this research. The lithofacies added context to the stratigraphy and made the sequence stratigraphic framework possible. If there were a large paleotectonic high in the project area during deposition of the Ellis Group, then yes there would be marked signs in the stratigraphic architecture, in both stratal stacking patterns and bounding relationships.

The stratigraphy does show signs of a paleotectonic high in SQ 1. There is a large area over the modern day South arch where non-deposition prevailed. There is obvious thinning of the stratigraphy onto this high. The stratigraphy shows the syntectonic activity of the Joplin Structure influencing sediment routing and accommodation. Furthermore, the stratigraphy shows the north-south trending patterns of varying accommodation associated with the high, strongly supporting the concept of it being a peripheral bulge. The fact that the stratigraphy is in a chronostratigraphically significant framework, which shows the dynamics of the setting further supports the concept of a peripheral bulge, which then supports the argument for a developing foreland basin, resulting from crustal loading to the west beginning as early as Middle Jurassic. Cross section EE' (Appendix A) shows this well, through the succession of sequences, there is an apparent change in accommodation and bounding relationship of the subsequent stratigraphy onto the peripheral bulge.

Understanding "Belt Island" in a modern geologic context would not have been possible without an established lithofacies characterization and sequence stratigraphic framework. Without these important components there would have been no depositional and temporal support for the influence of the Western North America Cordilleran Orogeny on this area. Specifically, supporting evidence for the Great Falls tectonic zone activity during deposition of the Ellis Group.

The term “Belt Island” is a paleogeographic area, from Bajocian to Oxfordian time, where concurrent sea level fluctuations interacted with syntectonic forces due to lithospheric flexure, differentially exploiting preexisting crustal weaknesses, to cause differential deposition/preservation of the Ellis Group. In the context of sequence stratigraphy and a foreland basin setting, “Belt Island” was an effect of fluctuating eustatic sea level in conjunction with a dynamic peripheral bulge.

This research has addressed some interesting questions and hopefully the insights gained from this work have some real world applicability to address concerns with geologic carbon sequestration in the region and enhanced oil and gas recovery. The lithofacies characterization will help in better understanding the Ellis Group as a regional seal. Furthermore a better understanding of the distribution of lithofacies can aide in more complete and efficient exploitation of hydrocarbon resources. The sequence stratigraphic framework can be combined with other such work outside of the project area to better understand the development of the foreland basin system during the Middle to Late Jurassic. Furthermore, a sequence stratigraphic framework can add to the success of play models for resource extraction. Additionally, this framework can point to potential leakage points or pathways, related to stratigraphic thinning and the associated lithofacies properties. This framework could additionally add more control to understanding the structural setting, as in fault activity and add to further work on recurrent fault activity.

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APPENDICES

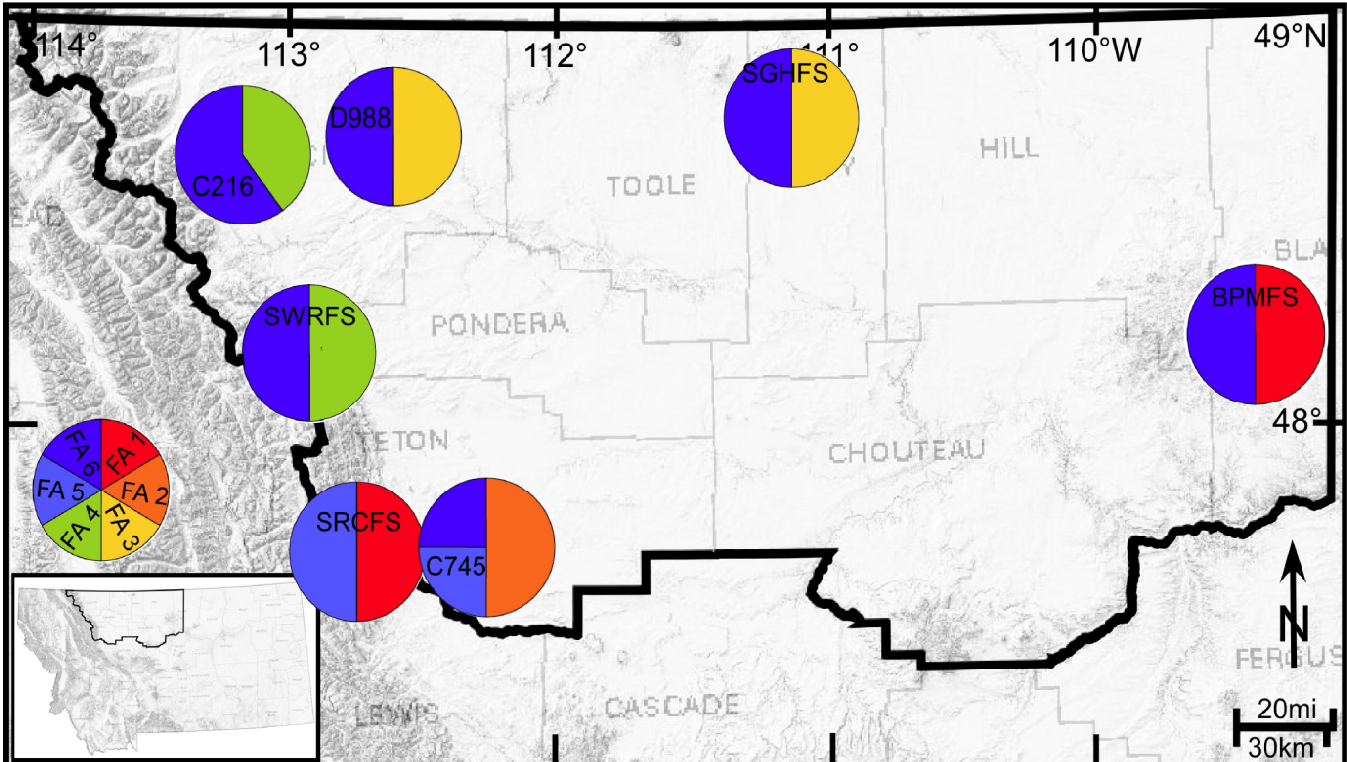
APPENDIX A

ADDITIONAL FIGURES

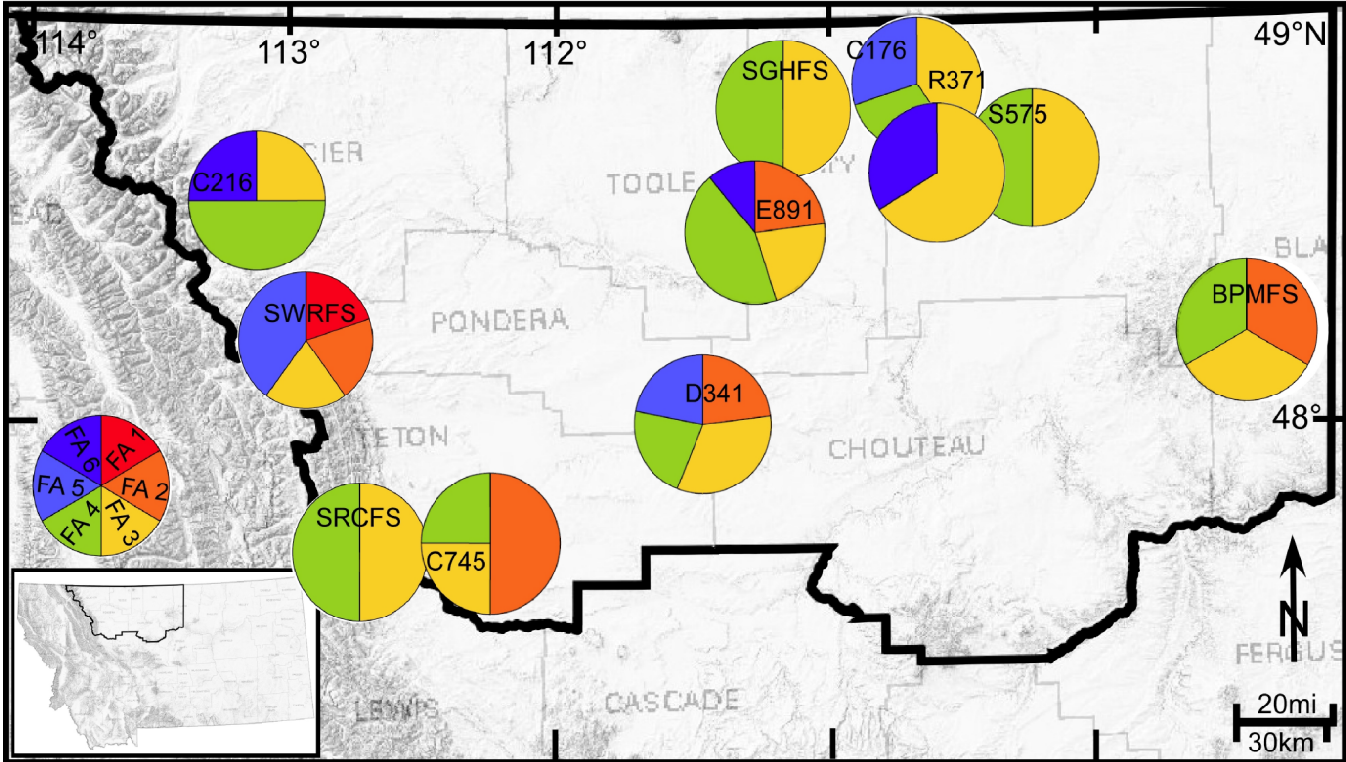
- Analysis and distributions of lithofacies and lithofacies associations. One table and one composite figure (p. 137-138).
- Application of the sequence stratigraphic framework over the project area. Four cross sections using just the alpha wells (p. 139-142).
- Oversized cross section EE' (p. 143).

This table shows the 17 geologic profiles (alphas) used in this project. The header shows the respective outcrops in a clockwise manner around the project area. The wells are organized in a alphanumerical order from left to right. On the left are the three sequences that make up the Jurassic Ellis Group, and their respective systems tracts. The numbers are the lithofacies associations as described in Chapter 3. The lithofacies associations are placed in the appropriate systems tracts in which they are found through description of the particular lithofacies. The lithofacies associations are arranged from bottom to top of each category each time an upward change in facies deems a change in lithofacies association.

