

INCISED VALLEY-FILL SYSTEM DEVELOPMENT AND STRATIGRAPHIC
ANALYSIS OF THE LOWER CRETACEOUS KOOTENAI
FORMATION, NORTHWEST MONTANA

by

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of the requirements for the degree

of

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in

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ABSTRACT

The Lower Cretaceous Kootenai Formation in northwestern Montana records some of the first deposition of siliciclastic sediment into the Cordilleran foreland basin system. These rocks are also of particular interest due to their viability as reservoirs for hydrocarbons. The delineation of incised valley-fill systems within in this stratigraphic interval is of specific importance to this study as these stratigraphic entities have proven to record significant changes in base level fluctuations as well as preserving productive reservoir facies.

For this study a densely spaced collection of well logs, limited core, and analogous outcrop exposures were used to investigate the Cretaceous Kootenai Formation. The specific objectives of this research are three fold: (1) construct a regional stratigraphic framework of the Kootenai Formation and immediately adjacent strata in order to reconcile lithostratigraphic and chronostratigraphic units, (2) utilize the framework to delineate the stratigraphic position and architecture of local-scale incised valley-fill systems, and (3) construct a valley-fill model that incorporates environments of deposition interpreted from the observation of lithofacies in core and analogous outcrop.

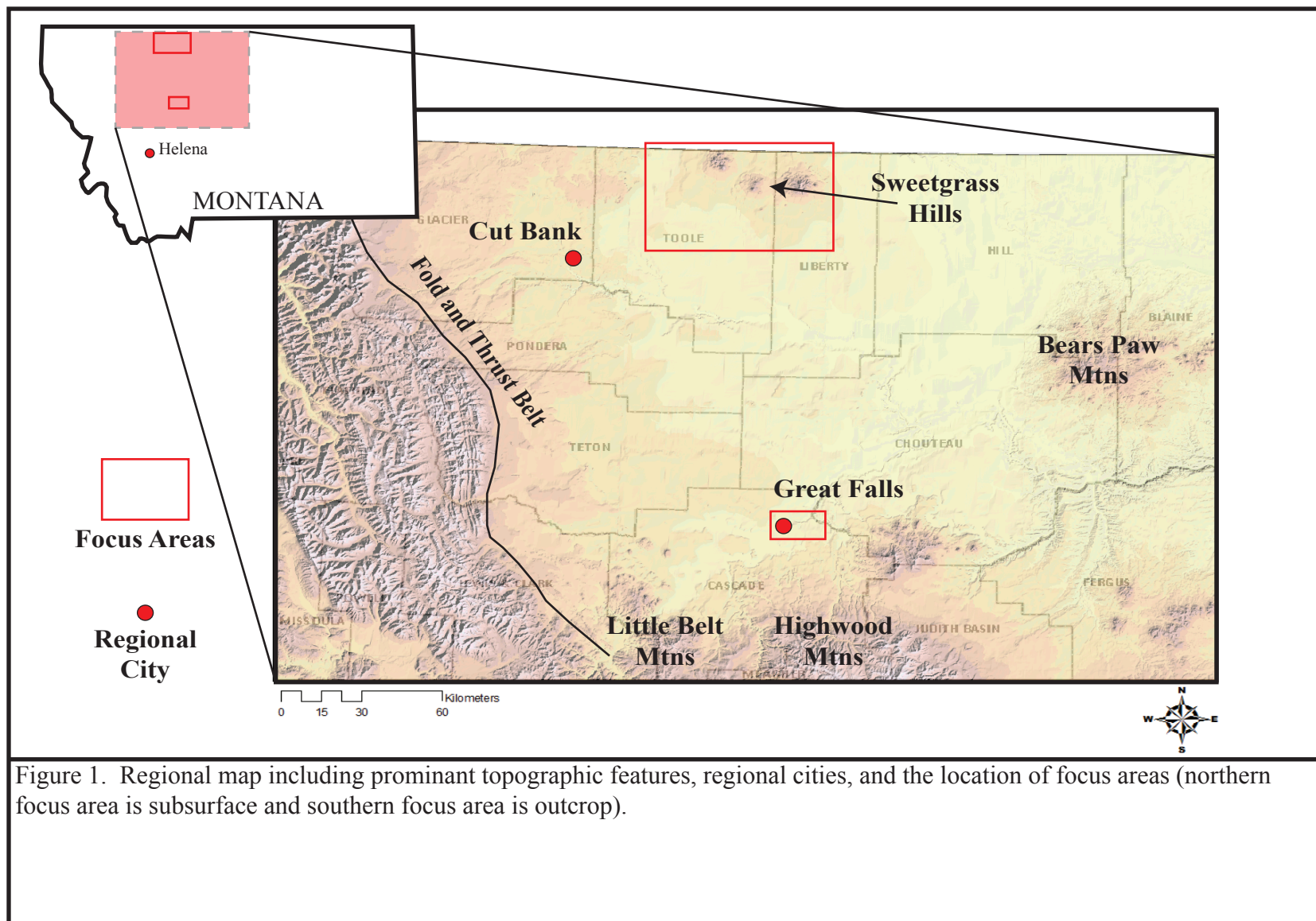
The stratigraphic analysis revealed a classic non-marine to marginal marine depositional sequence (Mitchum et al., 1977) within the Kootenai Formation. A sequence boundary at the base of the depositional sequence separates highstand marine strata of the Jurassic Ellis Group from lowstand incised valley-fill strata of the basal Sunburst member of the Kootenai Formation. Within the Lower Cretaceous depositional sequence, four distinct depositional environments stack to form the lowstand, transgressive, and highstand systems tract following fluvial incision into underlying Jurassic highstand strata. The first depositional environment is remnant amalgamated fluvial channel sandstone with pebble mud-clast lags. As base level began to rise a transgressive estuarine system developed. A transgressive surface is interpreted where incised valley-fill caps the valley. A lateral shift in depositional environments led to deposition of mud and fine-grained sand interpreted to represent tidal mud flats. Finally, as the rate of base level rise slowed an alluvial plain system developed, which marked the onset of the highstand systems tract.

CHAPTER 1

INTRODUCTION, OBJECTIVES, & SIGNIFICANCE OF STUDY

Introduction

An investigation of the Lower Cretaceous Kootenai Formation in northwestern Montana (Figure 1) provides insight into the deposition and preservation of incised valley-fill systems in a foreland basin tectonic setting. While incised valley-fill systems have been shown to record both autocyclic and allocyclic processes (Dalrymple, 2006) important for reconstructing the geologic history of a region, the Lower Cretaceous Kootenai Formation in northwestern Montana has also proven to contain prolific oil and gas reservoirs. For instance, the Fred & George Creek field alone has produced over 13 million barrels of oil and nearly 744,000 million cubic feet of gas from this stratigraphic interval (MBOG, 2012). The breadth of available subsurface data in this region, due to a long history of oil and gas exploration and development, affords this project a unique data set with which to frame the fill of incised valleys in terms of sedimentary processes and stratigraphic packages that define reservoir architecture. Utilizing this dataset, a detailed stratigraphic framework of the lower Kootenai Formation was constructed. Within this framework, one simple (*sensu* Zaitlin et al. 1994) incised valley-fill system, was identified. Due to the lack of drill core in the subsurface study area, a supplementary outcrop investigation was conducted in order to provide a useful analog for reservoir architecture and characterization.



The valley-fill system of interest is situated in the lower portion of the Kootenai Formation. Generally, the lower informal members of the Kootenai Formation are considered to represent the first major influx of clastic sediment into the foredeep (DeCelles and Giles, 1996) of the Cordilleran foreland basin system (Fuentes et al., 2011). While the physical location of the incised valley-fill system in this study was adjacent to the developing foredeep, provenance of the sediment is dominantly sourced from the encroaching fold and thrust belt.

The general appearance of the incised valley-fill system is congruent with the first class of incised valley-fill systems described by Dalrymple et al. (1994) where the valley is floored by an erosional sequence boundary and the ensuing valley-fill is comprised of fluvial to marine deposits. The valley-fill is confined within Segment 2 – Middle Incised Valley System of the idealized longitudinal section of an incised valley-fill system presented by Zaitlin et al. (1994) (Figure 2A). However, the assignment of sequence stratigraphic systems tracts within the valley-fill are more closely aligned with the designations proposed by Van Wagoner et al. (1990) where the majority of the valley-fill is assigned to the lowstand systems tract (Figure 2B).

Correlation and mapping of Upper Jurassic and Lower Cretaceous strata in northwestern Montana has proven a challenging undertaking. Together, the complexity of the evolving tectonic and depositional activity, a lack of exposed outcrop, and the proliferation of informal stratigraphic nomenclature (from both academic and industrial institutions) have led to an inadequate understanding of the stratigraphic evolution and heterogeneity of these systems.

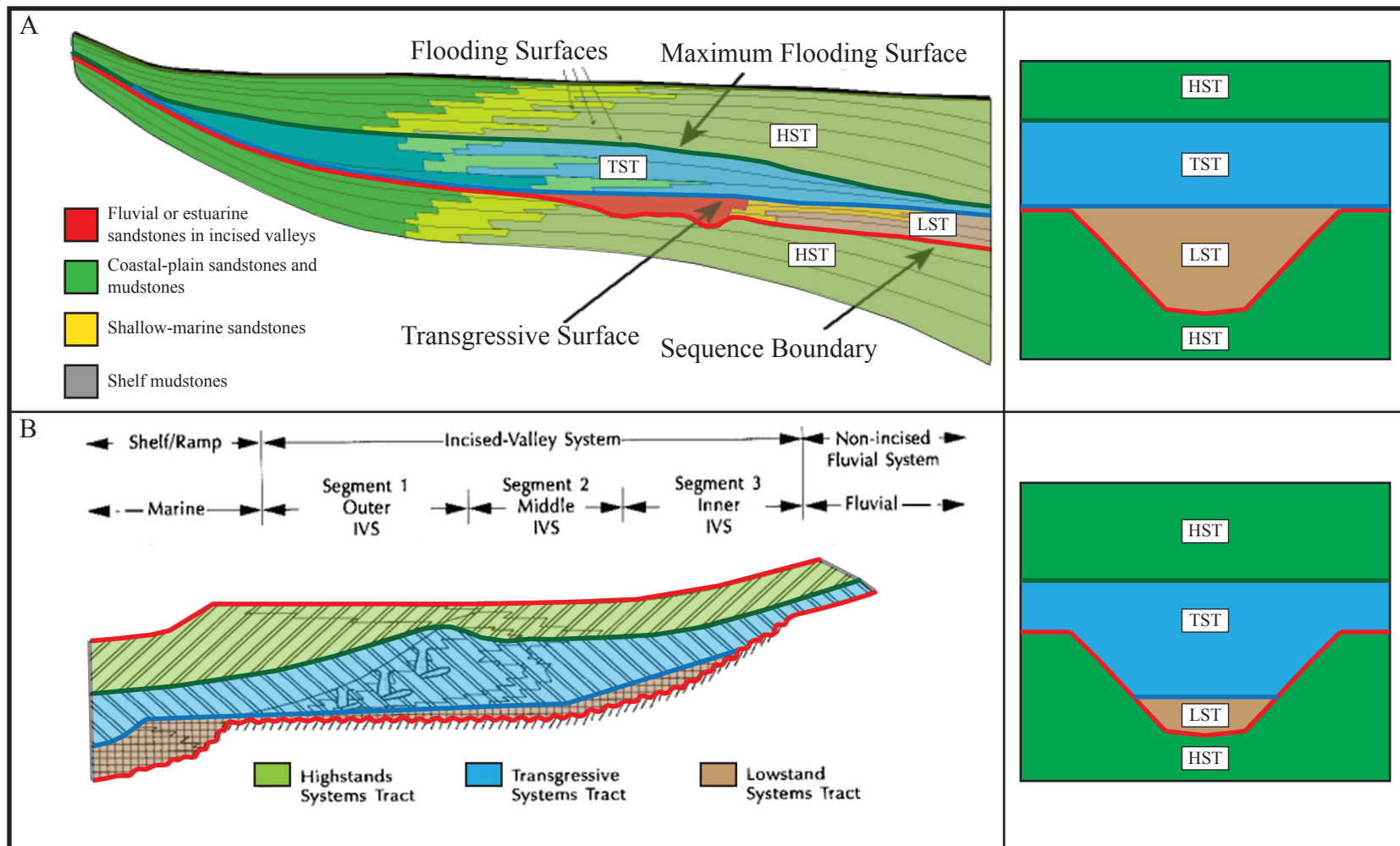


Figure 2. Idealized sequence stratigraphic models. In both models the incised valley system is bound by a basal sequence boundary that can be traced regionally. Model (A) differs from (B) in the placement of sequence stratigraphic systems tracts and surfaces, which is apparent in their cross-section. Model (A) was developed at Exxon by Van Wagoner et al. (1990) and Model (B) comes from Zaitlin et al. (1994).

Accordingly, the overall objective of this research is to provide a detailed regional analysis of Lower Cretaceous incised valley-fill systems in the northwestern Montana portion of the Cordilleran foreland basin and to delineate how these stratigraphic entities fit into a regional stratigraphic framework.

Objectives

The specific objectives for this research are three fold:

1. Construct a regional stratigraphic framework of the lower Kootenai Formation and immediately adjacent strata in northwestern Montana in order to reconcile lithostratigraphic and chronostratigraphically significant units.
2. Utilize the framework to delineate the stratigraphic position and architecture of local-scale incised valley-fill systems. (i.e. the planform geometry and geomorphic expression of the valley or “container”).
3. Construct a valley-fill model that incorporates environments of deposition interpreted from the observation of lithofacies in core and analogous outcrop.

Significance of Study

With conventional wildcat exploration methods decreasing due to dwindling frontier acreage and the decline in production of many small oil and gas fields in northwestern Montana, a new exploration method must be considered. Coupling a strong understanding of the depositional models of incised-fill systems with sequence stratigraphy, a stronger exploration tool has begun to be developed. This project builds

on the success of academic and industry stratigraphers in Alberta who have intensely investigated the stratigraphy of the Lower Cretaceous and the incised valley-fill systems it contains (Ardies et al., 2002; Lukie et al., 2002; Zaitlin et al., 2002; Ratcliffe et al., 2004).

This study will also serve as a case study for ancient incised valley-fill systems that developed in a proximal foreland basin tectonic setting, providing another example with which to continue the Kuhnian “mopping-up” phase of research on incised valley-fill systems (Kuhn, 1970; Dalrymple, 2006). Table 1 provided by Dalrymple (2006) provides the geologic setting for numerous incised valley-fill systems for which this study and others concerning these stratigraphic entities should be compared and contrasted.

CHAPTER 2

REGIONAL SETTING

Introduction

The first section of this chapter will detail the limits of the study area. The subsequent sections will detail the regional structural and stratigraphic setting, which is most effectively explained through a review of refereed literature. The structural section emphasizes the influence of both regional tectonic and local structural features in the area, while the stratigraphic section highlights the lithostratigraphic attributes of the Kootenai Formation, its informal members, and the attributes of immediate strata. The final section will feature an analysis of two major oil and gas fields investigated in this thesis.

Study Area

The study area for this project is located in northwestern Montana (Figure 1) and is bordered by the North American Cordilleran fold and thrust belt to the west; the Big Belt, Little Belt, and Highwood Mountains to the south; the Bear's Paw Mountains to the east; and the American – Canadian international border to the north. Much of the northern plains of Montana are remote and lack significant topographic relief. Numerous river systems dissect this plain into Cretaceous strata, but rarely into the section of interest.