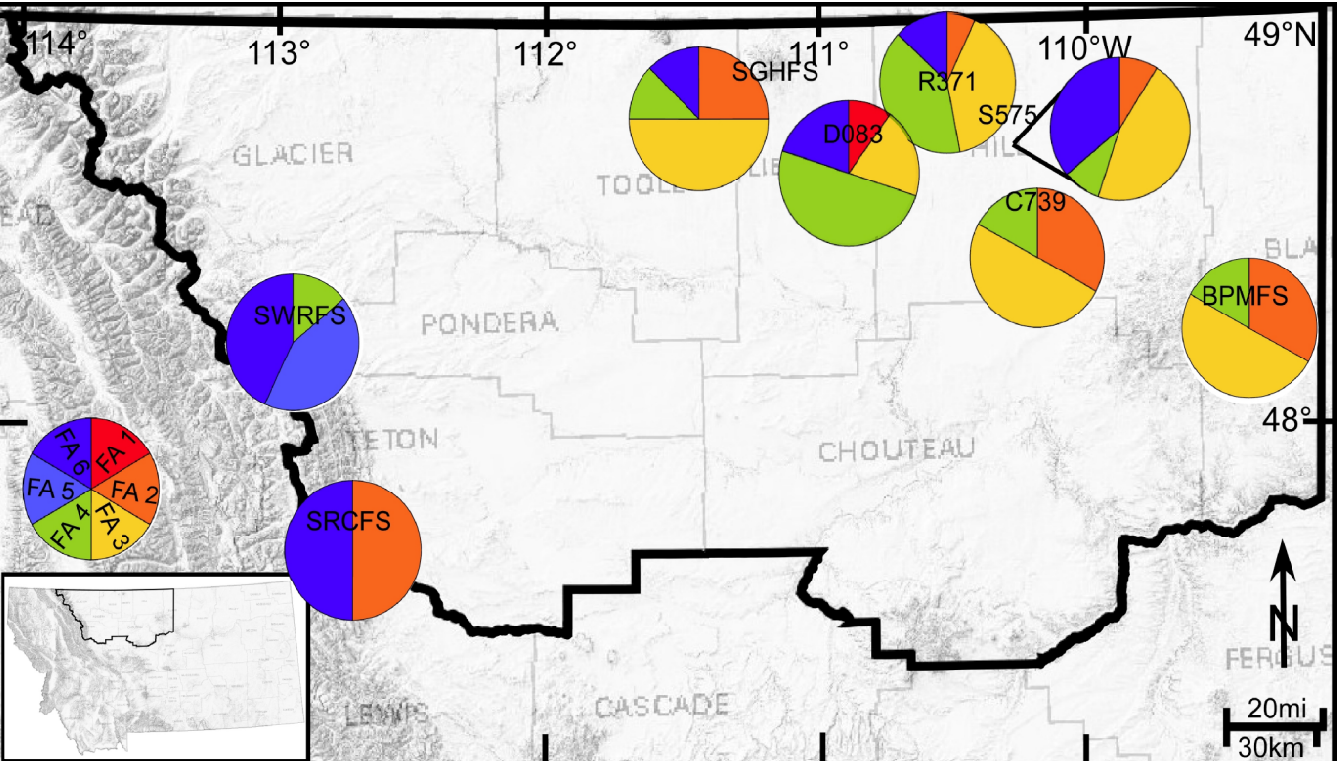
- FA1 - Lithofacies association 1; consisting of lithofacies Ccb and Cgp. In most occurrences is interpreted as a lag deposit or sediment gravity flow above a surface of erosion. This association did not appear to be restricted to an environment of deposition.
- FA2 - Lithofacies association 2; consisting of lithofacies Lfs, Lgd, Lgs, Scd, Smd, Sfp, Sfd, and IB 1. The interpreted environment of deposition is shallow marine to coastal, proximal to the depositional shoreline break.
- FA3 - Lithofacies association 3; consisting of lithofacies Sms, Sfr, Lpd, Lpr, Lpp, Lwk, Lwn, and Lwa. The interpreted environments of deposition are tidal to subtidal down to middle shoreface.
- FA4 - Lithofacies association 4; consisting of lithofacies Sfs, IB 1, IB 2, Lwk, and Lwn. The interpreted environments of deposition are lower shoreface or outboard of base of reef.
- FA5 - Lithofacies association 5; consisting of lithofacies Sfh, IB 1, IB 2, IB 3, IB 4, and Msr. The interpreted environments of deposition are lower shoreface to offshore transition zone.
- FA6 - Lithofacies association 6; consisting of lithofacies Lwk, Lwn, Mcr, Mcd, and Lm. The interpreted environments of deposition are offshore below both fair-weather and storm wave base.



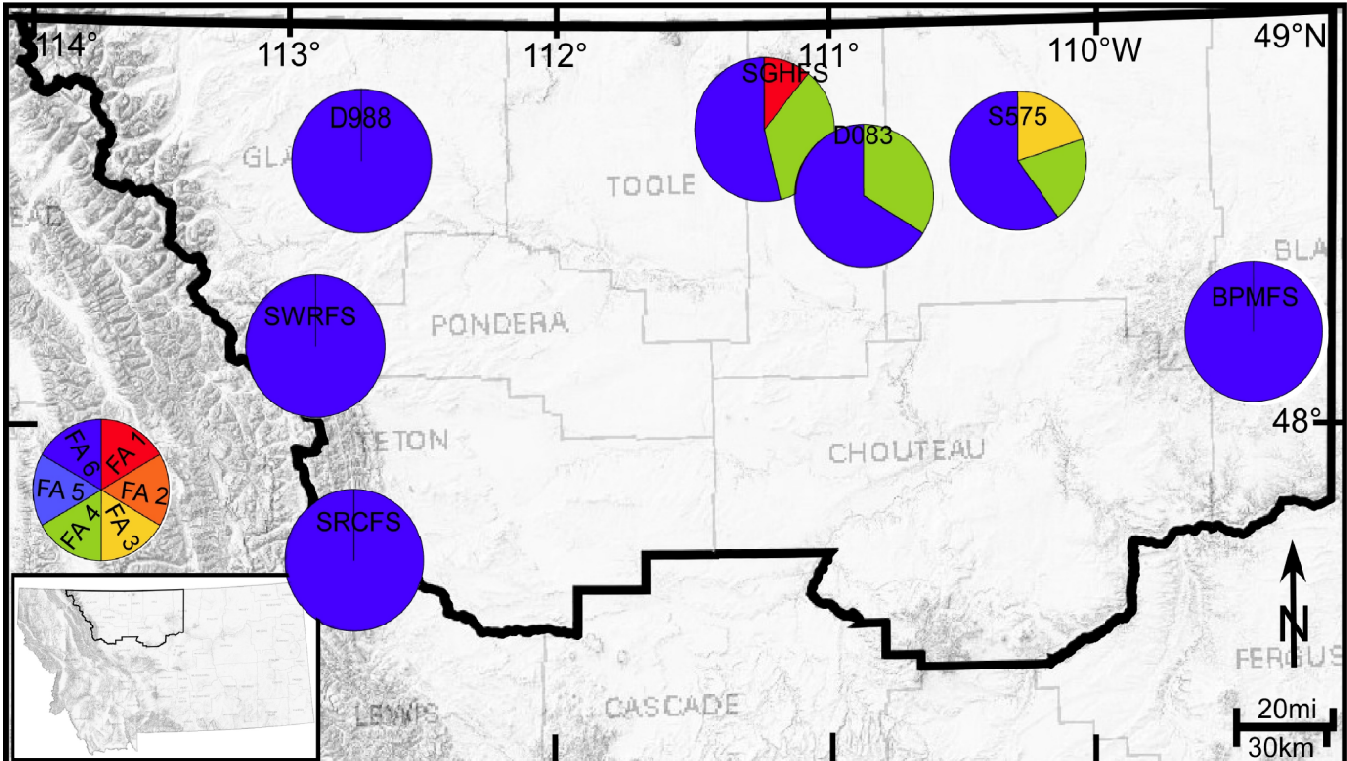
This figure is of the TST of SQ 3.



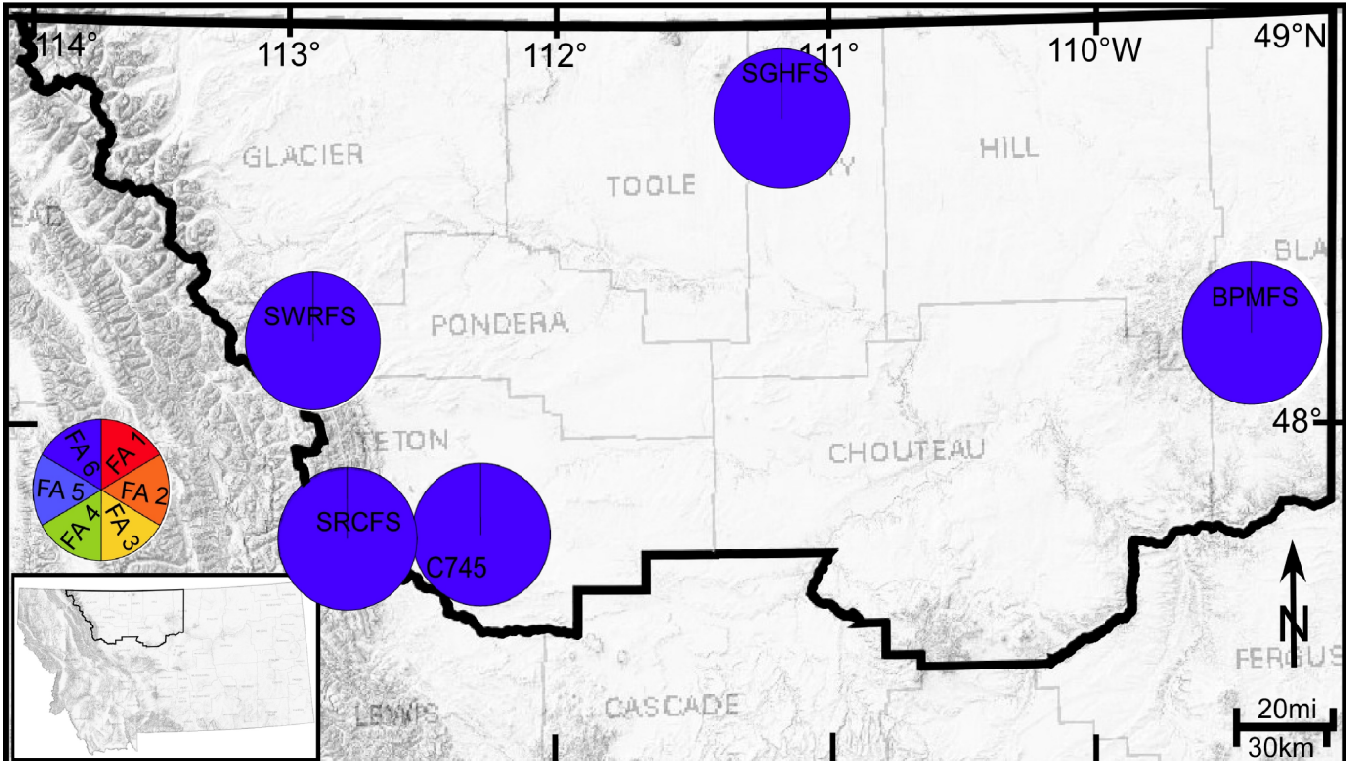
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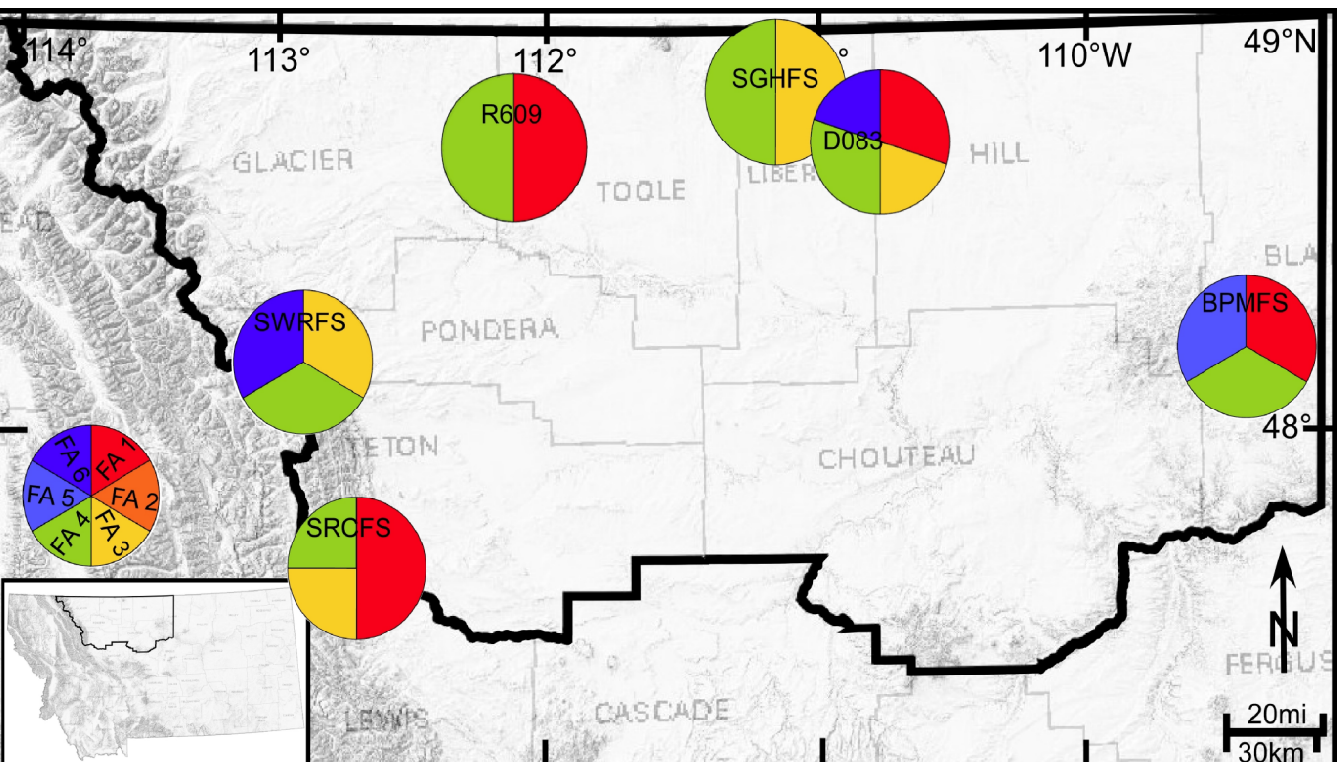
This figure is of the LST of SQ 2.



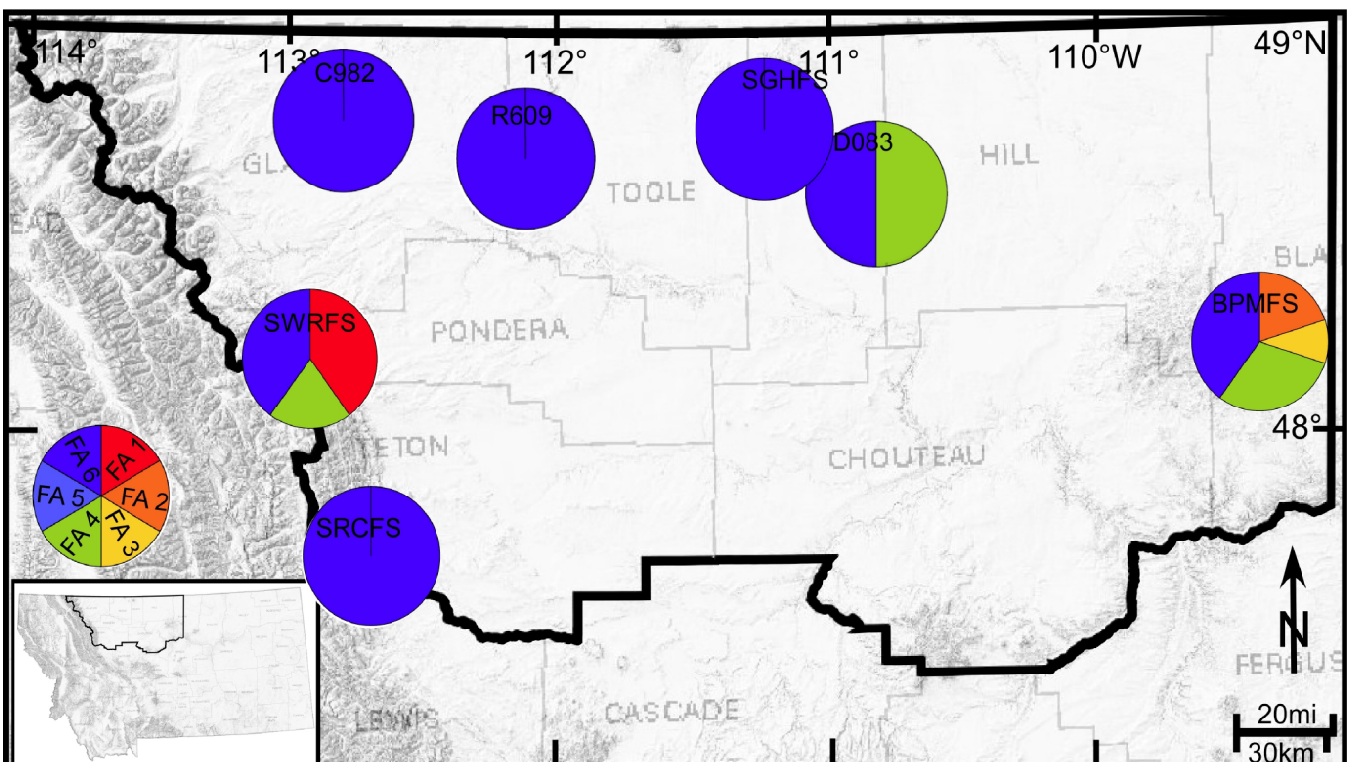
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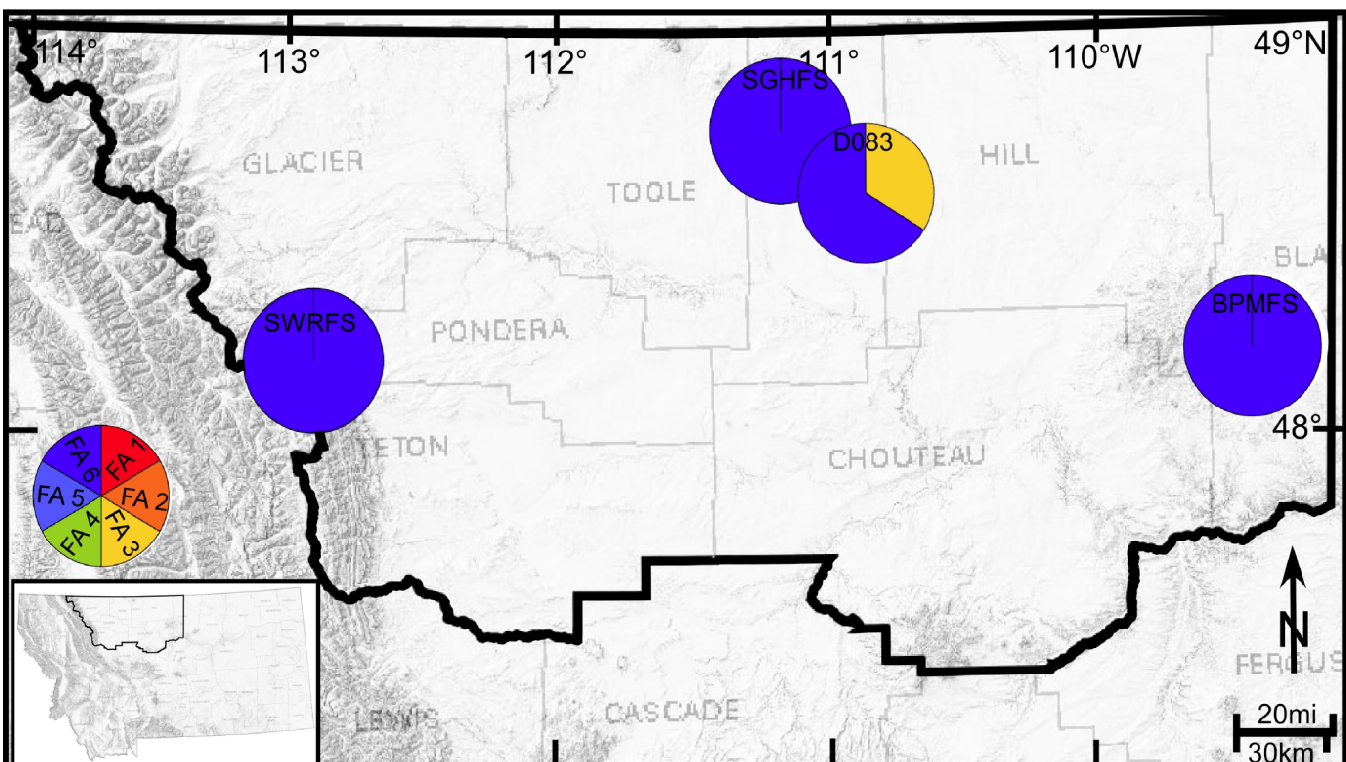
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This figure is of the LST of SQ 1.