The study area is sub-divided into two distinct focus areas, 1) a subsurface study area located in Toole and Liberty counties and 2) outcrops to the south along the Missouri River in Cascade county northeast of Great Falls, MT (Figure 3). A number of exploration wells in Cascade, Choteau, Pondera, and Teton counties were used for subsurface to outcrop correlations and are considered part of the subsurface study area.

The subsurface study area is comprised of 55 townships located in Toole and Liberty counties in northwestern Montana. The location of the subsurface study area is governed by three factors: (1) the vast expanse of wells drilled in the northern plains of Montana, (2) the proximity to the American – Canadian border where pertinent subsurface stratigraphic analysis has been conducted (Ardies et al., 2002; Lukie et al., 2002; Zaitlin et al., 2002), and (3) the presence of the Sweetgrass arch, a paleotopographic high that influenced deposition and/or erosion during the Late Jurassic and Early Cretaceous.

An excellent outcrop of the Lower Cretaceous Kootenai Formation lies along the Missouri River near Ryan Dam northeast of Great Falls, MT. A 6km (3.7mi) stretch between Ryan and Morony Dam just northeast of Great Falls exposes a continuous outcrop that was correlated to subsurface stratigraphy in the subsurface study area. While the outcrop is significantly removed from the subsurface study area ~150km (93mi), the lack of available core and the exceptional quality of this outcrop provided stratigraphic refinement that can only be gained from a detailed outcrop investigation.

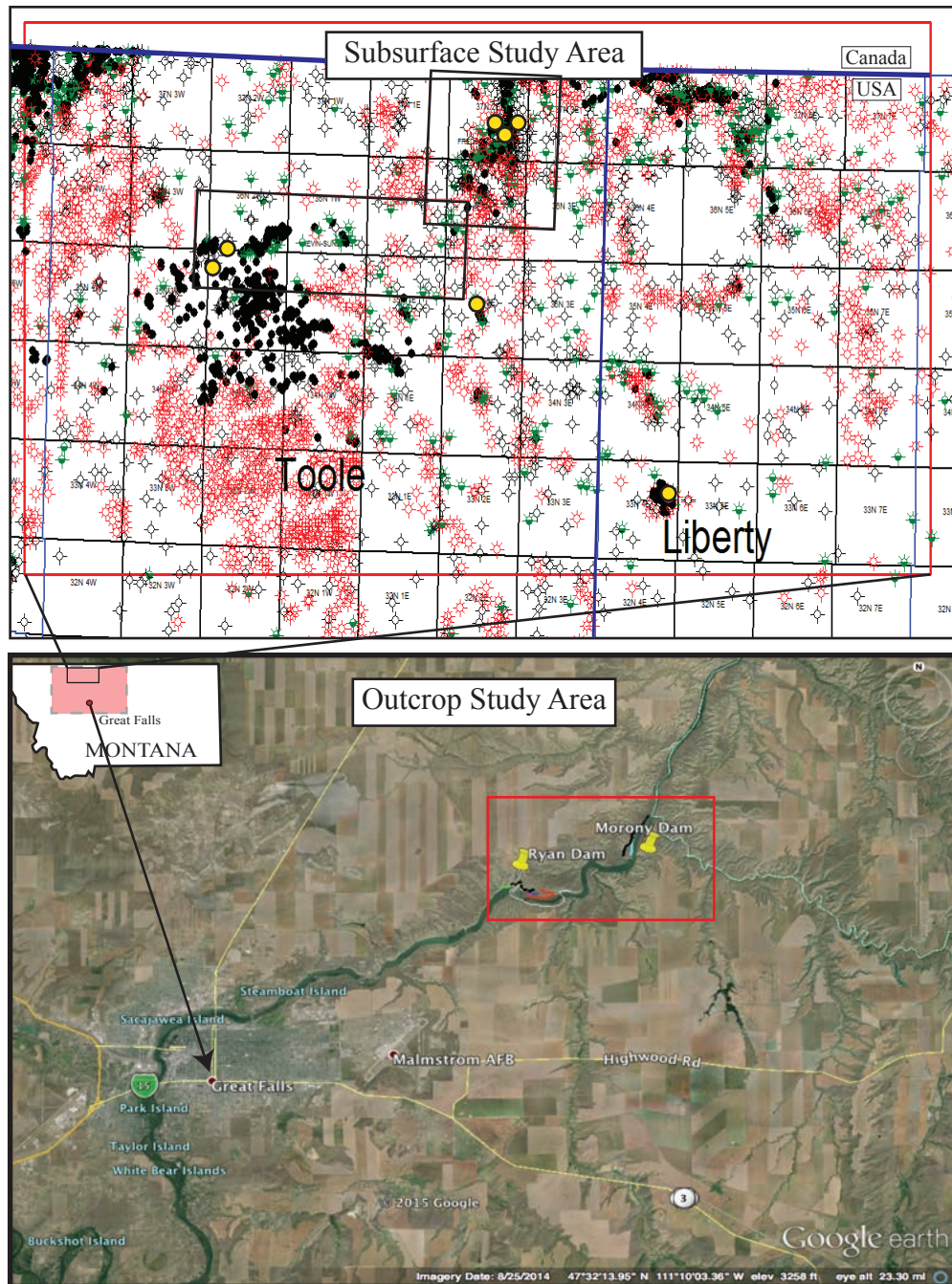


Figure 3. Zoomed in map of focus areas. The top image shows the subsurface study area, drilled wells, wells with described core (yellow dot), and two black boxes where the Fred & George Creek and a portion of the Kevin-Sunburst fields are located. The bottom image shows a GoogleEarth map of Great Falls, MT. Outcrops were examined along the Missouri River to the NE at Ryan and Morony Dam. Colored lines are field transects.

Tectonic Setting

While the focus of this project is to develop the stratigraphic nature of the Early Cretaceous in northwestern Montana, it is imperative for all stratigraphers to assess the tectonic setting and structural character of the region in order to identify how structural entities might have influenced the deposition of sediments. In northwestern Montana the encroaching North American Cordilleran orogeny and the development of the Cordilleran foreland basin system dominated the tectonic setting at a regional scale (Figure 4 and Figure 5). Locally, structures include: (1) the Sweetgrass arch, (2) the Sweetgrass Hills, and (3) the Pendroy Fault Zone (Figure 6). These features likely influenced the deposition, non-deposition, and/or erosion of the sedimentary units within the foreland basin system from Jurassic to present time.

North American Cordilleran Orogeny: and Foreland Basin System

The North American Cordilleran Orogenic Belt stretches ~6,000km from Alaska to Mexico and is considered the archetypal collisional system between oceanic and continental lithosphere (Dickinson, 2004) (Figure 7). This type of collisional system developed as the North American continental plate moved westward and overrode the colder more dense Kula-Farallon plate following the break up of the super-continent Pangea (Coney, 1984). Contractional tectonics began sometime in the Early Mesozoic (Dickinson, 2004) and continued until the Early Cenozoic, during which the tectonic setting changed from a contractional to an extensional regime, due to orogenic collapse (Coney, 1984).

North American Paleogeographic Map -
Late Jurassic 150Ma

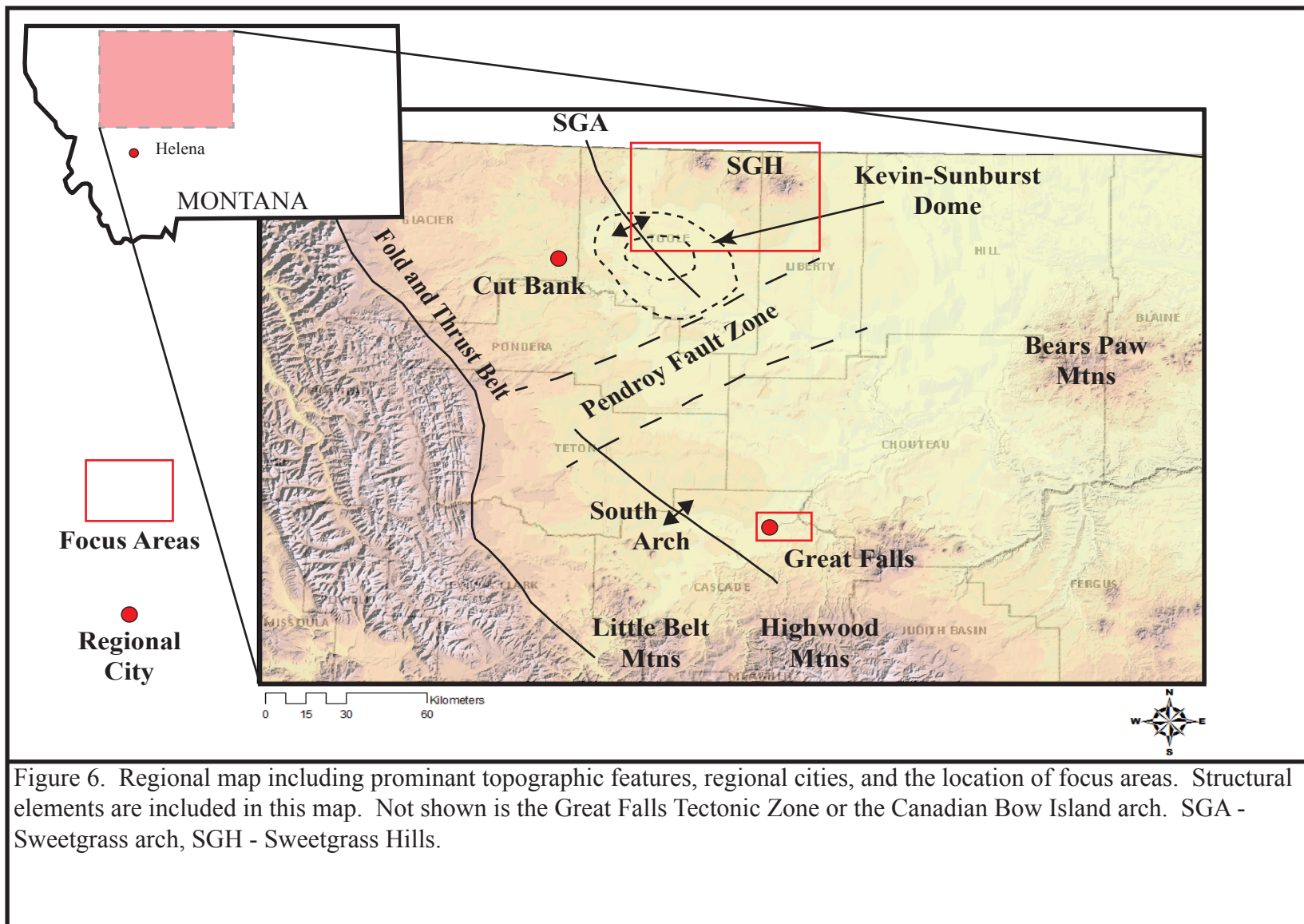


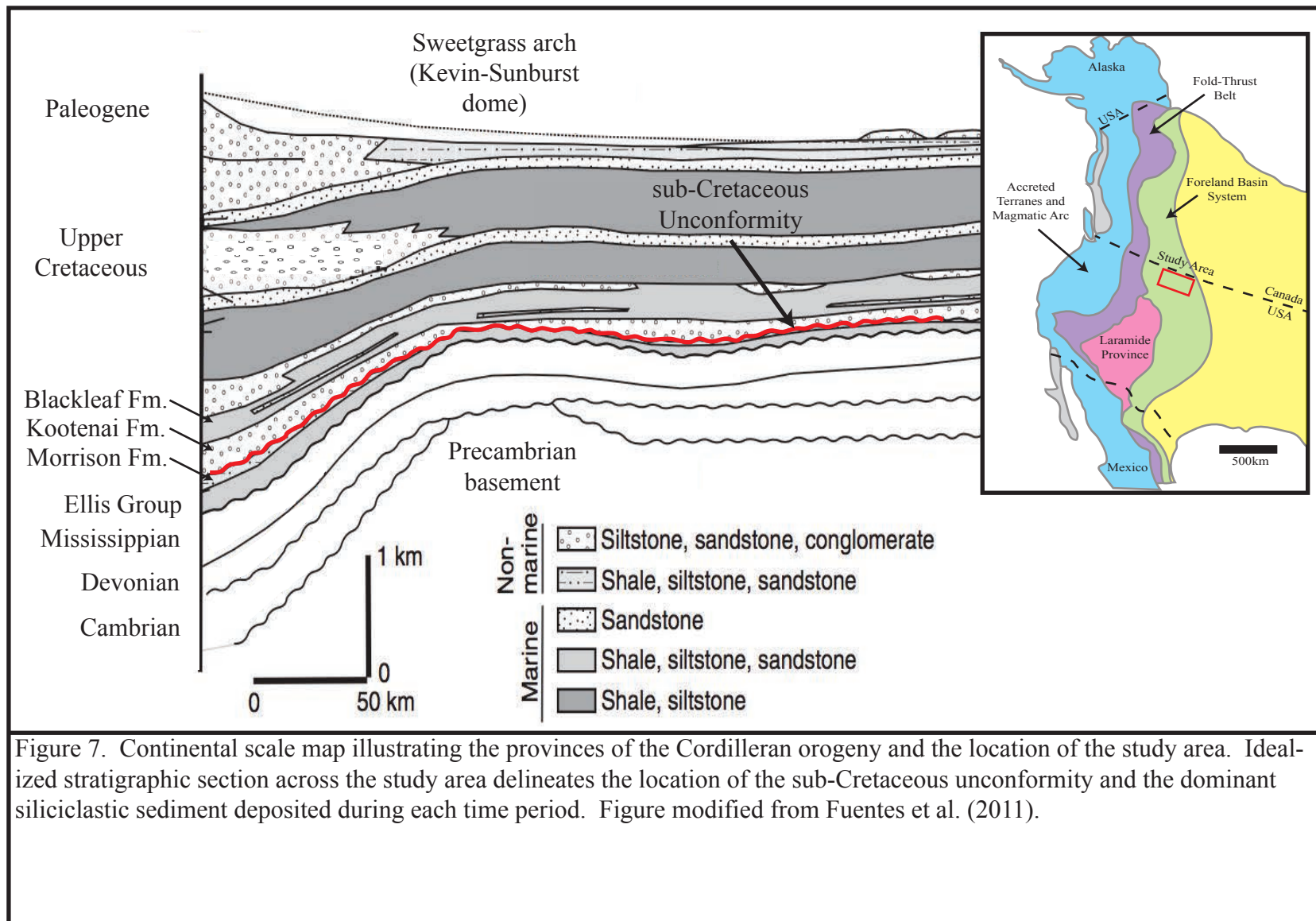
Figure 4. Paleogeographic reconstruction of the Late Jurassic 150Ma (Blakey et al., 2003).

North American Paleogeographic Map -
Early Cretaceous 140Ma



Figure 5. Paleogeographic reconstruction of the Early Cretaceous 140Ma (Blakey et al., 2003).