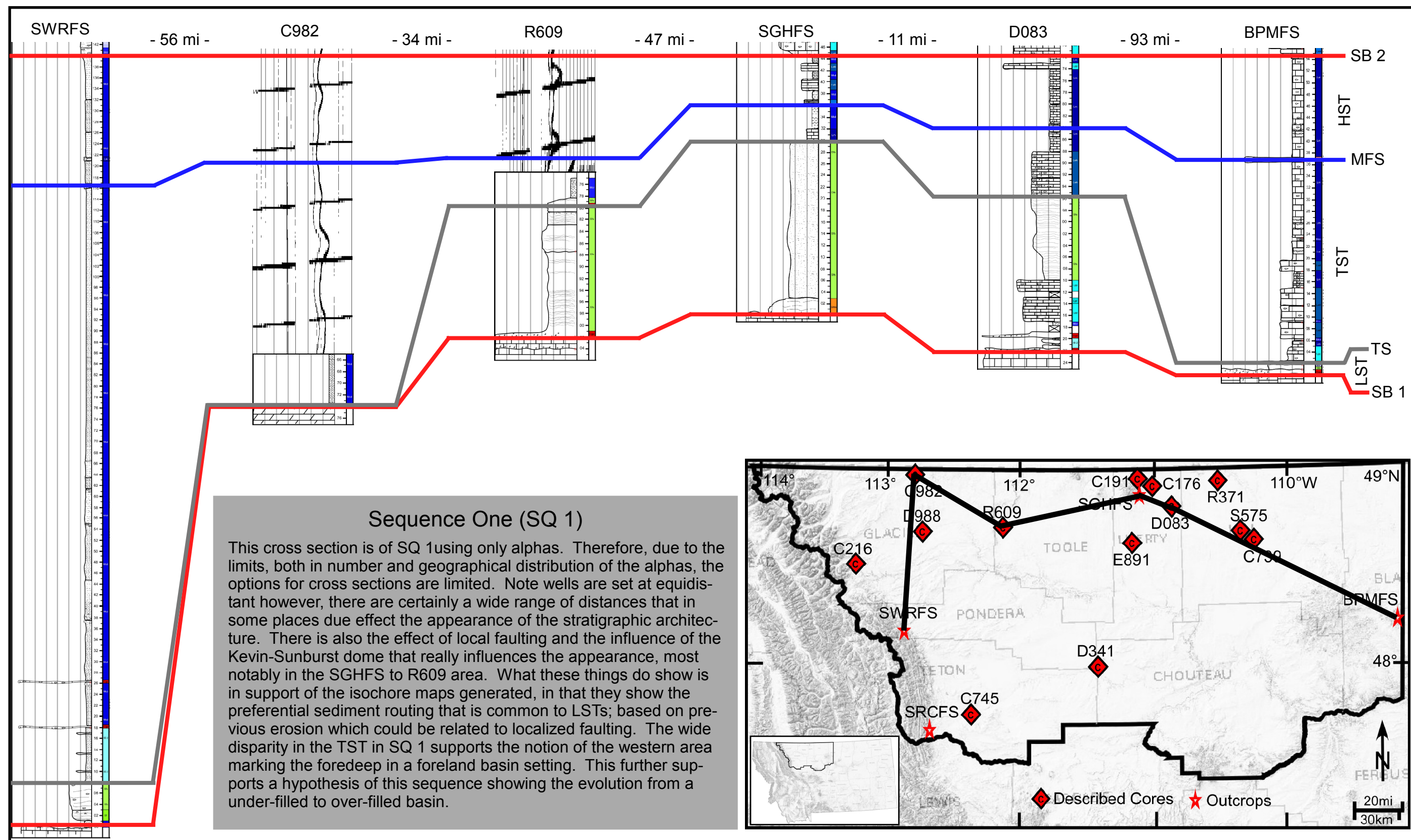


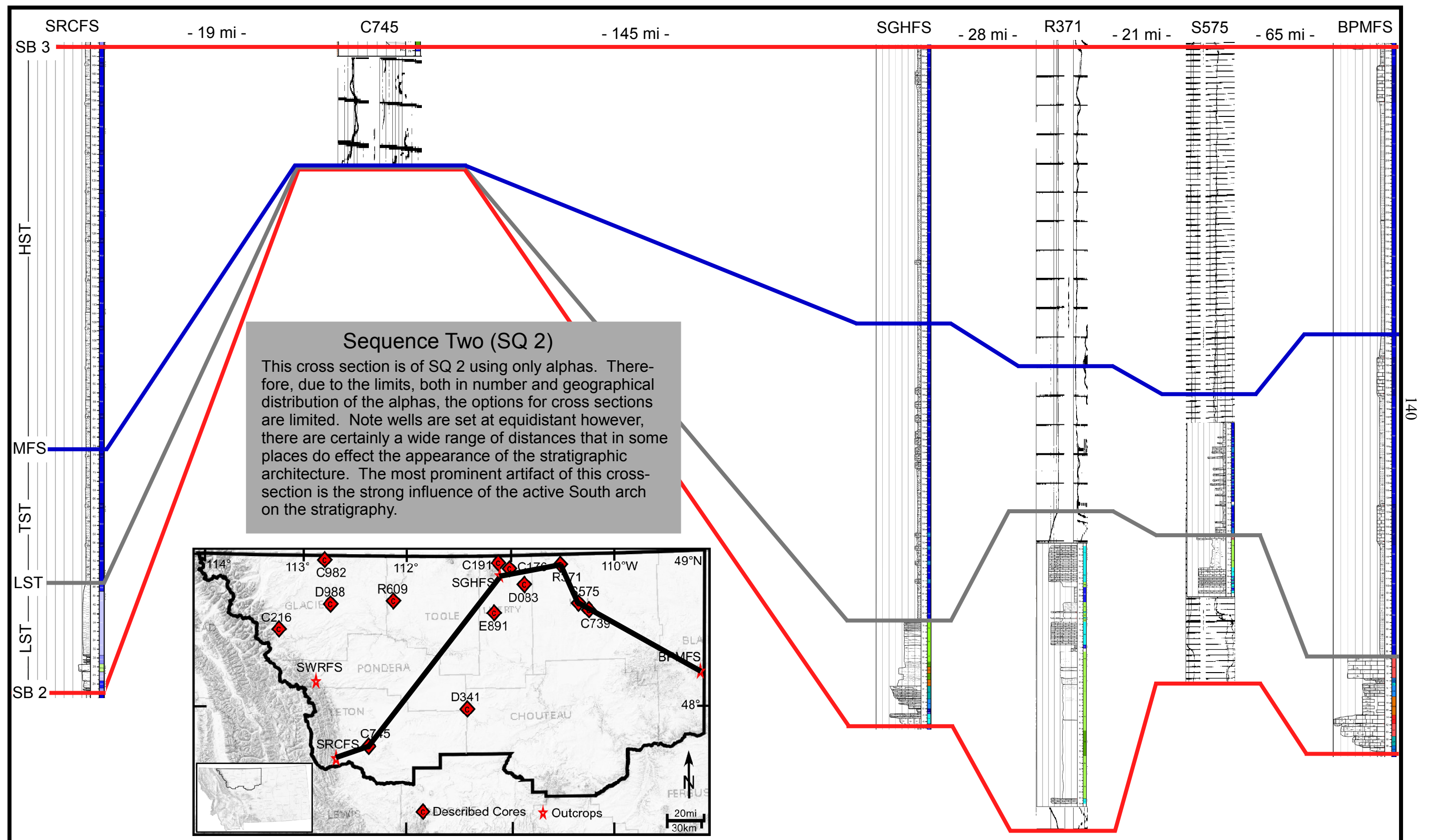
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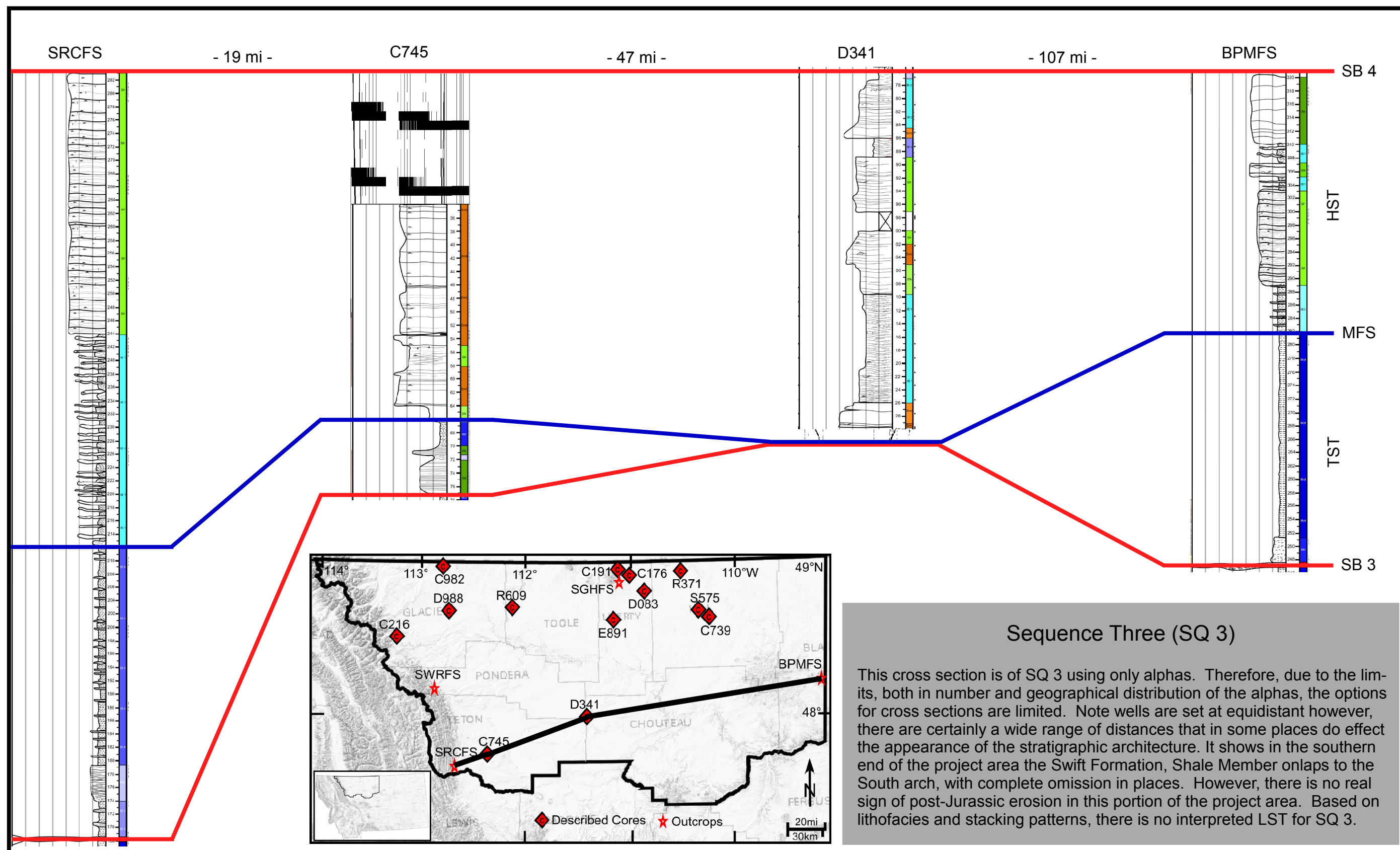