Downward flexure of the crust due to the extreme loading of the lithosphere by stacked sedimentary thrust sheets to the west initiated foreland basin subsidence to the east of the Cordilleran (Beaumont, 1981; Jordan, 1981). In northwestern Montana, foreland basin subsidence is recorded by the deposition of the Jurassic Ellis Group in the backbulge portion of the basin (Fuentes et al., 2011) (Figure 7). A major regional unconformity, commonly referred to as the sub-Cretaceous unconformity (Glaister, 1959; Lukie, 2002; Boyd et al., 2006), separates marine strata of the Jurassic Ellis Group from fluvial to estuarine-dominated deposits in the Lower Cretaceous. Multiple workers have examined and estimated the duration of this unconformity. Hayes (1982) suggested a period of approximately 40m.y., but recent work by Fuentes (2010) suggests a period of 20m.y. The latter author interprets the sub-Cretaceous unconformity to be related to: (1) the eastward migration of the forebulge, (2) a fall in eustatic sea-level, (3) decreased dynamic subsidence, or (4) some combination of these processes.

Sweetgrass Arch

In this study the term Sweetgrass arch will be used to describe the collection of large cratonic structural features in northwestern Montana and across the international border into southern Alberta, Canada. The Sweetgrass arch, from south to north, is comprised of the NW-trending South arch, the Kevin-Sunburst dome, and the NE-trending Bow Island arch in Alberta.

One of the earliest mentions of the SA in American literature comes from Stebinger's (1916) report on the "Possibilities of Oil and Gas in North Central Montana". Stebinger (1916) makes no comments on the formation of the structure, but accurately

describes the northward plunging nature of the arch and predicted its future importance as a structural trap for oil and gas. Lorenz (1982) later insinuated that the Sweetgrass arch began as an “upwarping” of the lithosphere in late Precambrian time, due to the load of Belt strata deposited on the continental shelf, and remained a high through the Paleozoic. Lorenz’s (1982) history of the arch continues into the Late Jurassic when the arch is theorized to have been a topographic high related to the forebulge of the encroaching Cordilleran foreland basin system. Lorenz (1982) and Fuentes et al. (2011) both consider the forebulge of the Cordilleran foreland basin to be caught up in or controlled by the pre-existing crustal weaknesses associated with the Sweetgrass arch. Mischener (1934) and Cobban (1945) described the thinning of Jurassic strata over the Bow Island arch and Kevin-Sunburst dome, respectively, which provides further evidence that the arch was a positive feature in the Late Jurassic (Porter, 2011).

The nature of the arch becomes much more problematic during Early Cretaceous time and reports of the arch’s activity become inconsistent. Specifically, Podruski (1988), and Hayes (1982) report that, prior to the onset of Laramide deformation in Late Cretaceous time, the Bow Island arch did not influence Cretaceous deposition. However, Schröder-Adams et al. (1998) indicates that Santonian age strata (86-83m.y) were never deposited on the crest of the Bow Island arch, suggesting it had positive relief at this time.

Sweetgrass Hills

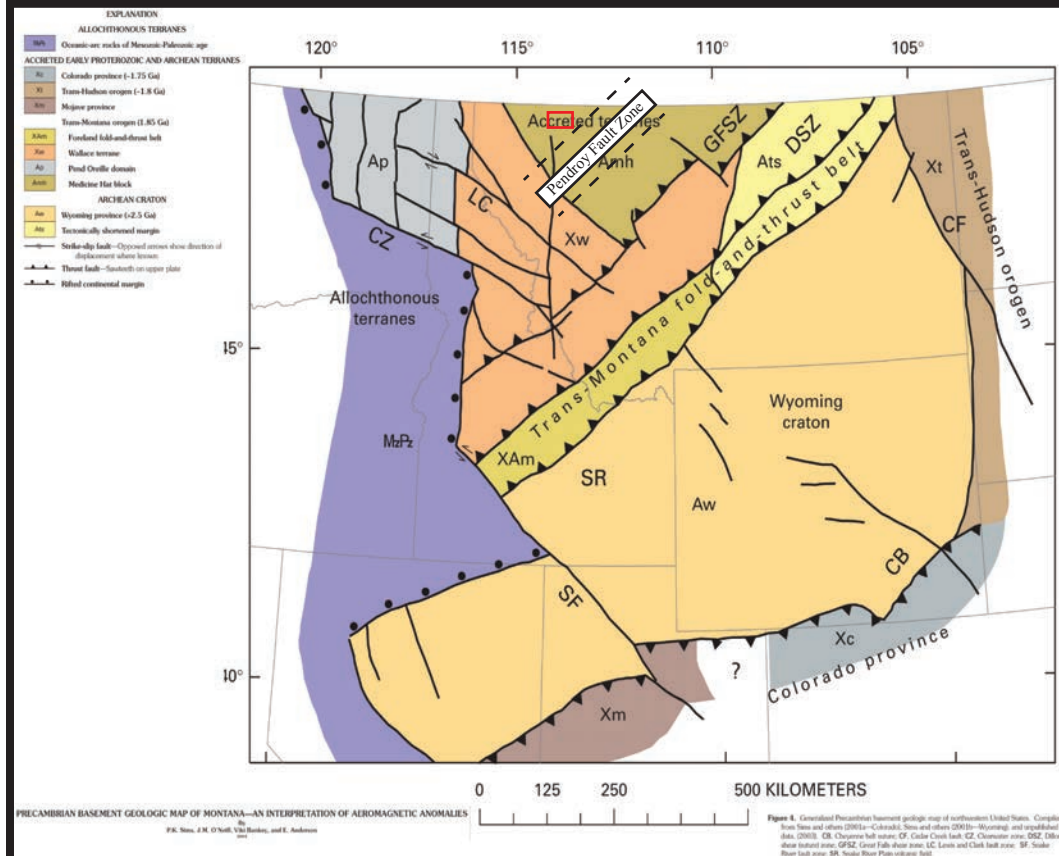
The Sweetgrass Hills are a small cluster of Eocene intrusive syenite to diorite porphyry-cored buttes located in Toole and Liberty counties (Lopez, 2000). An

investigation by Kjarsgaard and Davis (1994) suggests that the origin of the Sweetgrass Hills and other intrusive igneous bodies within the Montana alkaline province emanated from Laramide compressive stresses. Local deep-seated Precambrian basement faults near the Sweetgrass arch and Kevin-Sunburst dome were likely reactivated by Laramide compression (Lopez, 2000), uplifting Mississippian-aged strata to the surface and allowing magma to rise along the resulting faults and fractures. The Sweetgrass Hills can be viewed as analogous to many local subsurface anticlinal and domal structures that have proven to be significant oil and gas traps exploited in drilling exploration.

Pendroy Fault Zone

The Pendroy fault zone, which offsets a portion of the Sweetgrass arch (Lorenz, 1982), is a prominent northeast trending basement feature (Smith, 1970). The Pendroy fault zone is sub-parallel to a number of Precambrian structural trends in the region including the Great Falls tectonic zone to the south (Figure 8). O'Neill and Lopez (1985) traced these sub-parallel trends from the Cordilleran miogeocline through the fold and thrust belt, into the subsurface basement rocks of northern Montana, and across the border into southwestern-most Saskatchewan, Canada. The Pendroy and Great Falls fault zones appear as northeast trending gravity high anomalies (Smith, 1970) and have been interpreted to represent Precambrian igneous activity (Alpha, 1955; Smith, 1970). This igneous activity was likely generated during the accretion of the Medicine Hat block and the Wyoming craton during the Trans-Montana Orogeny (O'Neill and Lopez, 1985). The importance of the Pendroy fault zone in this study is its potential as a structural control on depositional patterns in northwestern Montana. Specifically, Dalrymple (2006) noted

Precambrian Basement Map



the influence of tectonic-warping or fault-generated dislocation as a major control on the location of incised valley-fill systems.

Lithostratigraphy

Introduction

A summary of the lithostratigraphic attributes of the Kootenai Formation and immediate strata will be presented here. The review will begin with oldest strata first, starting with the Upper Jurassic Ellis Group and ending with the Early Cretaceous Blackleaf Formation. Stratigraphic nomenclature in this region is highly variable due to the proximity of the international border and the history of hydrocarbon production by numerous operators following proprietary and informal stratigraphic schemes (Figure 9).

Ellis Group (Je)

The Jurassic Ellis Group unconformably overlies carbonates of the Mississippian Madison Group. The Ellis Group is comprised of three formations the Sawtooth, Rierdon, and Swift. Jurassic lithostratigraphic boundaries record major periods of base level rise (Hayes, 1982; Ardies, 1999).

Sawtooth Formation (Jswt)

The Sawtooth Formation is the oldest Jurassic formation in northwestern Montana and is separated from the Mississippian Madison Group by a major regional unconformity. The Sawtooth Formation takes its name from the Sawtooth Mountain Range in Teton County, where Cobban (1945) identified the type section at Rierdon

Ardies et al. (2002)			Blixt (1941)		This Study		Time	
South-central Alberta			Montana (SGA) West Flank (Cutbank Field)		Montana (SGA) East Flank		Group	Series
Upper Mannville	Upper Blairmore	Nonmarine Shales and Sandstones	Kootenai Fm.	Upper Blairmore	"Hodgepodge of Floodplain and Deltaic Deposits"	Kootenai Fm. upper	Kootenai - undifferentiated sands and shales	LOWER CRETACEOUS
		Glaucconitic Facies		Moulton Sand				
Lower Mannville	Basal Quartz	Ostracod Mbr.		Lander Sand ??	Kootenai Fm. lower	Moulton mbr.	Morrison Fm.	
		Ellerslie		Sunburst Sand		Sunburst mbr.		
		BAT 2		Upper Cutbank Sand				
		BAT 1		Lower Cutbank Sand				
		Horsefly 2						
		Horsefly 1						
		A-Sandstone						
Swift Fm.		Ribbon Sand		Swift Fm.	Ellis Group	JURASSIC		
Rierdon Fm.		Ellis Shale		Rierdon Fm.				
Sawtooth Fm.		Local White Porous Sand		Sawtooth Fm.				
Madison Fm.		Madison Fm.	Madison Fm.	Madison Group	MISSISSIPPIAN			

Figure 9. Stratigraphic nomenclature of the Lower Cretaceous for this study area, on the west side of the Sweetgrass arch, and in south-central Alberta.

Gulch (Sec. 23, T. 24N., R. 9W.). No outcrops or cores of the Sawtooth Formation were described, and only a few of the wells analyzed penetrated this formation. The lithology provides context for the paleogeography of the Middle Jurassic. As described by Cobban (1945) the Sawtooth Formation can be subdivided into three separate units based entirely on lithology. The units include a basal quartz dominated sandstone, a dark grey interbedded calcareous and non-calcareous shale, and a slightly calcareous quartz-rich siltstone. Imlay (1957) described the paleogeography of the Sawtooth Formation as a “shallow, warm, clear, generally well aerated sea”. Imlay’s (1957) interpretations are based on megafauna and the lithologies present in outcrop. In this project, the Sawtooth Formation is demarcated by a left deflected excursion in the geophysical gamma ray curve just above the easily identifiable limestone of the Mississippian Madison Group. The Mississippian Madison Group can be recognized by an extreme left excursion of the gamma ray curve and a strong right excursion of the resistivity log.

Rierdon Formation (Jr)

The Rierdon Formation is the intermediate formation of the Ellis Group. The type section was identified and described by Cobban (1945) at Rierdon Gulch (Sec. 23, T. 24N., R. 9W.) in the Sawtooth Mountain Range. At the type section, Cobban (1945) identified four separate units of alternating grey to green limy shale and limestone. While no Rierdon Formation outcrop or cores were described, many of the wells penetrate this interval, as the grey-green shale is a common marker for operators targeting Jurassic and Cretaceous reservoirs to conclude drilling. Determining which of Cobban’s (1945) four Rierdon units the well penetrated can be difficult due to variable post-

Rierdon erosion and discontinuous lithologic units (Hayes, 1982). Thus, with no cuttings or core, the individual units were lumped into a single Rierdon Formation pick. Across the study area, the formation has variable thickness from tens of feet to hundreds of feet.

The Rierdon Formation records widespread shallow marine deposition. The abundant fossils described by Imlay (1945, 1948) including *Arctocephalites*, *Cadoceras*, *Keplerites*, and *Cosmoceras* and the lithologic character provide evidence for this depositional setting.

Swift Formation (Jsw)

The Swift Formation is the uppermost formation of the Ellis Group. In western Montana an unconformable surface separates the Swift Formation from the Rierdon Formation due to post-Rierdon erosion (Hayes, 1982). The upper contact is conformable with the Jurassic Morrison Formation to the south and unconformable with the Cretaceous Kootenai Formation in the subsurface study area. The type section is located along the north shore of the Swift Reservoir (Sec. 27, T. 28N., R. 10W.) in Pondera County. According to Cobban (1945) the Swift Formation contains a lower dark grey shale unit and an upper sandstone unit that is flaggy and has ripple marks.

Morrison Formation (Jmr)

Eldridge (1896) first described the Morrison Formation near Morrison, Colorado. Much of the Morrison Formation, as it is recognized throughout the Rocky Mountain region, is a mix of gray-green variegated siltstones with interbedded calcareous limestone and sandstone, mudclast conglomerates, paleosols, and thin beds of black shale (Smith et

al. 2006; Demko et al. 2004). In northwestern Montana, Mudge (1972) found the Morrison Formation grading conformably into the underlying Swift Formation near the “Disturbed Belt”, but others have noted the absence of the Morrison Formation near the Sweetgrass arch (Weimer, 1959; Hayes, 1982) and Sweetgrass Hills (Branch, 1976). A regional unconformity marking the Jurassic-Cretaceous boundary separates the Morrison Formation, where it is present, from the Kootenai Formation. However, much debate has centered on the age of the Morrison Formation and its depositional environment. Walker (1974) provides a synthesis of this subject and will be referred to here when the Morrison Formation is discussed, but because the formation is mostly absent in the subsurface study area little emphasis is placed on its characteristics.

Kootenai Formation (Kk)

In northwestern Montana, the Kootenai Formation was deposited in Early Cretaceous time. The rocks of the Kootenai Formation represent the first consistently thickening westward wedge of strata deposited in the nonmarine foredeep depocenter (i.e. the first rocks related to foreland basin development of the North American Cordilleran foreland basin system) (Suttner, 1969; Schwartz and DeCelles, 1988; DeCelles, 2004; Fuentes et al., 2011). While a lack of quality chronostratigraphic markers are present in the Kootenai Formation, Fuentes et al. (2011), utilizing four new palynology samples and detrital zircon data, has placed the age of the Kootenai as late Barremian (129-125m.y.) to early Albian (113-100m.y.), with a Hauterivian age (132-129m.y.) from a sandstone grain in the basal conglomeratic sandstone.

The Kootenai Formation in the study area can be informally broken into a lower and upper section. The lower section of the Kootenai is dominated by a succession of fine to coarse-grained sandstone members known informally as the Cut Bank, Sunburst, and Moulton, (Cobban, 1955). The upper section of the Kootenai Formation is dominantly fine-grained non-marine shale, which is unconformably overlain by marine shale of the Blackleaf Formation, which marks the earliest southward transgression of the Cretaceous interior seaway (Hayes, 1982; Berkhouse, 1985). The focus of later chapters will mainly be on the Sunburst member.

The Cut Bank sandstone is stratigraphically the lowest informal member of the Kootenai Formation and is chiefly a quartz-rich sandstone with black and grey chert (Cobban, 1955). Historically, the Cut Bank sandstone has produced hydrocarbons from medium to coarse-grained channel sandstone reservoirs that cut into the underlying Jurassic formations. As defined by Oakes (1966) and described by Rice (1975) the type section of the Cut Bank sandstone is core from the Salt Dome No. 1 Kruger well, NW $\frac{1}{4}$ SW $\frac{1}{4}$ Sec. 12, T. 37N., R. 5W., Glacier County, MT from 2,571 to 2642 feet. The Cutbank sandstone has been interpreted as both a braided (Dolson and Piombino, 1994; Lukie, 1999) and meandering river deposit (Cant, 1982; Weimer et al. 1985).

Next in the vertical succession is the informal Sunburst member. Glaister (1959) and Ardies (1999) describe the Sunburst member as a quartz rich sandstone with some grey to black chert grains and Cobban (1955) adds to the description the presence of white specks and red, orange, and brown grains (likely calcite cement and chert). Dominantly, the Sunburst member is medium to coarse-grained sandstone and has proven

to be a moderate hydrocarbon producer. In the Cut Bank oil and gas field the Sunburst generally overlies a yellow shale, but is often in contact with the Cut Bank sandstone. Across the Sweetgrass arch the Sunburst directly overlies the Jurassic Ellis Group. The deposits of the Sunburst member have been interpreted as non-marine fluvial channel sandstone by Lukie (1999), sand deposited in a shallow-, fresh-, or brackish-water estuarine to deltaic environment by Glaister (1959) or as sand deposited in ribbons and sheets, where the ribbons are fluvial channel fill and the sheets are beach and offshore shoal sand by Farshori and Hopkins (1989). The type section for the Sunburst member is core from the Johnson No. 1 Johnson "D" well, NW $\frac{1}{4}$ NW $\frac{1}{4}$ Sec. 32, T. 35N., R. 1W., Toole County, MT from 1,220 to 1,245 feet (Rice, 1975).

Finally, the informal Moulton member is the last unit in the lower Kootenai section. The Moulton member has proven to be a marginal hydrocarbon producer. The Moulton member as described by Cobban (1955) is of mixed lithology including sandstone, siltstone, mudstone, and limestone. Oakes (1966) interprets the depositional environment as a lake to swamp setting with fluvial deposits. The type section for the Moulton member is core from the Montana Power No. 4 Farbo well, NW $\frac{1}{4}$ SE $\frac{1}{4}$ Sec. 3, T. 37N, R. 4W., Glacier County, MT from 2,388 to 2,485 feet (Rice, 1975).

Blackleaf Formation (Kbl)

Above the Kootenai Formation is the Colorado Group, which is divided into the Blackleaf Formation and the Marias River Formation. Further subdivision of the Blackleaf Formation depicts four formal members, the: Flood, Taft Hill, Vaughn, and Bootlegger. The stratigraphically lower and older Blackleaf Formation disconformably

overlies the Kootenai Formation. Cobban et al. (1976) describes the lower portion of the Blackleaf Formation as a “transgressive-regressive marine unit that marks the earliest appearance of the Early Cretaceous sea.” Three distinct lithologies described by Cobban et al. (1976) make up the lower portion of the Blackleaf Formation (Flood Member). These lithologies from oldest to youngest include a: (1) lower sandstone and siltstone unit of which has been interpreted as reworked sediment from the top of the Kootenai Formation, (2) middle carbonaceous shale, and (3) upper light-gray, poorly sorted siltstone to fine-grained sandstone.

Oil And Gas Fields

A number of maturing fields on the eastern flank of the Sweetgrass arch, in Toole and Liberty counties (Figure 10) produce from the Lower Cretaceous Sunburst member of the Kootenai Formation. Two prolific fields, the Fred & George Creek and Kevin-Sunburst, will be detailed in the subsequent chapters to better define reservoir characteristics and geometries. A brief description of these two fields and a table of other minor fields within the study area document historical production from the Sunburst member. (MBOG, 2012).

Fred & George Creek Oil and Gas Field

The Fred & George Creek oil and gas field was discovered in 1963 and produces from the Sunburst member of the lower Kootenai Formation and from the Jurassic Swift Formation. Productive reservoirs include incised valley-fill sandstone and “sheet sand” of the Sunburst member with minimal production from the Swift Formation “ribbon

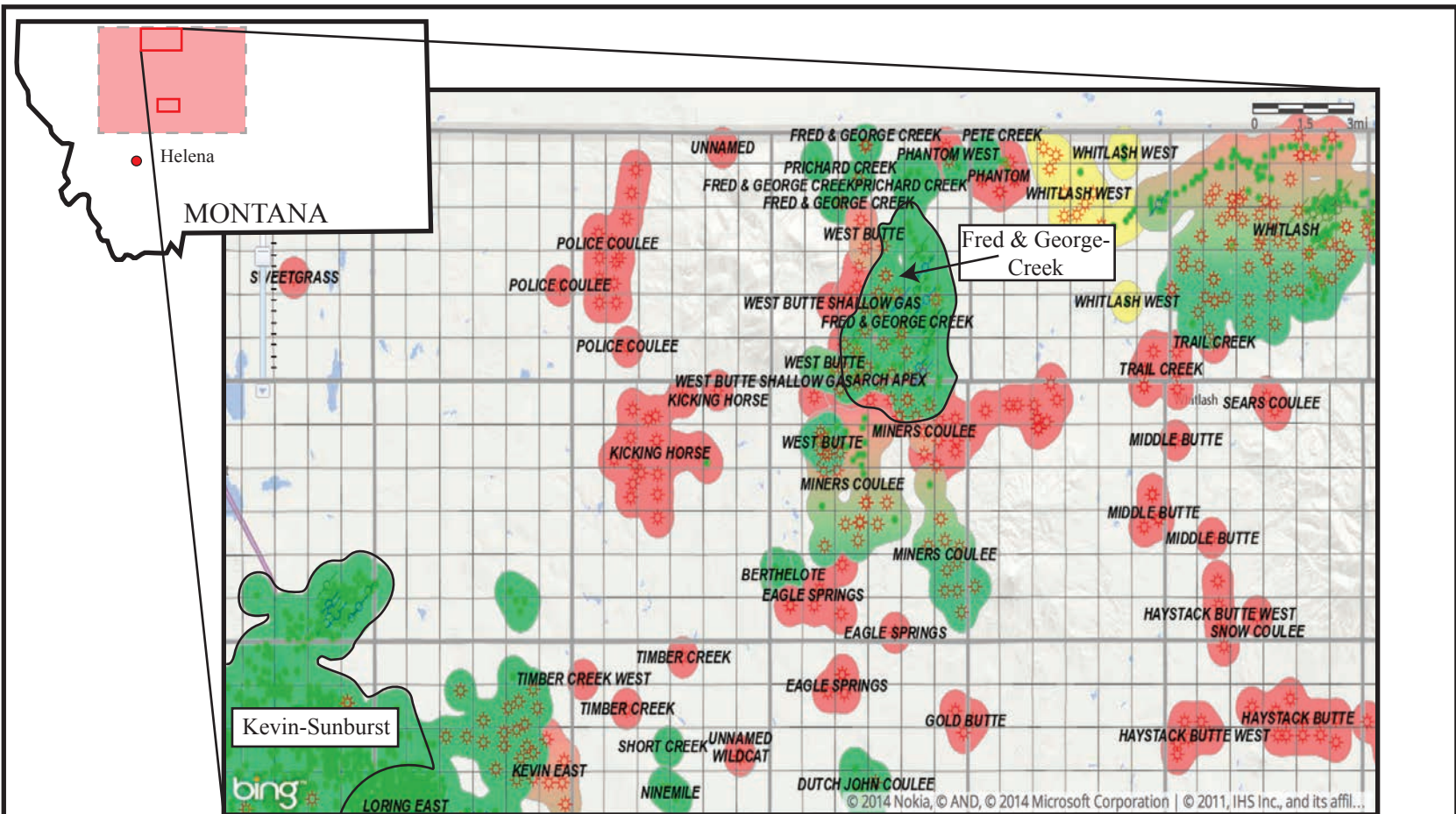


Figure 10. Subsurface study area map showing the location of oil and gas fields. The Fred & George Creek and Kevin-Sunburst fields are investigated in this study.

sand” (Branch, 1976). The field is approximately 3.62km (2.25mi) long and less than 1.6km (1mi) across or roughly 625 acres. The field is a structurally enhanced stratigraphic trap located on the east flank of the previously discussed Sweetgrass arch. Average well depths in this field are 786m (2,580ft) and the reservoir thickness varies from 6-18m (20-60ft) (Hughes, 2006). Cumulative production from well to well varies considerably, but the entire field to date has produced over 13 million barrels of oil and nearly 744,000 million cubic feet of gas (MBOG, 2012).

Kevin-Sunburst Oil and Gas Field

The Kevin-Sunburst oil and gas field comparatively is one of the largest in terms of areal extent and hydrocarbon production, in Toole and Liberty counties. The first commercially successful well, drilled in 1922, produced some 100BOPD from the Sunburst member (Jones, 1985). Since 1922, intermittent periods of exploration and development have taken place (1922-1944 / 1948-1972 / 1973-present) (Jones, 1985). Production has historically come from Cretaceous, Jurassic, Mississippian, and Devonian age strata in mainly stratigraphic traps with structural influence. Specifically, Jones (1985) reports production from the Cretaceous interval to be related to porosity lenses. To date the Kevin-Sunburst field has produced over 84 million Bbls of oil and more than 13 million MCF (post-1986) (MBOG, 2012).

Field Name	Oil and Gas Conservation Annual Report (2012)			Ave. per Well Production	
	<i>Cum. Sunburst GAS (MCF)</i>	<i>Cum. Sunburst OIL (Bbls)</i>	<i>Number of Wells</i>	<i>GAS (MCF)</i>	<i>OIL (Bbls)</i>
Amanda	35,239	0	4	8,810	0
Arch Apex	1,689	0	1	1,689	0
Berthelote	0	578	3	0	193
BlackJack	38,695	0	9	4,299	0
Border	3,399	0	1	3,399	0
Cutbank	9,729	749	14	695	54
Dutch John Coulee	57,678	7,392	4	14,420	1,848
Eagle Springs	834	0	1	834	0
Fitzpatrick Lake	3,328	0	1	3,328	0
Fred & George Creek	3,247	34,113	30	108	1,137
Grandview	0	6,114	2	0	3,057
Kevin Southwest	16,953	0	6	2,826	0
Kevin, East Gas	8,446	0	1	8,446	0
Kevin-Sunburst	60,662	19,918	96	632	207
Kicking Horse	3,458	0	3	1,153	0
Laird Creek	0	48	1	0	48
Miners Coulee	9,588	18,184	7	1,370	2,598
Phantom	3,432	0	2	1,716	0
Phantom, West	16,211	0	2	8,106	0
Prairie Dell	47,003	0	17	2,765	0
Prichard Creek	0	122	1	0	122
Snow Coulee	372	0	1	372	0
Timber Creek, West	823	0	1	823	0
Trail Creek	8,327	0	2	4,164	0
West Butte	204	253	2	102	127
Whitlash	19,179	0	2	9,590	0
Whitlash, West	12,296	796	7	1,757	114
Willow Ridge, South	81,353	31	2	40,677	16

CHAPTER 3

DATA AND METHODS

Introduction

A major strength of this study is the array of multi-scale data sets. While each data set has obvious limitations, which will be discussed later in this chapter, the ability to supplement well logs with core, outcrop, and thin section analysis provides a more balanced deduction of the study objectives. Due to the exceptionally large number of wells drilled in northwestern Montana, geophysical well logs constitute the most complete data set of this project and were relied on heavily for interpreting regional stratigraphy and paleo-geomorphic expression of the local valley-fill “container”. Core, outcrop, and geophysical well logs calibrated with petrophysical attributes were utilized to develop a model of how the valley filled and the distribution of facies within the valley-fill “container”. Finally, a portable X-Ray Fluorescence analyzer was used to distinguish the major- and trace-element geochemistry of 18 samples from three wells in order to determine if chemostratigraphy could be incorporated as a viable stratigraphic correlation technique. The following sections of this chapter will summarize the data and detail the procedures for how each data set was employed.

Geophysical Well Logs

The most abundant and heavily utilized data set in this study were geophysical well logs. The plains of northwestern Montana have been extensively, albeit

intermittently, drilled since the early 1920's. One of the first commercially successful oil and gas wells was drilled in what would become the Kevin-Sunburst field (Sec. 16, T. 35N., R. 3W) of Toole County, Montana. Gordan Campbell and associates drilled the well in 1922 (Collier, 1930). Four years later, drilling commenced in the Cut Bank Field in Toole County with the Sand Point Oil Company No. 1 Berger Well (Blixt, 1941). Since these initial discoveries, drilling has been pervasive in the region and continues today. Due to the lengthy period of oil and gas exploration and constant advancement of technology the quality of the available geophysical well logs vary considerably. The logs examined in this study were in raster image format and were interpreted using the geologic software Petra®.

Wells were available in every county in northwestern and north-central Montana. Specifically, wells in Cascade, Chouteau, Liberty, Pondera, Teton, and Toole counties were examined for regional and local subsurface cross-sections. Well spacing is often uneven due to the inherent nature of trapped hydrocarbons and clustered production wells, but within the subsurface study area 106km x 48km (66mi x 30mi) or roughly 55 townships, 2987 wells were available for investigation, or a well log density of nearly 50 per township.

The most abundant and useful geophysical curves available included the gamma ray (GR), spontaneous potential (SP), shallow resistivity (R_s), deep resistivity (R_d), and neutron porosity (NPHI). For the purposes of this study, the gamma ray tool was assumed to be an indicator of lithology. While this assumption is common, the gamma

ray tool actually measures the natural gamma radiation of uranium, potassium, and thorium in the rock adjacent to the borehole. More argillaceous facies commonly have higher amounts of natural gamma radiation while clean sandstone is generally low. Thus, lithology can be assumed and stratal correlation of inferred lithologic units can be made.

SP is another common geophysical well log used to infer lithology. Left deflection of the SP log indicates more permeable units like sandstone and flat-line curves denote shale. However, the gamma ray tool is preferred as SP is actually a measure of the electric potential difference between the rock adjacent to the borehole and the surface. The gamma ray also has much better vertical resolution valuable in distinguishing thin beds.

Resistivity logs measure the conductivity of the adjacent subsurface rock. There are many variations of the resistivity tools, but the basic information recorded on the log portrays the absence or presence of fluids. Resistivity logs can be used to calculate the saturation of hydrocarbons or water in a reservoir, but are less useful in correlation and lithology identification.

While most of the wells in the study area have a combination of gamma ray, SP, and resistivity logs, wells with neutron porosity logs are much less common. Neutron porosity logs work by the bombardment of neutrons into the rock and the subsequent measurement of returning radiation following collisions with hydrogen atoms in formation water or oil.

Using well logs, the stratigraphic interval of interest was first partitioned into lithostratigraphic units. Lithostratigraphy provides commonplace nomenclature useful when comparing previous studies and is a widely recognized form of stratigraphy whereas sequence stratigraphy has been deemed only an informal method (Owen, 2009). Group, formation, and member picks were based on lithologic descriptions from previous outcrop and core investigations and matched with well log signatures.

Sequence stratigraphic surfaces, such as sequence boundaries and flooding surfaces were then picked in order to construct a chronostratigraphic framework. The sequence stratigraphic picks were made in both the Fred & George Creek and Kevin-Sunburst fields and immediately surrounding townships. Cross-sections were constructed representing depositional dip and strike through both oil and gas fields. A grid of subsequent cross-sections was constructed and continuously looped to the original cross-sections to maintain consistency. Regional cross-sections from the subsurface study area to analogous outcrops near Great Falls, MT were also constructed. From the cross-sections, stacking patterns of reservoir units and the behavior of genetically associated packages could be inferred.