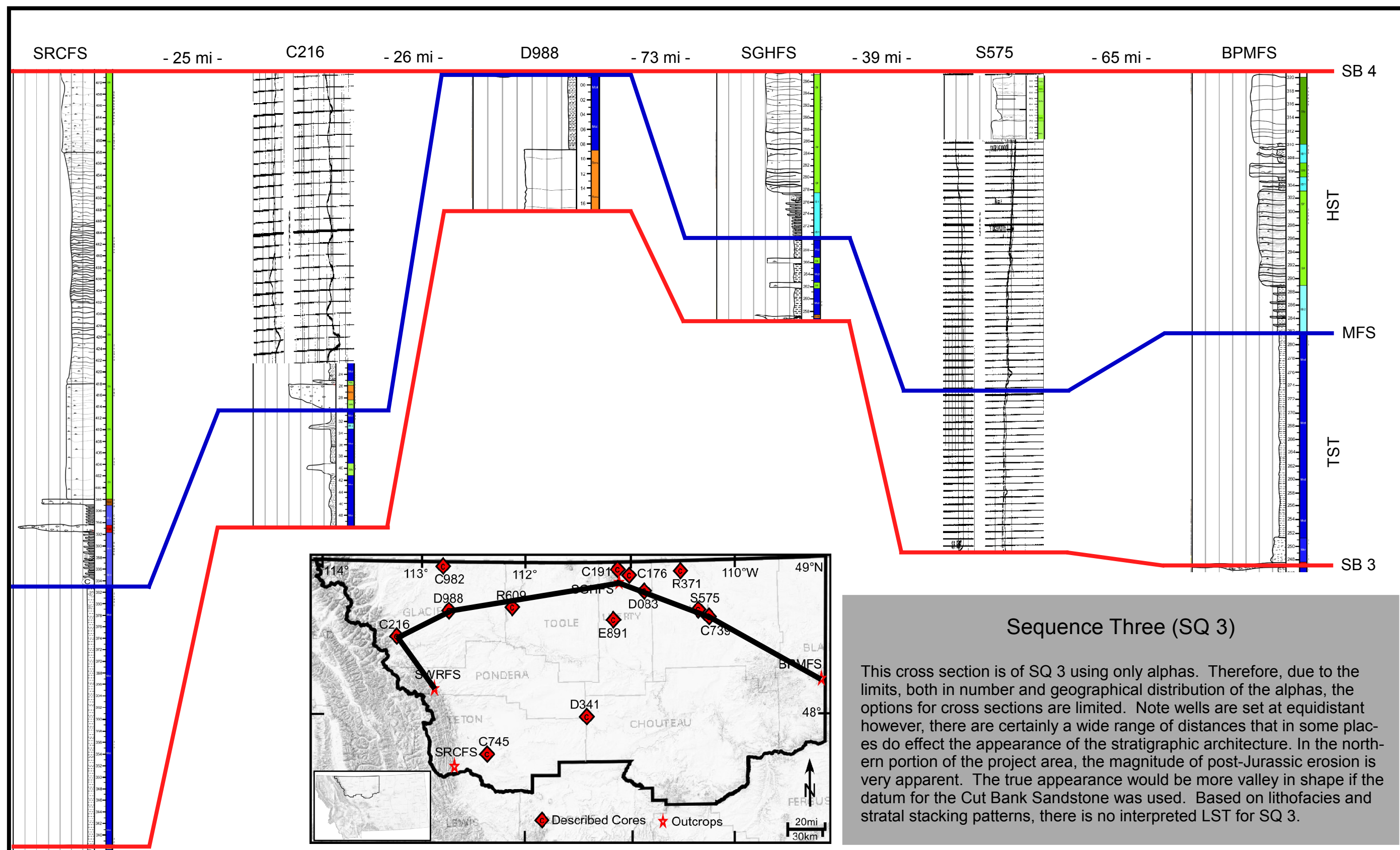
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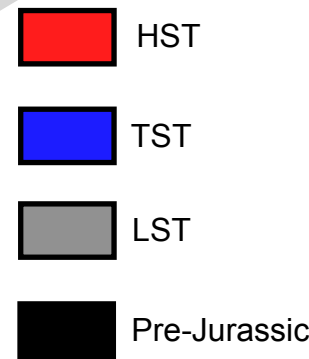
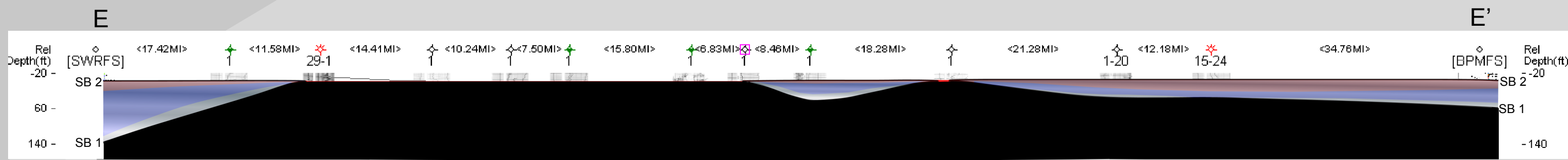
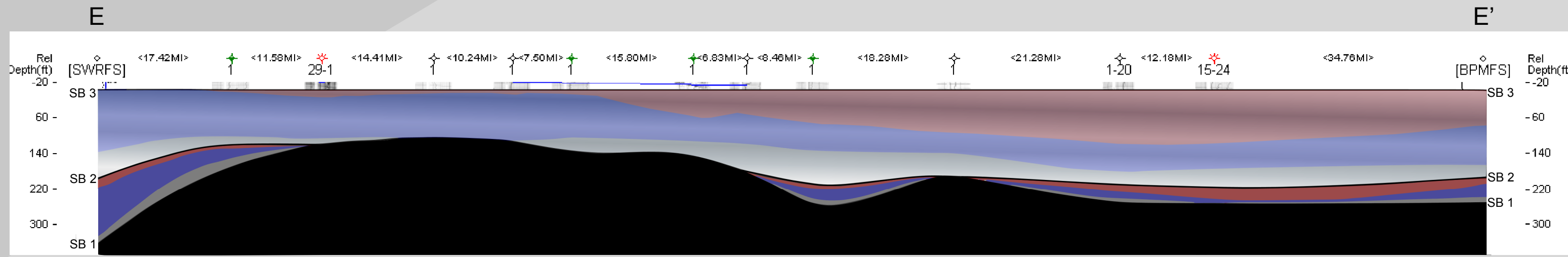
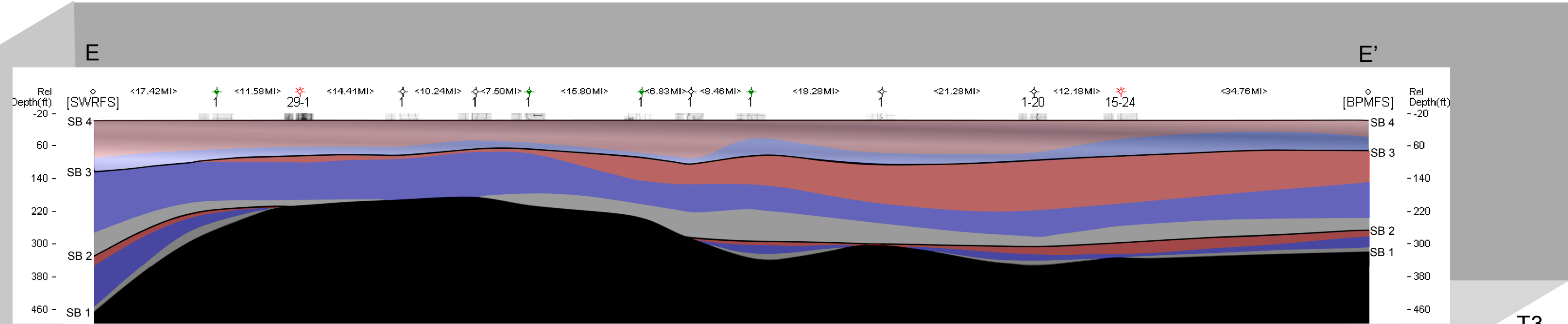
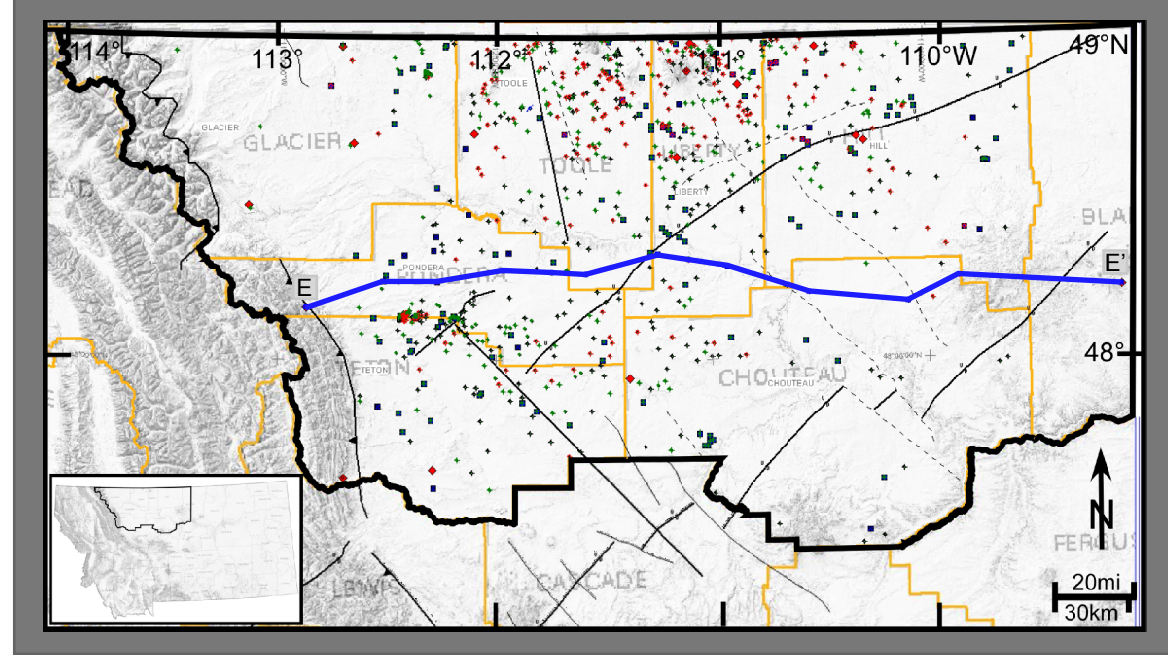
This composite figure shows the eight systems tracts that comprise the three sequences that make up the Jurassic Ellis Group. Arranged from left to right bottom to top in chronostratigraphic order. Each map shows the lithofacies distribution through lithofacies association distributions of the project area within their respective temporal constraints. As laid out in the previous table, the lithofacies associations were assigned to each geologic profile every time there was an upward change in lithofacies that deemed a new lithofacies association category. Therefore, the pie charts are showing the percent occurrence of the respective lithofacies association for that given sequence stratigraphic interval. In this coeval context, one can compare across the project area the dominant lithofacies association(s) to aid in determining the influence of the peripheral bulge, local or regional subsidence, and variation in environments of deposition.