Finally, isochore maps were constructed using the contouring capabilities of Petra®. Contour map limits were set to include the 55 townships for lithostratigraphic elements and to the immediate townships surrounding the Fred & George Creek and Kevin-Sunburst Fields for sequence stratigraphic picks. The maps were used to determine the influence of structural entities on stratigraphic units and to map valley-fill deposits, highlighting regions where productive reservoir trends. Both types of maps

were used to resolve the development of incised valley-fill systems both physically and temporally.

Drill Core

The drill cores examined in this study were located through the geologic software Petra® and cross-referenced with the USGS Core Research Center (CRC) in Denver, CO to determine availability. A criteria checklist was utilized to determine whether or not each core was suitable for description. The following criteria were considered when searching for suitable core: proximity to the study area, the stratigraphic interval the core penetrated, and if there were associated geophysical curves that could be calibrated. However, the limited number of available core in the region led to more lax selection criteria.

Eight cores in total were described from the subsurface study area (Figure 8). Of the eight cores four were from the Sunburst member. Two of the Sunburst member cores were incised valley-fill a third and the fourth were interpreted to be a fine- to medium-grained sandstone above the valley-fill and a paleosol respectively. Of the remaining four cores, three were from the Jurassic Swift Formation and the final core came from above the Sunburst member. In total, 76.2m (250ft) of core was described. When describing the cores important features cataloged (when possible) included: composition, texture, grain size, sedimentary structures, relative oil staining, unit thickness, and contact relationships. The cores will be referred to using their CRC#.

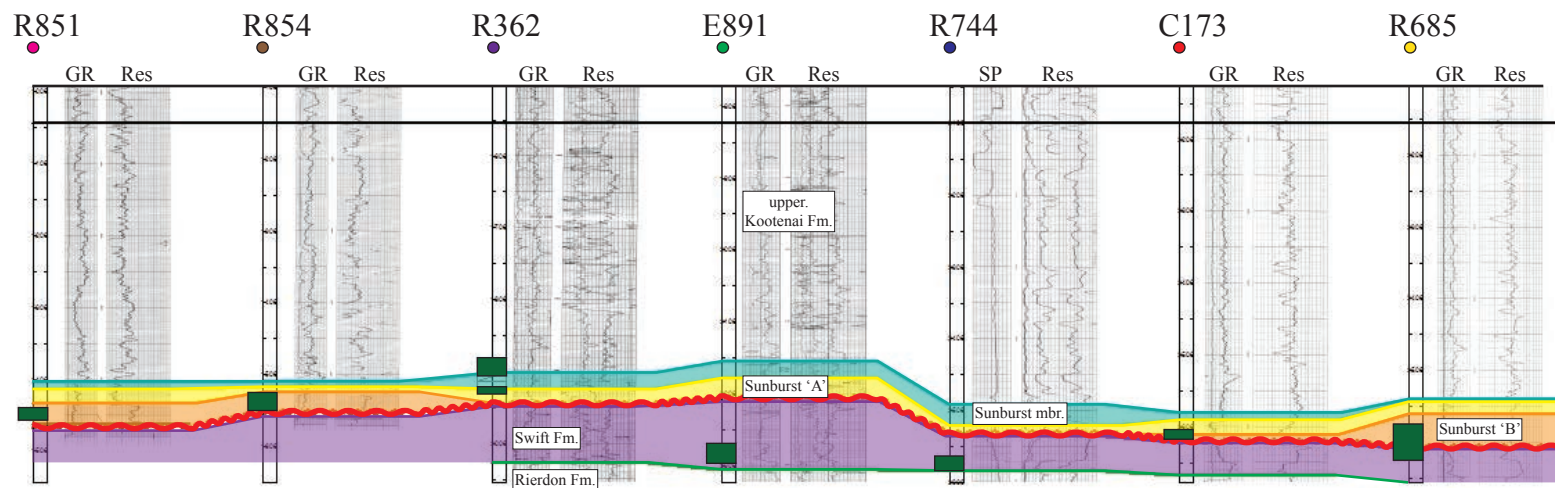
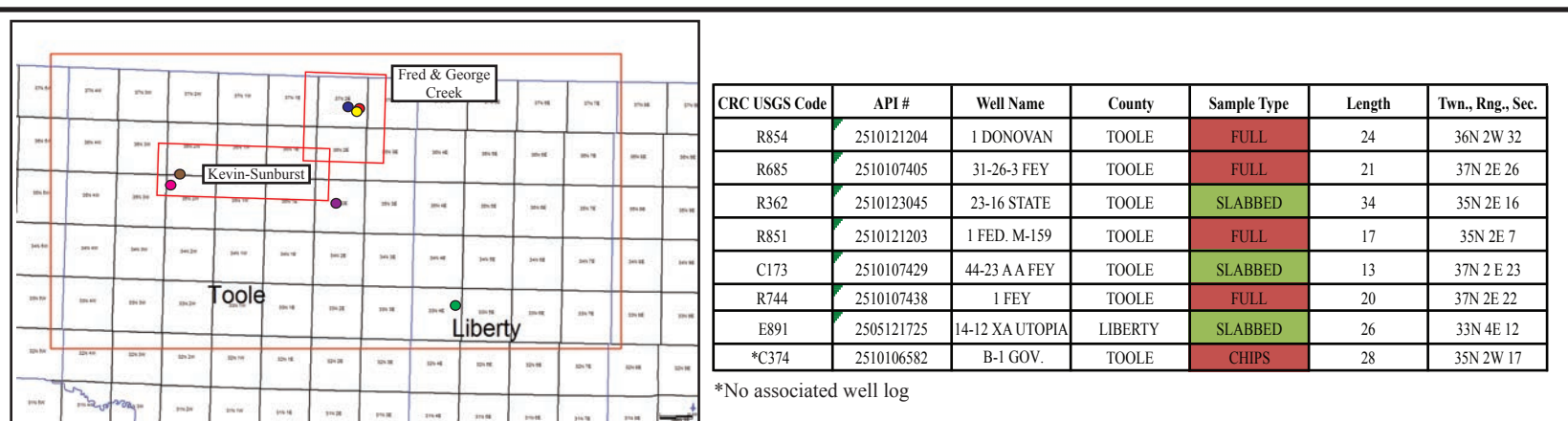


Figure 11. Subsurface study area map showing the location of wells with cores described in this study. The table lists the core sample type and identification information. A cross-section of the wells with core illustrate the lithostratigraphic interval each core was recovered from.

Outcrop

The outcrop described in the study area was found through Walker's (1974) comprehensive investigation of the Jurassic Morrison and Cretaceous Kootenai Formations. The field investigation included characterizing lithofacies, delineating the stratigraphic architecture, and collecting samples to be analyzed with a portable X-ray fluorescence analyzer. Due to the nature of the outcrop, which is along the steep valley walls of the Missouri River numerous gigapixel images were taken, as sections of the outcrop were sometimes inaccessible. A Jacob's staff, a 50-meter tape measure, a rock hammer, and a field notebook were essential field items used to collect and manage data.

Thin Sections

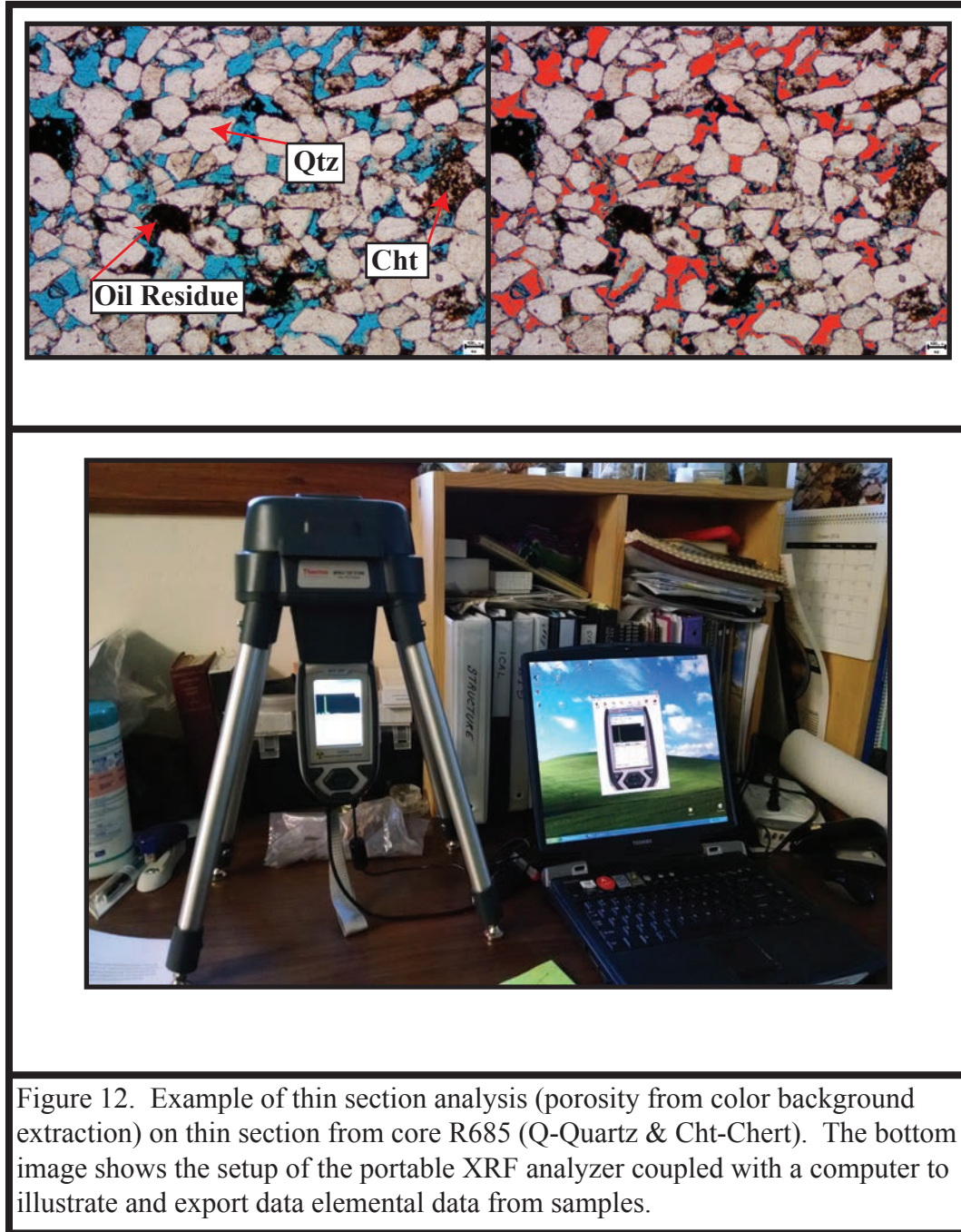
Twenty thin sections were analyzed in this study. The limited collection of thin sections directly relates to the availability of core from which all the samples were collected. Each sample was prepared with a blue vacuum impregnation and a sodium cobaltnitrite staining for potassium feldspar identification by National Petrographic Service, Inc. Porosity was calculated in three wells from drill cores R851 and R854 (Kevin-Sunburst Field) and R685 (Fred & George Creek Field), using the software JMicroVision 1.2.7. The percentage of available porosity was calculated by color background extraction (where pore space impregnated with blue epoxy was shaded red and the percentage of red occupying the total thin section view was calculated and considered roughly equal to porosity).

Portable X-ray Fluorescence

Using the pXRF 30 samples were analyzed. The pXRF used is a ThermoScientific Niton XL3t portable XRF analyzer. In this study, the analyzer was interfaced with a PC to view, manipulate, and export data (Figure 9). The analysis collected concentrations of 44 elements in parts per million (ppm) in the *TestAllGeo* analysis setting. Data acquisition time was 120 seconds per sample and three shots were taken of each sample and later averaged to account for heterogeneity in the rock. An optical picture of the sample through the viewing window, an elemental spectra, and element concentrations were produced for each shot. For this project, only the element concentrations were utilized. Data was exported to Microsoft Excel in comma-delimited format and later organized by sample and desired elements.

A number of element concentrations were investigated, but the most common rock forming minerals for sedimentary rocks were selected (Al, Ca, Fe, K, Mg, Ti, and U). Uranium (U) was chosen as it can be used to correlate with the gamma-ray geophysical well log curve if thorium and potassium are accounted for. Similarly, three major elements (Al_2O_3 , K_2O , and TiO_3) were investigated. The major elements were converted from a conversion table and the abundance of trace elements reported by the pXRF data.

In order to better determine if a chemostratigraphic method could be incorporated into the broader study, a pseudo well had to be constructed from three different wells. The pseudo well had samples from wells R362 (above the reservoir), R851 (reservoir), and E891 (below the reservoir). Knowing that the samples were from different locations,



but retained a similar stratigraphic order an assumption was made that by combining the samples a pseudo-type well could be constructed.

Data Assumptions

While a variety of data sets were used in combination to establish the most accurate and detailed descriptions possible, a number of assumptions and limitations associated with each data set must be addressed and will provide a context for which this study can be evaluated.

As previously mentioned, the enormous collection of wire-line well logs from northwestern Montana provided this project with the most complete dataset with which to investigate the subsurface. However, because of the extensive history of oil and gas exploration in this region, many of the well logs vary in image quality, scale, and tool availability.

The drill cores used in this research had significant limitations. Firstly, because coring is often an expensive endeavor, long coring runs capturing multiple chronostratigraphic surfaces, most useful for a study of this nature, are nonexistent. More often, coring appears to have been restricted to reservoir intervals, limiting variation in facies to mainly productive sandstone. Secondly, many of the available cores are unslabbed leading to difficulty in recognizing sedimentary structures apart from core recovery tool marks.

While the outcrop along the valley walls of the modern Missouri River and its tributaries provide exceptional exposures of un-deformed Lower Cretaceous strata the

distance between the subsurface study area and outcrop is nearly 150km (100mi). Thus, a number of assumptions regarding lateral variations in depositional environment and physical processes must be accounted for.

CHAPTER 4

LITHOFACIES, FACIES ASSOCIATIONS, AND ELECTROFACIES

Introduction

A major goal of this project was to determine the presence and quality of productive subsurface reservoir intervals within the informal members of the Lower Cretaceous Kootenai Formation. Outcrop and drill core were described in order to evaluate the lithofacies present within this stratigraphic succession. Lithofacies are defined by Scheihing and Atkinson (1992) as “subdivisions of a sedimentary sequence based on lithology, grain size, and stratification that bear a direct relationship to the depositional processes that produced them.”

The following questions were considered during lithofacies analysis:

- 1.) Which lithofacies are productive reservoirs?
- 2.) Is there a unique arrangement or distribution of lithofacies in the lower informal members of the Kootenai Formation that influence reservoir quality?
- 3.) Are the lithofacies present congruent with other studies and models documenting incised valley-fill systems?

This chapter classifies the lithofacies that characterize the sedimentary rocks comprising the stratigraphic interval previously introduced. The lithofacies scheme emulates Miall (1978), but includes lithofacies from continental (terrestrial), marginal marine, and marine environments. The lithofacies schemes by Lukie (1999) and Ardies

(1999) were similarly considered as they investigate the same lithostratigraphic interval across the border in Canada.

After breaking out lithofacies, groups of lithofacies or facies associations were defined according to interpreted depositional processes and hydrodynamic forces. A depositional model populated with lithofacies associations observed in this study was constructed and is incorporated into the stratigraphic framework in subsequent chapters.