Cross Section (EE')

This figure is showing the cross section at three different times, with respect to the three sequences. For each time the upper sequence boundary was used for the datum. This format allows for the stratigraphic architecture to be viewed through time as it changes, relative to the local accommodation.

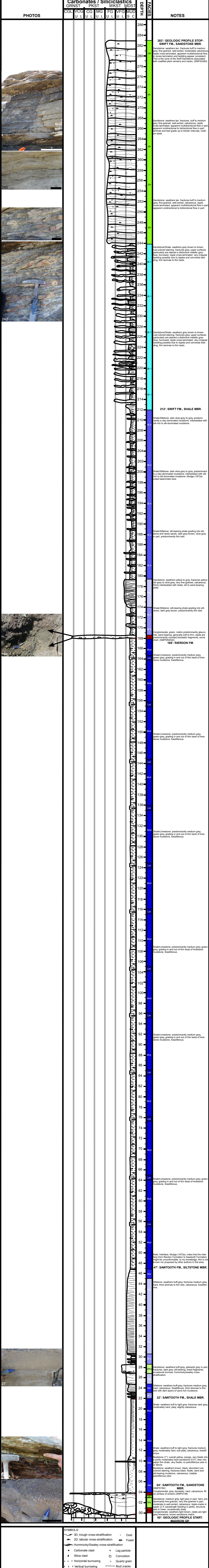
Beginning at T1, SQ 1 is shown as an incomplete interval across the cross section. In looking at the architecture, it can be noticed that SQ 1 onlaps to the main paleotectonic high. It appears there is greater accommodation on the west side of the high, however, all systems tracts were deposited and preserved. Furthermore, attention should be drawn to the isolated accumulation in the middle of the cross section showing the influence of the Joplin Structure on syntectonic deposition. In SQ 2 and T2, the greater accommodation appears to be on the east side of the high. Note, the HST thins to the west to complete absence, this is an erosional vacuity, during the hiatus after SQ 2 (J-4). In SQ 3 and T3, there is no LST preserved. This sequence could be recording a period of quiescence, as there is no real difference in accommodation between the west and east side of the high.

APPENDIX B

OUTCROP DATA

Location: Sun River Canyon (SRCFS), S 25 and 36, T 22N, R 9W, Teton County, MT

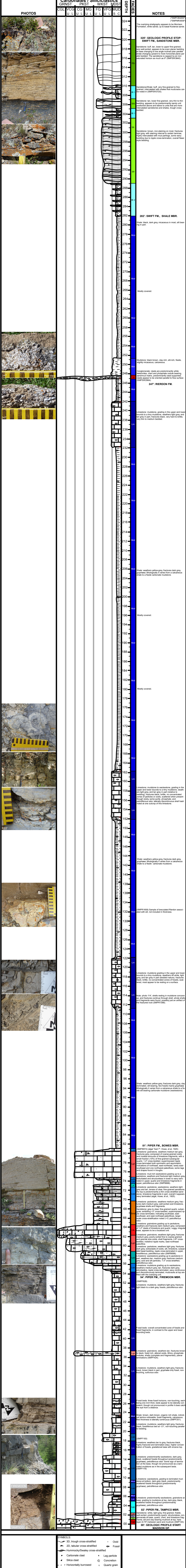
Date: 06.27.09



NOTE: This geologic profile is a composite of the author's field work and modified works of Cobban (1945), Imily, et al. (1948), Mudge (1972a,1972b), and Porter (1989).

Location: Bear's Paw Mountains (BPMFS), S 1, 11, and 12, T 28N, R 20E, Blaine County, MT