This chapter is laid out accordingly, a table summarizing the lithofacies of the project (Table 2 and Table 3), a succinct write-up detailing lithofacies observations, with photos of the lithofacies being described, a section describing the grouping of lithofacies into lithofacies associations and interpreted depositional environments, and finally, a section on drill core facies calibrated to associated well logs (electrofacies).

Lithofacies

Facies F1 (Cglm.): Conglomerate

Facies F1 is characterized as a granule to cobble conglomerate that is matrix supported (Figure 13). Clasts are sub-rounded to rounded and range in size from 3 to 63.5mm. Generally, the clasts are polymodal and extraformational, but one instance of unimodality occurs where all clasts are small pebbles (<10mm). The composition of the clasts from most to least common include: light to dark grey and brown mudstone; some with pyritized areolas, black carbonaceous nodules, dark red iron nodules, and some intraformational quartz and chert clasts. The mudstone clasts appear to be flattened and have faint normal grading. The thickness of F1 deposits vary from 0.15m (0.5ft) to a

Code	Facies (Name and Color Scheme)	Lithology, Grain Size	Sedimentary Structures	Other Notes	Hydrodynamic Processes
F1 (Cglm)	Conglomerate	Medium sand matrix- supported gravel	Faint normal grading Horizontal bedding, slight imbrication	Clasts are chert, iron, or ductile light grey to brown mudstone; sizes range from pebble to cobble; often some pyritization around mudstone clasts	Rip-up from substrate or erosion of bank deposited as bedload during current or turbulent flow
F2 (St)	Trough cross- bedded sandstone	Sand, fine to coarse	Trough and tabular cross-beds	Stratification is observable due to differential sorting of quartz and chert	Unidirectional current, lower flow regime, migrating 3- D dune bedform
F3 (Sp)	Planar cross- bedded sandstone	Sand, medium	Planar beds	Stratification is observable due to or differential erosion between forsets	Unidirectional current, lower flow regime, migrating 2- D dune bedform
F4 (Sr)	Ripple cross- laminated sandstone	Sand, fine to medium	Critically(?) climbing ripples; Symmetrical, flat- topped, straight to sinuous wave ripples	Irregular interbedded sandstone and mudstone; some pyritized and carbonaceous clasts; siderite common; moderately sorted; clay cements; upward fining	Uni- and bi- directional current, lower flow regime, migrating ripple bedform
F5 (Sh)	Hummocky sandstone	Sand, fine to medium	Hummocks	Sandstone is buff to tan colored, bedding is gently dipping at ~12° or less	Bedforms form under strong oscillatory wave surges during storms

Code	Facies (Name and Color Scheme)	Lithology, Grain Size	Sedimentary Structures	Other Notes	Hydrodynamic Processes
F6 (Sm)	Massive sandstone	Sand, medium	Massive (no sedimentary structures visible, possibly due to limited width and unslabbed drill cores)	Appearance of "rusty beds" and cementation	Rapid deposition or bioturbation
F7 (SFh)	Interbedded sandstone, siltstone, and mudstone	Sand, silt, mud	and Flaser bedding (sandstones: planar beds and isolated current ripples; siltstones: planar laminated to	Sandstone can be light grey to buff colored, siltstone and mudstone light to dark grey and maroon	Intermittent periods of high current flow and quiescence (suspension settling)
F8 (Fm)	Massive siltstone and mudstone	Silt, mud	Massive	Dark grey to black, can be mottled and oxidized , well or poorly consolidated	Suspension settling
F9 (P)	Pedogenically altered mudstone	Paleosol	Lacking sedimentary structures, but crumbly and rubbly, some rootlets	distinctive light grey and red to purple or dark grey beds	Pedogenesis

Facies F1 (Cglm) - Conglomerate



Figure 13. Conglomerate in core R362 and in outcrop near Ryan Dam northeast of Great Falls, MT.

maximum thickness of 0.76m to (2.5ft) and in outcrop exhibit horizontal to low-angle bedding.

Hydrodynamic Interpretation:

Due to the appearance of normal grading and flattened mudstone clasts, this facies would have been deposited by high energy flows ripping up underlying muds and transporting clasts as bed load during times of increased flow velocity (Miall, 1996, pg. 100).

Facies F2 (St): Trough Cross-Bedded Sandstone

Facies F2 is characterized by trough cross-bedded medium to coarse grained sandstone (Figure 14). The sandstone is dominantly composed of quartz and chert, is sub-angular to sub-rounded, and well sorted. Differential sorting of quartz and chert reveals trough foresets and the process of lee-slope avalanching. Trough cross-bedding was observed in core E891 with total co-set thicknesses of 3-5cm and in outcrop with set thicknesses ranging from 0.15-1.1m (0.5-3ft).

Hydrodynamic Interpretation:

Trough cross-bedding in Facies F2 was deposited by the migration of 3-D dunes in a unidirectional current (Harms et al., 1975). The depth of the current must have been greater than a few decimeters (Harms et al., 1975) and within the lower flow regime. Asymptotic foresets in the trough cross-bedding is related to high water stage and the development of a strong separation eddy (Collinson, 1970).

Facies F2 (St) - Trough cross-bedded sandstone



Figure 14. Trough cross-bedded sandstone in core E891

Facies F3 (Sp): Planar Cross-Bedded Sandstone

Facies F3 is characterized by planar cross-bedded fine to coarse-grained sandstone (Figure 15). The sandstone is dominantly composed of quartz and chert, is sub-angular to sub-rounded, and well sorted. The foresets range from asymptotic to angular. Foresets were noticeable due to differential erosion, most likely related to finer-grained material, which once mantled the eroded portion of the foresets.

Hydrodynamic Interpretation:

Planar cross-bedding occurs in a similar unidirectional current as trough cross-bedded sandstone (F2), except by the migration of 2-D instead of 3-D dunes (Harms et al., 1982). While both 2-D and 3-D dunes can form within flow depths >0.05m to 10m (2inches to 32ft), 3-D dunes require higher flow velocities (Harms et al., 1982). The variation of asymptotic to angular forests see in Facies F3 is cause by fluctuating energy of a separation eddy during intermediate water stage (Collinson, 1970).

Facies F4 (Sr): Ripple Cross-Laminated Sandstone

Facies F4 is characterized by current and wave ripple cross-laminated sandstone (Figure 16). The light grey to tan or buff sandstone is fine- to medium-grained, moderately to well sorted, and sub-angular to sub-rounded. The bed thickness varies between 10's of cms to 1m and is commonly separated by planar laminated beds of similar thickness. Mud drapes are common. The ripple heights range from 1-4cm (0.4-1.6in). Current ripple-laminated sandstone is differentiated from the less common wave

Facies F3 (Sp) - Planar cross-bedded sandstone

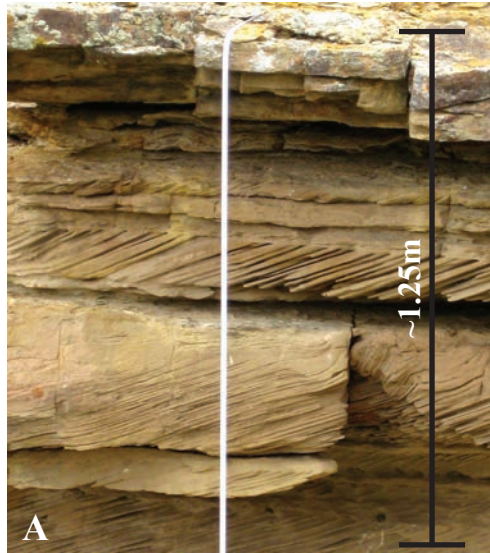


Figure 15. Planar cross-bedded sandstone in outcrop northeast of Ryan Dam.

Facies F4 (Sr) - Ripple cross-laminated sandstone



Figure 16. Ripple cross-laminated sandstone in outcrop southeast of Morony Dam. The lower right photograph depicts ripple form sets.

ripple-laminated sandstone by asymmetry and regular bifurcation (Reineck and Singh, 1975, Fig. 29)

Hydrodynamic Interpretation:

Ripple cross-lamination forms under lower flow regime conditions and rapid sedimentation as ripple forms migrate (Leeder, 1982). Flow velocity for ripple migration is generally low and they may form in both unidirectional current and oscillatory wave conditions (Boggs, 2001, pg. 98). Flaser and lenticular bedding (Reineck and Wunderlich, 1968) also occur in Facies F4 and are related to fluctuating hydraulic conditions where sand is deposited during periods of current activity and mud is deposited during quiescence. Flaser bedding is more sand rich than lenticular bedding where rippled sandstone becomes isolated between layers of mudstone.

Facies F5 (Sh): Hummocky Cross-Bedded Sandstone

Facies F5 is only observed at one location in this study area (Figure 17). The sandstone is comprised of fine- to medium-grained, well-sorted grains and occurs in 10-20cm (3.9-7.8in) beds. The bedding is gently dipping at 12° or less.

Hydrodynamic Interpretation:

Hummocky cross-bedding was first introduced by Harms et al. (1975), but interpretations for its formation is still debated (Dumas and Arnott, 2006). Many suggest that these bedforms form under strong oscillatory wave surges during storms (Dott and Bourgeois, 1982; Cheel and Leckie, 1993). The surges scour the

Facies F5 (Sh) - Hummocky sandstone



Figure 17. Hummocky sandstone in outcrop southeast of Morony Dam.

seabed into antiformal hummocks and synformal swales. Oscillatory waves are generated from storms in near-shore and outer-shelf facies (Dott and Bourgeois, 1982).

Facies F6 (Sm): Massive Sandstone

Massive sandstone is found both in core and in outcrop (Figure 18). In both settings the sand grain size ranges from fine to medium and is moderate- to well-sorted. The sand exhibits a “salt and pepper” appearance, which can be attributed to its constituents of quartz and black chert. Facies F6 also has some minor clay cementation and the appearance of “rusty beds”. Carbonaceous debris, most likely carbonized vegetation, is commonly found within Facies F6, but is often less than 5% of the total rock composition.

Hydrodynamic Interpretation:

Two possible processes for the deposition of massive sandstone include rapid deposition from suspension following a flood event and post-depositional modification due to bioturbation (McCabe, 1977). The noted lack of bioturbation and presence of carbonaceous material indicates that this facies was deposited quite rapidly following a river flood. However, Facies F6 is most commonly observed in un-slabbed core with minor to heavy oil staining, which could possibly be obscuring sedimentary structures.

Facies F7 (SFh): (Heterolithic) Interbedded Sandstone, Siltstone, and Mudstone

The composition of this lithofacies includes interbedded mudstone and medium grained sandstone that is subangular to sub-rounded and generally well sorted (Figure

Facies F6 (Sm) - Massive sandstone



Figure 18. Massive sandstone in core R362 (A & C) and from outcrop with carbonaceous plant material (B) near Ryan Dam.

19). The sandstone can be light grey to buff colored and have bed thicknesses of cm's to tens of cm's. Wavy to lenticular bedding with ripples are encapsulated in mudstone. The siltstone and mudstone of this group ranges from light grey to dark grey and maroon with bed thicknesses on the order of cm's to tens of cm's.

Hydrodynamic Interpretation:

Facies F7 was deposited in acutely fluctuating flow velocities from suspension and weak traction currents (Miall, 1996, pg. 99). While horizontal bedding is common and due to suspension, small ripple cross-lamination is also observable due to ripple migration.

Facies F8 (Fm): Massive Mudstone

Two types of massive mudstones characterize Facies F8 (Figure 20). The first occurs exclusively in outcrop, is poorly consolidated, and is a light to dark grey silty mudstone. This mudstone can be very thin to massive bedded and is sometimes mottled and oxidized. Faint horizontal stratification is sometimes observed. The second massive mudstone occurs in core and is dark grey to black, well consolidated and has no visible sedimentary structures.

Hydrodynamic Interpretation:

Facies F8 was deposited by suspension settling in quiet water. Faint horizontal stratification suggests periods of very weak flow conditions, separated by consistent quiescence.

Facies F7 (SFh) - Interbedded sandstone, siltstone, & mudstone
(heterolithic)



Figure 19. Interbedded heterolithic strata in core E891 (A) and in outcrop near Morony Dam (B) and near Ryan Dam (C).

Facies F8 (Fm) - Massive mudstone



Figure 20. Massive mudstone found in core E891 (A) and near Ryan Dam (B & C)

F9 (P): Pedogenically Altered Mudstone

Facies F9 is comprised of pedogenically altered fine-grained siliciclastic material (Figure 21). This facies appears in core C173 and in outcrop and lacks any distinctive sedimentary structures, but has a massive to rubbly, slightly blocky texture. In outcrop F9 has distinctive light grey and red to purple or dark grey beds. In core F9 is dark grey and contains pebble sized mudstone clasts that are light grey, as well as, black carbonaceous material, likely rootlets.

Hydrodynamic Interpretation:

Facies F9 appears to be a ferruginous or ferralitic palaeosol. The massive to rubbly, slightly blocky texture with rootlets and the alternating grey to red and purple coloration suggests the development of a soil horizon with goethite and hematite (Besly and Fielding, 1989; Retallack and McDowell, 1988).

Facies Associations, Depositional Process, and Interpretation

Five lithofacies associations have been identified based on the grouping of nine lithofacies observed in this study, which comprises the Jurassic Swift Formation and Lower Cretaceous Kooteani Formation. The grouping of lithofacies into facies associations is used to interpret depositional environments.

FA1: Description – Shoreface (Lower to Middle)

FA1 is composed of the lithofacies ripple cross-laminated (Sr), hummocky sandstone (Sh), heterolithich sandstone, siltstone, and mudstone (SFh), and massive

Facies F9 (P) - Pedogenically altered mudstone



Figure 21. Pedogenically altered mudstone (Paleosol) in core C173 and in outcrop near Ryan Dam.

mudstone (Fm) (Figure 22). FA1 is unconformably overlain by FA5 and where exposed is the lowest FA observable. The thickness of the exposed succession of FA1 was estimated from a photo panel at roughly 20m (65.6ft). In this study, the upper portion of the succession was inaccessible so the lower portion is more accurately described and measured with a thickness of 4.6m (15ft). FA1 is also observed in 7.9m (26ft) of core E891. This facies association contains laterally extensive, coarsening upward successions of maroon mudstone with hummocky and rare ripple laminated sandstones. Individual beds of sandstone ranged from medium to massive and were very well sorted, rounded, and composed almost entirely of quartz. The ichnogenera of the ichnofacies *Cruziana*, was observed in core E891.

FA1: Interpretation

FA1 in outcrop is interpreted to represent a middle to upper shoreface depositional environment. The tabular and lateral extensiveness, wave ripples, planar heterolithic beds and coarsening upward nature of the sandstones are indicative of this environment. (Walker, 1984). In core E891, the lower shoreface is interpreted. The core is much more muddy and with limited ripples and the ichnogenera *Planolites*, which is associated with locomotive and feeding behavior (MacEachern et al., 2007).