Dates: 06.2009 and 09.2010

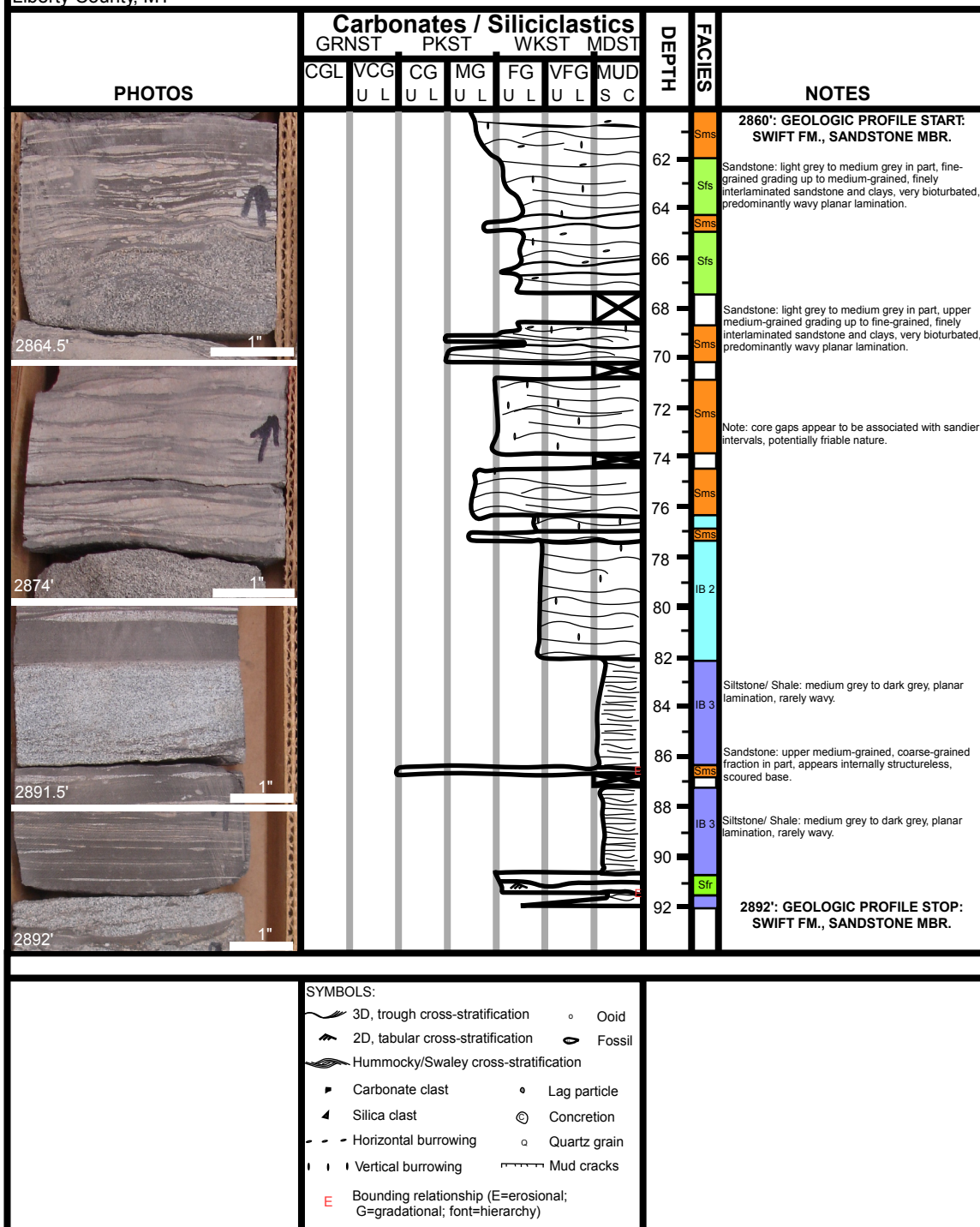


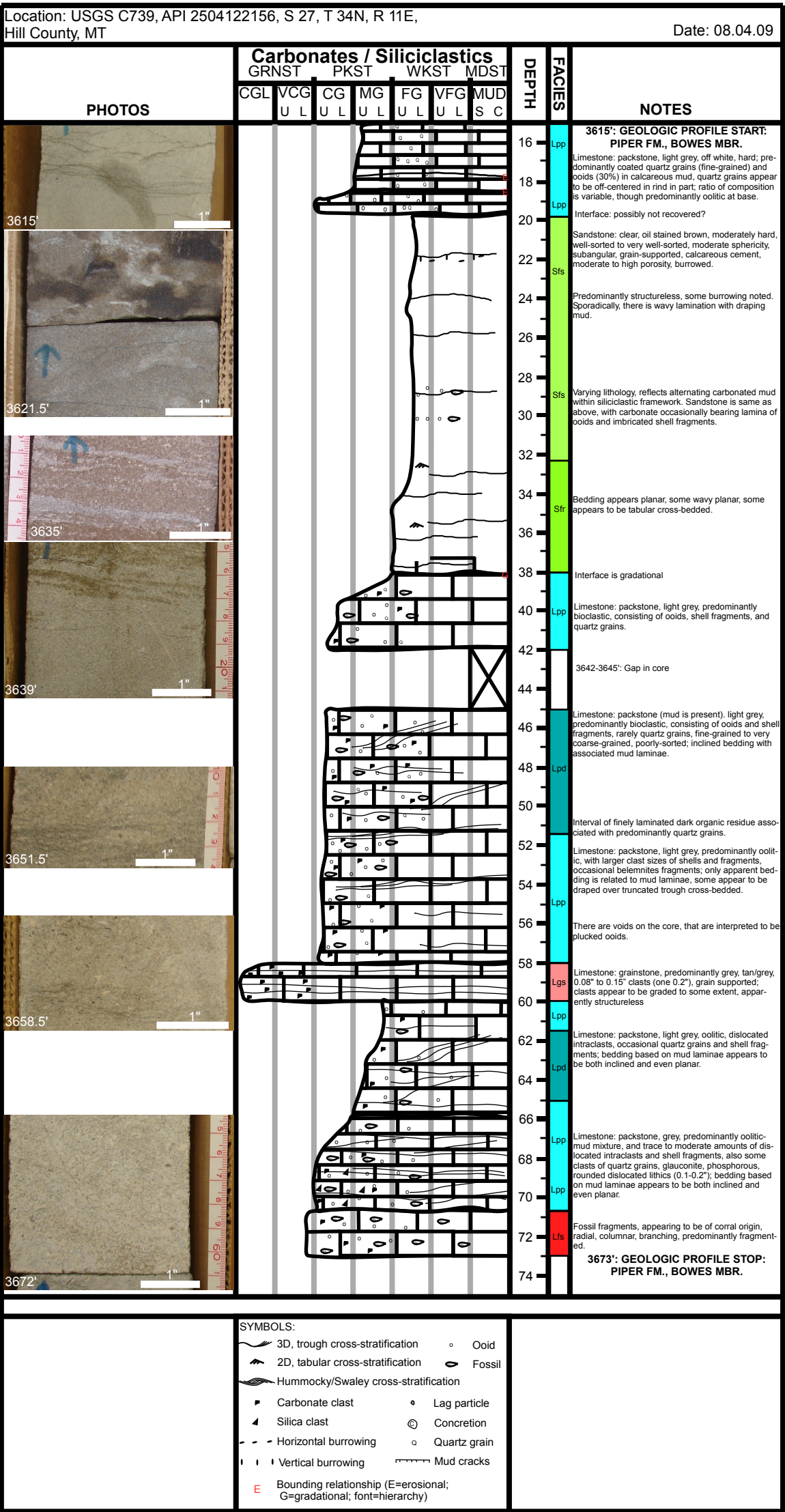
APPENDIX C

CORE DATA

Location: USGS C176, API 2505121012, S 26, T 37N, R 5E,
Liberty County, MT

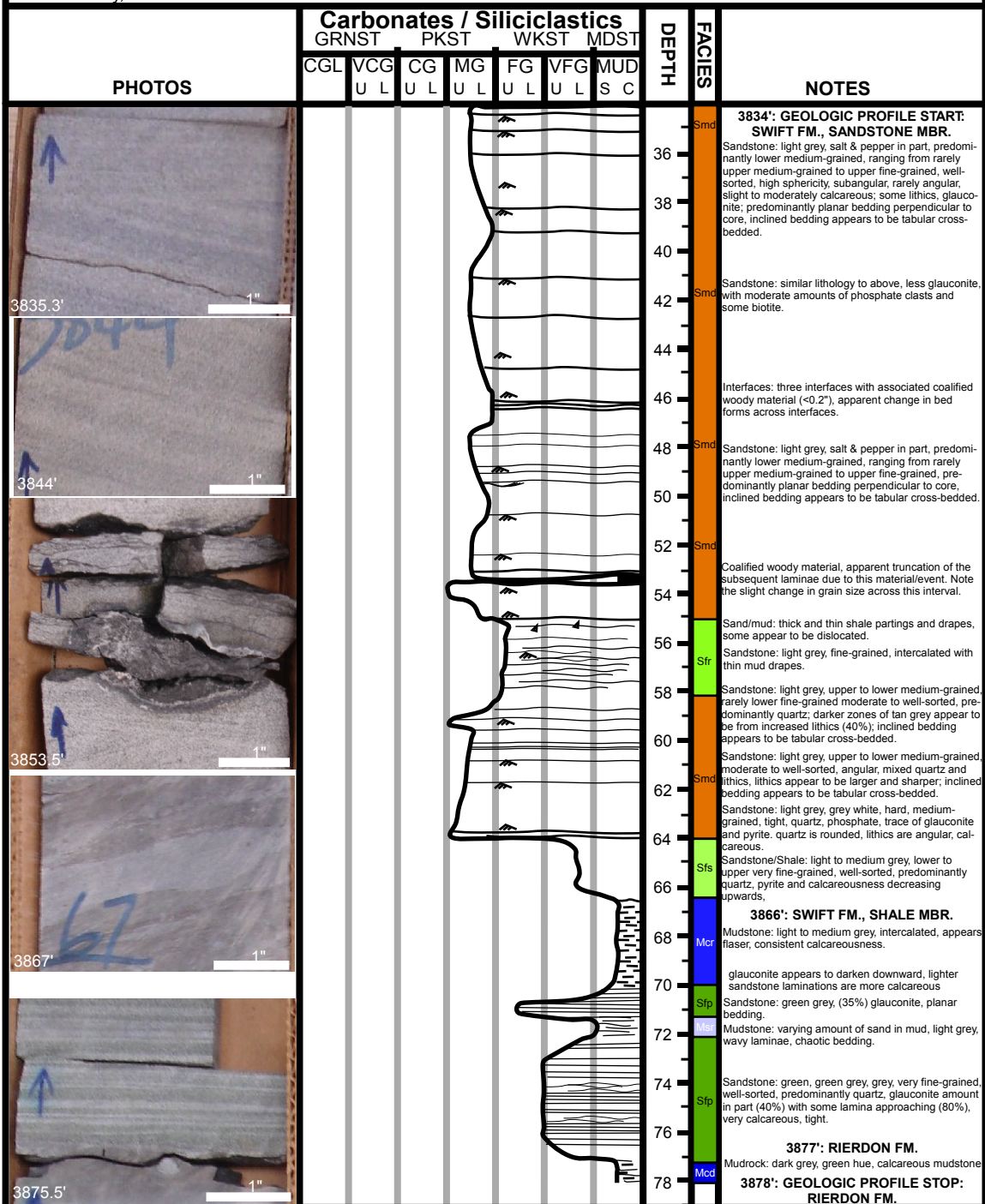
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Location: USGS C745, API 2509921147, S 18, T 22N, R 5W,
Teton County, MT

Date: 07.27.09



SYMBOLS:

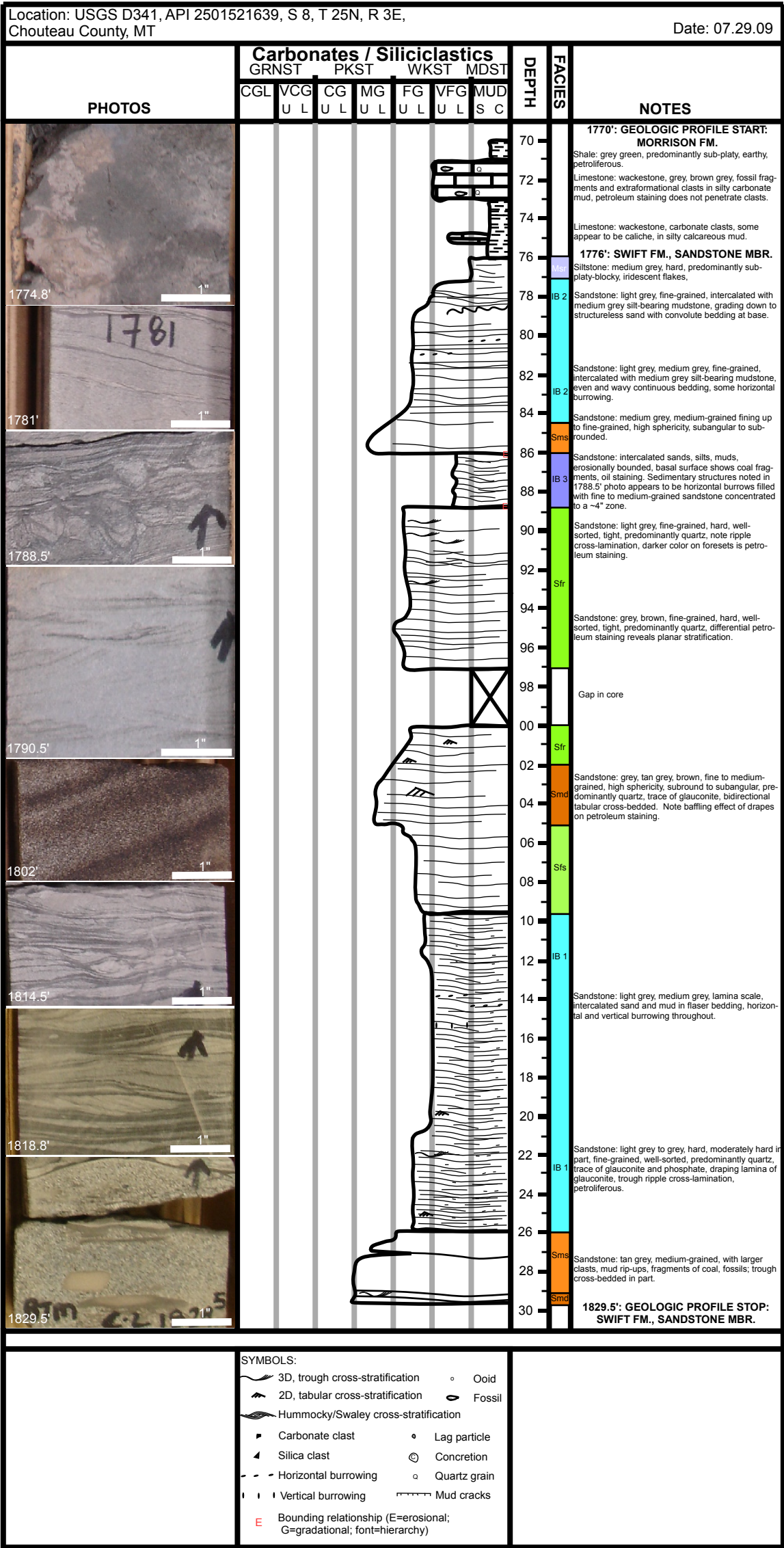
- 3D, trough cross-stratification
- 2D, tabular cross-stratification
- Hummocky/Swaley cross-stratification
- Carbonate clast
- Silica clast
- Horizontal burrowing
- Vertical burrowing
- Bounding relationship (E=erosional; G=gradational; font=hierarchy)
- Ooid
- Fossil
- Lag particle
- Concretion
- Quartz grain
- Mud cracks