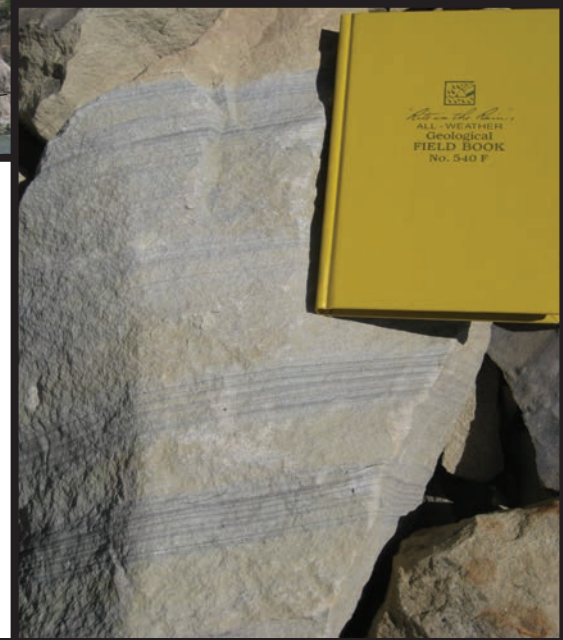
FA2: Description – Fluvial Channel Fill

FA2 is comprised dominantly of trough cross-bedded sandstone (St) and massive sandstone (Sm), includes the conglomerate lithofacies (Cglm), and minor beds of massive mudstone (Fm) (Figure 23). The thickness of FA2 in outcrop is 6.1 to 9.1m (20-30ft) and

Facies Association FA1 - Shoreface



Figure 22. FA1 is interpreted to represent a lower to middle-lower shoreface depositional environment. The sandstone beds in the figure at the top are tabular, lateral extensiveness, and fine upward.



Facies Association FA2 - Fluvial channel fill



Figure 23. Fluvial channel fill in outcrop near Ryan Dam and in core R685. Intraformational flattened shale-clasts near the base of trough cross-stratified cosets and trough cross-stratified sandstone is observable in this FA.

in core has a minimum thickness of 5.5 to 8.2m (18-27ft). In outcrop the thickness of the beds decreases stratigraphically upwards and more thin beds of lithofacies Fm are present. The grain size does fine upward in some instances, but it was not consistently observed throughout the outcrop. Commonly, the conglomerate lithofacies is positioned above an erosional surface, which demarcates the base of FA2, but the conglomerates were also observed higher in the succession where internal higher order erosional surfaces exist.

Trough cross-bedded sandstone (St) and massive sandstone (Sm) overlie the conglomerate in outcrop and are composed primarily of quartz and black chert, which exhibits a “salt and pepper” appearance, a common description of Kootenai Formation sands. The observable sedimentary structures in the sandstone lithofacies comes entirely from outcrop as the sandstone in core appears massive or are heavily oil stained and unslabbed. Typically, the sandstones are separated by erosional surfaces that indicate changes in lateral accretion direction. Massive mudstone (Fm) sometimes overlies these erosional surfaces and is much more common towards the top of this association.

At the base of FA2 is the sub-Cretaceous unconformity. Directly overlying FA2 is an estuarine system that is broken into three separate facies associations. The transition between FA2 and the estuarine system appears to be conformable and gradational. However, the deposits of the estuarine system are much thinner, have higher mud to sand content, and a variety of different sedimentary structures indicating changing hydrodynamic conditions.

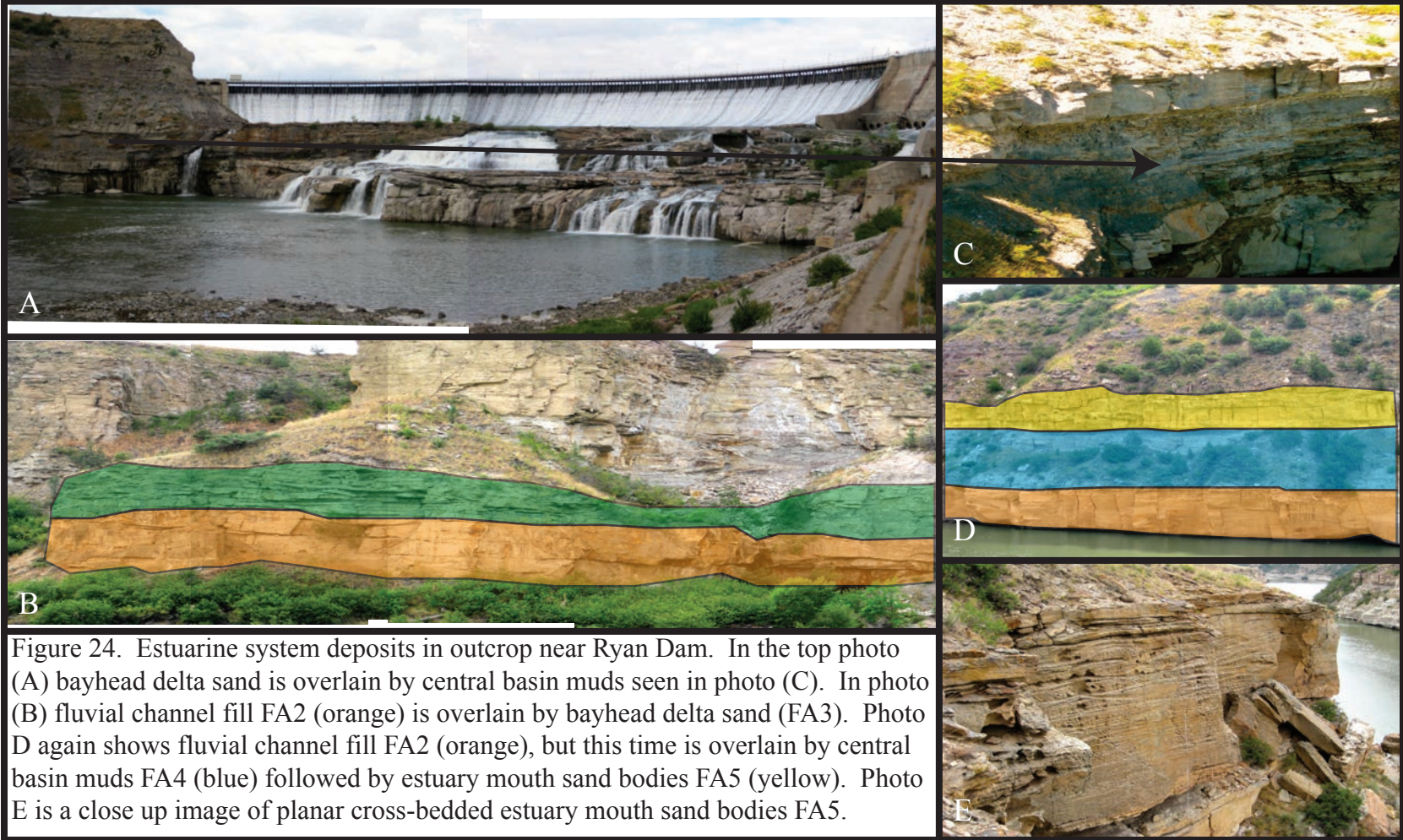
FA2: Interpretation

FA2 is interpreted to represent the fill of a fluvial channel. The presence of intraformational flattened shale-clasts near the base of trough cross-stratified cosets is indicative of cutbank erosion during channel avulsion (Miall, 1992) and the presence of trough cross-stratified sandstone indicates the migration of 3-D dunes across the channel floor as bedload transport. The fluvial channel system does not show pervasive fining-upward successions and sedimentary structures, such as planar cross-stratification and ripples, but aligns with the basal portion of Miall's (1996, Fig. 8.8) sandy meandering profile. The cause of the missing upper succession could be due to the amalgamation of channels in a low accommodation or tightly confined setting where the upper fine sediments have been repeatedly truncated (Lukie, 1999).

Estuarine System

Facies Associations FA3, FA4, and FA5 are all interpreted to represent a mixed wave and tide dominated estuarine system (Dalrymple et al., 1992) (Figure 24). The facies associations within the estuarine system are similar to the facies model developed by Allen and Posamentier (1994) based on the Gironde estuary in France. FA3 and FA4 are interpreted to represent the inner estuary, while FA5 would be located near the estuary mouth of this model. The estuarine system deposits described here are comprised of trough cross-bedded sandstone (St), planar cross-bedded sandstone (Sp), ripple cross-laminated sandstone (Sr), heterolithic sandstone, siltstone, and mudstone (SFh), and massive mudstone (Fm).

Estuarine System: Facies Association FA3, FA4, & FA5



FA3: Description – Bayhead Delta

FA3 locally occurs above FA2 and is composed of planar cross-bedded sandstone (Sp), ripple cross-laminate sandstone (Sr), and heterolithic sandstone, siltstone, and mudstone (SFh). The thickness of FA3 ranges from 2m to 13m (6.5ft to 42.6ft) and is on average ~6m (19.6ft). The thickness was estimated from one tape-measured section and applied to the outcrop on a photo-panel. FA3 is comprised of numerous stacked lenticular or channel forms, which are generally <4m (13.1ft) and are dominated by quartz-rich fine to medium grained sandstone with intervening beds of SFh. Planar cross-bedding along with cross-bedding, ripples, and mud drapes are common. Schwartz and Vuke (2006), documented moderate to abundant bioturbation, but individual ichnofacies were unidentified.

FA3: Interpretation

FA3 is interpreted to represent tidal dominated estuarine sand and mud in the inner estuarine portion of the facies model proposed by Allen and Dalrymple (1992). Tabular, ripple-laminated, coarsening-upward, sandstone deposits are interpreted to represent bay head deltas. Lenticular fining-upward, fine- to medium-grained, ripple-laminated sandstone with minor mud drapes, and more heterolithic strata is indicative of tidal channels where tidal fluvial energy has waned and tidal currents being to dominate (Allen and Posamentier, 1994).

FA4: Description – Central Basin Mud

FA4 occurs either above FA2 or above FA3 and is composed dominantly of massive mudstone (Fm) and has minor ripple cross-laminate sandstone (Sr). The thickness of FA4 was estimated from a photo-panel, but can range from 3m to 6m (12ft to 20ft). Moderate bioturbation, is observable in thin beds of ripple-laminated sandstone and horizontally inclined mud and siltstone.

FA4: Interpretation

The abundance of fine-grained dark organic rich muds with moderate bioturbation is indicative of an open water low energy region of a lagoon or estuary (Dalrymple et al., 1992). The gradational contact with underlying bay head delta deposits (FA3) indicates a central basin region within an estuarine system.

FA5: Description – Mouth Sand Bodies

FA5 occurs above FA4 exclusively and is comprised of planar cross-bedded sandstone with minor thin beds of massive mudstone (Fm). FA5 is characterized by a thick succession of medium grained, well sorted, quartz dominated, stacked planar cross-stratified sandstones. The total thickness of FA5 ranges from 7.6m to 12.5m (25ft to 41ft), with average cross-stratified set thicknesses of 0.9m (3ft). The beds of the stacked cross-stratified sandstones retain consistent thickness until the top of the succession where thin beds of massive mudstone (Fm) become more abundant.

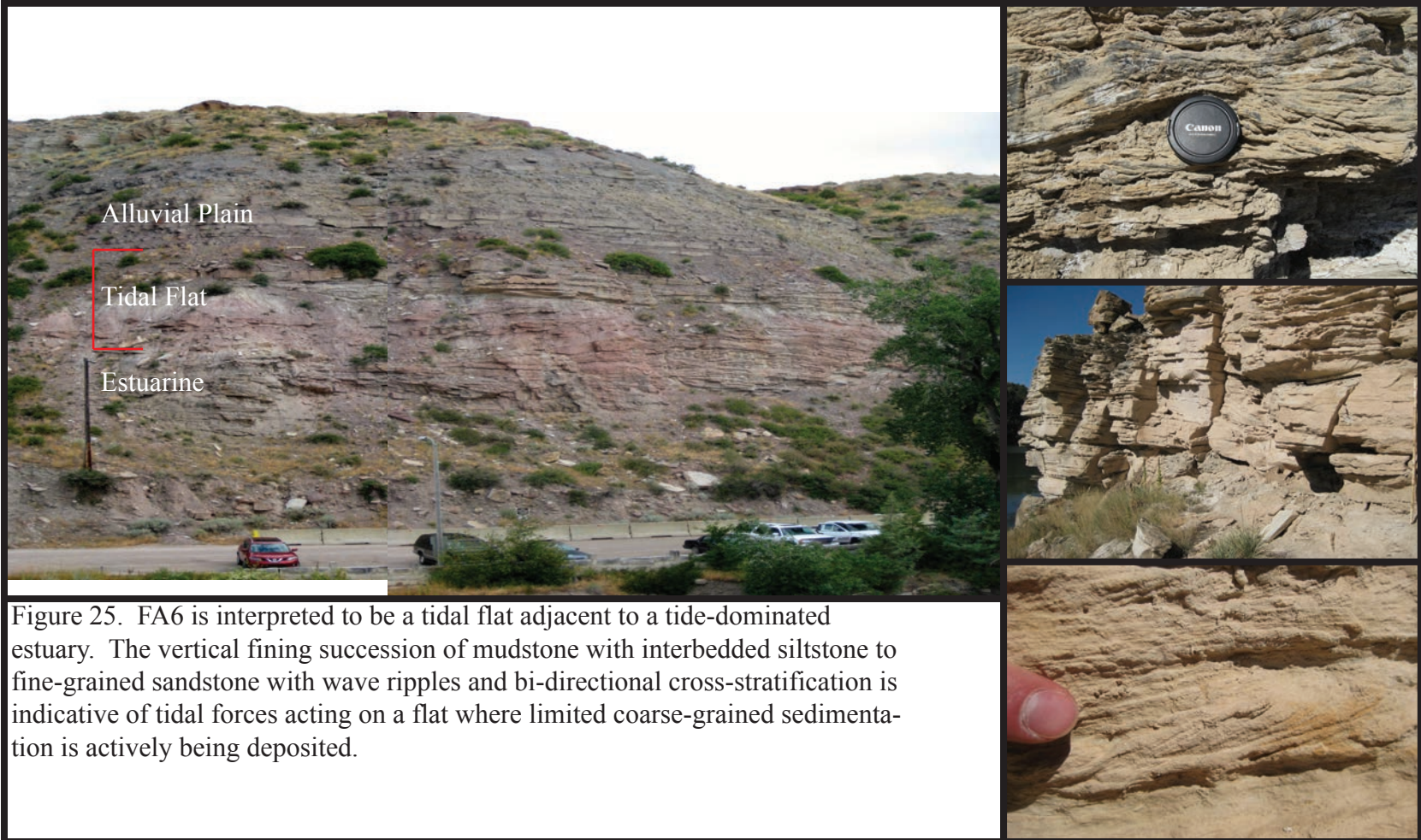
FA5: Interpretation

FA5 is interpreted to represent estuary mouth tidal-channel, subtidal shoals, and/or tidal-delta sand deposits. The presence of well sorted, quartz dominated, medium-grained sandstone is indicative of high-energy. In this case waves and minor tidal currents are interpreted to be responsible for the thick sand unit similar to the Gironde Estuary described by Allen and Posamentier (1994). Dalrymple et al. (1992) describe a tripartite total energy system within wave-dominated estuaries related to the distribution of facies (strong/coarse – weak/fine – strong/coarse), which fits with the three facies associations (FA3, FA4, and FA5) interpreted to be an estuary system.