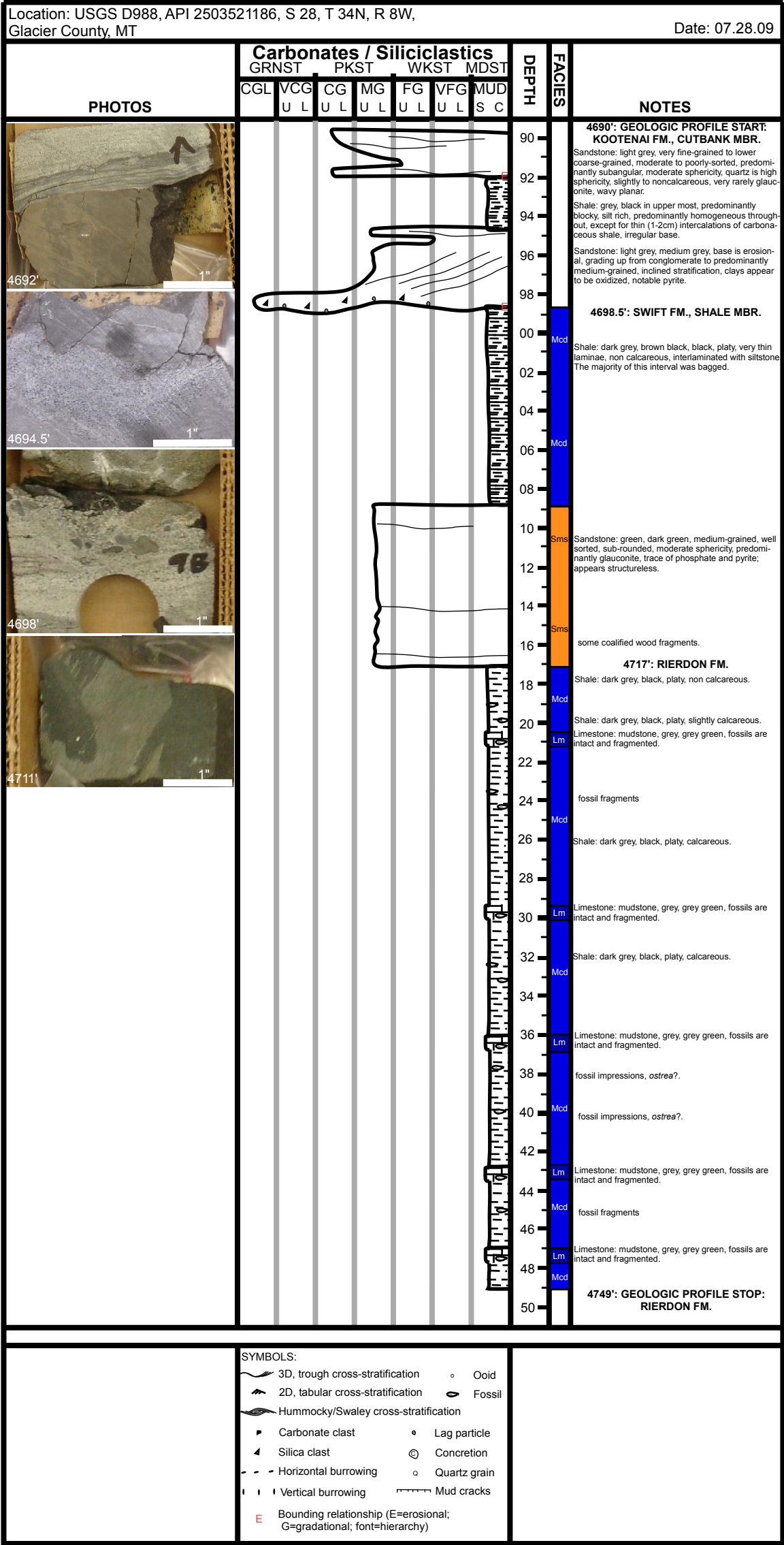
Location: USGS C982, API 2503521020, S 13, T 37N, R 9W,										Date: 07.27.09		
PHOTOS	Carbonates / Siliciclastics							DEPTH	FACIES	NOTES		
	GRNST	PKST	WKST		MDST		MUD					
	CGL	VCG	CG	MG	FG	VFG						
	U	L	U	L	U	L	U	L	S	C		
											66	Mod 4665': GEOLOGIC PROFILE START: SAWTOOTH FM., SHALE MBR. Shale: medium grey, dark grey, platy to sub-platy, predominantly smooth, very fissile (bagged in box), non-calcareous to slightly calcareous. 72 Mod Appears to be sandstone preserved in burrows of interface, interpreted as Sawtooth Sandstone Mem- ber. 4674': MADISON GP. Crystalline Carbonate: light grey, grainy texture, dolo- mitic, slow to effervesce. 4676': GEOLOGIC PROFILE STOP: MADISON GP.
											68	
											70	
											72	
											74	
											76	
SYMBOLS:  3D, trough cross-stratification  Ooid  2D, tabular cross-stratification  Fossil  Hummocky/Swaley cross-stratification  Carbonate clast  Lag particle  Silica clast  Concretion  Horizontal burrowing  Quartz grain  Vertical burrowing  Mud cracks E Bounding relationship (E=erosional; G=gradational; font=hierarchy)												

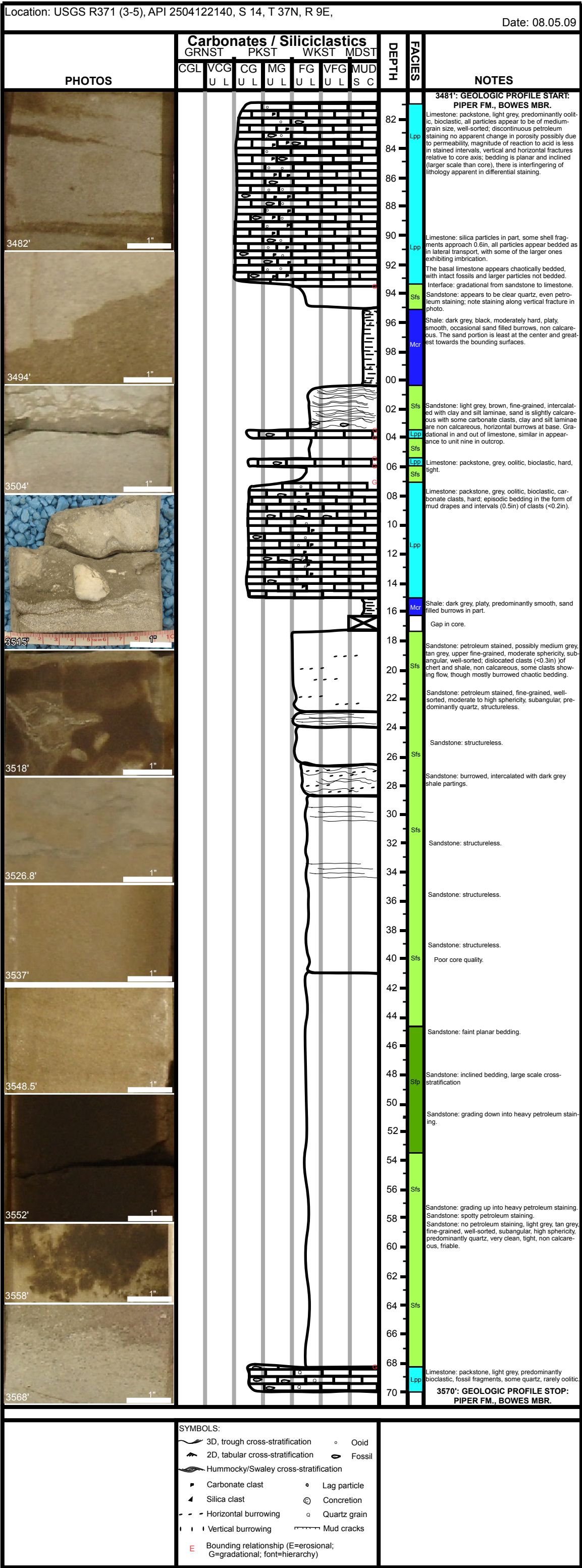
Location: USGS D083, API 2505105102, S 30, T 36N, R 7E, Liberty, MT

Date: 08.05.09

PHOTOS	Carbonates / Siliciclastics								DEPTH	FACIES	NOTES	
	GRNST		PKST		WKST		MDST					
	CGL	VCG	CG	MG	FG	VFG	MUD					
	UL	UL	UL	UL	UL	UL	UL	UL	UL			
											3201': GEOLOGIC PROFILE START:	
											Lwn	RIERDON FM.
											Mcd	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Lwn	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Mcd	Interface: limestone up to shale is lithologically sharp, however the amount of effervescing is gradational. However, on the shale up to limestone appears to be more gradational all around.
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input. Large rock (>2"), appears to be extraformational clasts.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, very thin laminae, calcareous.
											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, sub-platy to platy, calcareous.
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, sub-platy to platy, calcareous.
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, sub-platy to platy, calcareous.
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, sub-platy to platy, calcareous.
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
											Mcd	Shale: grey-brown, brown-grey, moderately hard, sub-platy to platy, calcareous.
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											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
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											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
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											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. Varying ratios of siliciclastic to limestone, seems to be variation in the clay input.
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											Mcd	Shale: green-grey, tan/green-grey, platy to sub-platy; fossil fragments; (bagged, complete recovery questionable).
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											Lwn	Limestone: wackestone, green-grey, tan-grey, moderately hard; floating fossil fragments and extraformational clasts, rarely bedded. V







Location: USGS R609, API 2510121770, S 15, T 34N, R 4W,
Toole County, MT

Date: 07.31.09