FA6: Description – Tidal Flat

This facies association is composed of planar cross-bedded sandstone (Sp), ripple cross-laminated sandstone (Sr), heterolithic sandstone, siltstone, and mudstone (SFh), and massive mudstone (Fm) (Figure 25). Facies association FA6 overlies and in some instances is laterally adjacent to the estuarine system. FA6 fines upward overall and the upper contact is a gradational with the overlying alluvial plain system. The average thickness of FA6 ranges from 4-4.5m (13-14.7ft). Wave ripple sandstone (Sr) and planar cross-bedded sandstone (Sp) are commonly interbedded with heterolithic sandstone, siltstone, and mudstone (SFh) and massive mudstone (Fm). Flaser to wavy bedding is present as well as tidal rhythmite packages. Bioturbation can be seen in this facies association and commonly disrupts original depositional fabric.

Facies Association FA6 - Tidal flat



FA6: Interpretation

Facies FA6 is interpreted to be a tidal flat adjacent to an estuary. The vertical fining succession of mudstone with interbedded siltstone to fine-grained sandstone with wave ripples and bi-directional cross-stratification is indicative of tidal forces acting on a flat where only fine-grained sediment is actively being deposited. *Planolites*, which are feeding traces, are common trace fossils and can be indicative of brackish-marginal marine environments (Pemberton et al. 1992).

Alluvial Plain System

Happ et al. (1940) suggested three types of alluvial associations: 1) alluvial fan or piedmont association, 2) flood plain association, and 3) coastal plain – delta association (Figure 26). A slightly modified coastal plain – delta association (where the delta is an estuary) is interpreted for strata above FA6. The coastal plain – estuary system is broken into two distinct facies associations flood plain deposits and channel deposits.

FA7: Description – Flood Plain Deposits

FA7 is composed of massive mudstone (Fm), minor ripple-laminated sandstone (Sr), and pedogenically altered mudstone (P). Laterally extensive, tabular beds of fine-grained sandstone to mudstone ranging in thickness from 15cm to 2m (5.9in to 6.6ft), and interbedded with maroon, green, and light grey mud to siltstone dominate this succession. Evidence of pedogenically-altered soil is evident in core C173 and outcrop where brecciated clasts and rubbly textures are prevalent. FA5 in outcrop unconformably overlies shoreface deposits of FA1 and conformably overlies tidal flat deposits of FA6.

Alluvial Plain System: Facies Association FA7 & FA8



Figure 26. Alluvial plain system deposits found in outcrop near Ryan Dam. The coastal plain – estuary system is broken into two distinct facies associations flood plain deposits and channel deposits.

- Flood plain deposits: Laterally extensive, tabular beds of fine-grained sandstone to mudstone with maroon to light grey rubbly paleosols.
- Channel deposits: Channel form composed of conglomerate (Cglm.), medium- to coarse-grained planar cross-bedded sandstone (Sp), ripple cross-laminated sandstone (Sr), heterolithic sandstone, siltstone, and mudstone (SFh), and massive mudstone (Fm). Coal stringers and iron nodules are also present within the channel form.



FA7: Interpretation

The succession of tabular and laterally extensive fine-grained (minor ripple-laminated) sandstone that grades into siltstone and clay is indicative of flood plain deposits. Pedogenically altered soils are well developed, which add to this interpretation (Kraus, 1999).

FA8: Description – Channel Deposits

FA8 is composed of conglomerate (Cglm.), medium- to coarse-grained planar cross-bedded sandstone (Sp), ripple cross-laminated sandstone (Sr), heterolithic sandstone, siltstone, and mudstone (SFh), and massive mudstone (Fm). The lithofacies in this association are contained within a large channel form, roughly 1.7km (1.05mi) wide and 10m (32.8ft) deep. The channel form has stringers of coal and iron concretions.

FA8: Interpretation

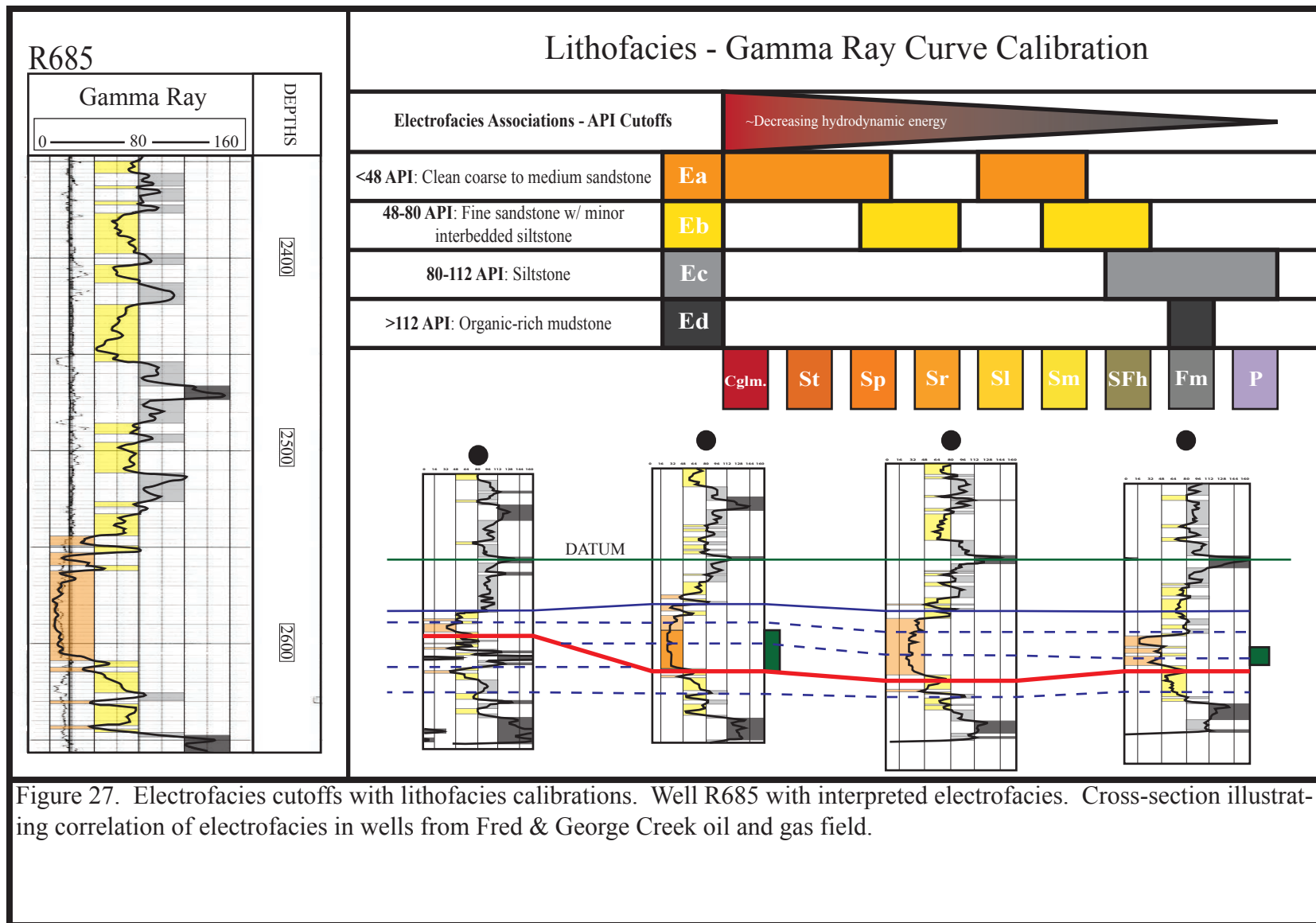
The channel form is interpreted to represent multilateral sheet sandbodies. Multiple succession fine-upward from conglomerate lag, planar cross-bedding, ripple cross-lamination, and finally mudstone, which is consistent with Miall's (1996, Fig. 8.8) sequence for sandy meandering channels. Coal stringers and iron concretions are likely to be related to flood plain deposits that were entrained as the channel accreted laterally.

Electrofacies

Electrofacies were also incorporated in this study to supplement facies associations deduced mainly from outcrop. The lack of core in this project requires well

logs to be correlated based solely on the signature of their curves (most generally the gamma ray curve). Electrofacies help to define a standard that is based on known well logs that are calibrated to available core and on assumptions of facies associations gathered from analogous outcrop (Figure 27).

Electrofacies A (< 48 API) represents thick-bedded and/or amalgamated sandstone deposits. The conglomerate lithofacies is included in this electrofacies as the clay clasts do not significantly affect the gamma ray curve. Electrofacies B (48-80 API) is comprised dominantly of thin-bedded sandstones with some interbedded heterolithic deposits. This electrofacies can represent facies associations FA2, FA4, and FA5. Electrofacies C (80-112 API) represents siltstone with minor interbedded fine-grained sandstone and represents FA2, FA3, FA4, and FA5. Finally, electrofacies D (> 112 API) is an organic rich black mudstone found only in the upper portion of core E891.



CHAPTER 5

INCISED VALLEY-FILL SYSTEMS

Introduction

Intense scientific publication documenting incised valley-fill systems on a case-by-case basis reflects the recent consideration of these depositional systems as viable economic stratigraphic entities (Dalrymple, 2006). Understanding the allogenic and autogenic drivers that influence the evolution of incised valley-fill systems has taken many decades. Even still, demonstrating criteria for what constitutes a valley-fill system versus a river channel remains somewhat contentious (Zaitlin et al., 1994, Dalrymple et al., 1994). However, productive valley-fill facies and the presence of a bounding unconformity, a key surface used to interpret stratigraphic variation and the past effects of base-level fluctuations, provide two significant motives for the proliferation of incised valley-fill system research.

Incised valley-fill systems are composed of two time and physically dependent elements, the valley or “container” and the valley-fill. The valley is a due to incision of the substrate, which is either the result of increased slope or increased water/sediment discharge ratio (Dalrymple, 2006). Several processes can induce increased slope or increased water/sediment discharge ratio including: (1) relative sea-level fall, (2) differential uplift, (3) changes in climate, and (4) subsidence of the source area (Dalrymple, 2006). The valley-fill is contingent on the presence of a container to fill and can be comprised of multiple facies in various arrangements. In sequence stratigraphic

terms, the incision of the valley occurs during the latter stages of the lowstand systems tract and is subsequently filled by lowstand systems tract fluvial remnants and estuarine to marginal marine deposits of the transgressive systems tract, following a rise in relative base-level (Van Wagoner et al., 1990).

Recognition Criteria

In order to assess the hypothesis that incised valley-fill systems are present in the Lower Cretaceous Kootenai Formation of northwestern Montana a list of recognition criteria must be established. The following criteria list is an attempt to formulize recognition for any and all types of incised valley-fill systems that may be present and is based on the criteria set forth by Van Wagoner et al. (1990) and discussed at length by Boyd et al. (2006). It is important to note that no single criterion can be considered diagnostic; rather a combination of criteria will ultimately provide a more accurate and precise interpretation. The following list is ordered from the most robust to least conclusive criterion.

Master Unconformity and Incision

A regionally extensive unconformity will floor the valley, extend along the walls, and correlate with an erosional surface on the interfluvies during a fall in relative sea level and ensuing lowstand systems tract (Zaitlin, 1994). This master unconformity outlines the geometry of the valley and juxtaposes genetically unrelated strata. The valley “container” will express a negative paleotopographic feature, which truncates underlying strata (Zaitlin, 1994).

Cuts Unrelated Strata (Violation of Walther's Law)

Johannes Walther is credited as elucidating the connection between vertical and lateral changes in facies and the conformable succession in which they could occur (Middleton, 1973). Hence a violation of Walther's law would require a disruption in the succession of vertical or lateral facies where genetically unrelated strata become in contact with one another.

Valley Morphology

An incised valley-fill system is confined to the profile of incision; thus a multistory hierarchical stacking pattern will be expressed whereas a river channel will exhibit a multilateral stacking pattern reflecting the freedom of the river to migrate across the entire floodplain.

Violation of Mass Balance

Time in incised valley-fill systems will more often be represented by stratigraphic surfaces of nondeposition and erosion than in river channels. Sediment in incised valleys can be deposited along the length of the master unconformity, whereas river channel deposits will not extend beyond the delta they source (M.H. Gardner, personal communication, 2013).

Pebble Lag/Ichnofacies/Paleosols

A veneer of pebble lag representing early transgression or the *Glossifungites* ichnofacies (in marine or marginal marine valleys) representing pauses in sedimentation or erosion may cover the unconformity surface at the base of the incised valley

(MacEachern and Pemberton, 1994). Paleosols or rooted horizons are often distinguishing features on the interfluves of incised valley-fill systems, but can also be in channel bodies. The importance of recognizing pebble lag, *Glossifungites*, or paleosols is rooted in the time value of their formation. If multiple events are represented more time has passed.

Discussion

Within the subsurface study area, an incised valley-fill system is present and can be delineated by the satisfaction of recognition criteria 1-3. (1) A negative paleotopographic feature can be recognized and traced regionally. Truncation of underlying strata, in this case the Jurassic Swift Formation, is seen where thickened Cretaceous Sunburst member strata have been deposited directly above. Along the interfluves the entire profile of the Swift Formation is evident, but a low order erosional surface remains. (2) A non-Waltherian, basinward shift in facies occurs in the incised valley-fill system of this study where marine deposits (FA1) of the Swift Formation are overlain by fluvial deposits (FA2) of the Sunburst member. (3) The fluvial deposits of the Sunburst member are constrained to the valley. The valley walls mitigated migration of channels within the system across a flood plain and are described as multi-storied channel forms rather than multi-lateral features.

CHAPTER 6

STRATIGRAPHY

Introduction

Two stratigraphic methods, lithostratigraphy and sequence stratigraphy, were utilized to accomplish the stated objectives of this study. Lithostratigraphy was used to construct a regional stratigraphic framework of the Upper Jurassic through lower Cretaceous strata, in a region that previously lacked detailed correlation and to provide an established reference (lithostratigraphic units) for which chronostratigraphic units could be reconciled.

Sequence stratigraphy was used to construct a chronostratigraphic framework in order to identify how the previously described lithofacies associations relate to each other in time (Catuneanu et al., 2009) and to delineate the stratigraphic position and architecture of hypothesized local-scale incised valley-fill systems. (i.e. the planform geometry and geomorphic expression of the valley or “container”). The geomorphic expression of the valley and valley-fill characteristics will be described following a section documenting the sequence stratigraphic architecture of the entire interval. A valley-fill model incorporating both sequence stratigraphic surfaces and depositional environments was constructed to illustrate the geologic evolution and location of productive intervals within the incised valley-fill system and will be presented in a series of diagrams. Lastly, a brief report on the applicability of chemostratigraphy of the strata investigated will be presented.

Lithostratigraphy

Limited studies documenting the lithostratigraphy of the Upper Jurassic and Lower Cretaceous strata on the east flank of the Sweetgrass arch have been published. While a few regional correlations across 100's of kilometers have included the larger Sweetgrass arch area (Glaister, 1959; Hayes, 1982) and numerous studies have detailed the Cut Bank oil and gas field (Blixt, 1941; Farshori and Hopkins, 1989; Ardies et al., 2002; Ramazanov, 2006) on the west flank of the arch, no publically available maps documenting lithostratigraphic changes at the scale of 10's of kilometers on the eastern flank of the arch exists. The following section provides well log descriptions and isochore maps with interpretations of major thinning and thickening trends across the study area at each of these intervals. Additional figures are presented in Appendix A.

Rierdon Formation:

No outcrop section or drill core of the Rierdon Formation was described in this project. Thus, selecting the top of the formation was based entirely on descriptions of the lithologies gleaned from literature (see Chapter 2), which were then associated to gamma ray, SP, and resistivity well log curves. The Rierdon Formation is generally assumed to represent an overall marine transgression dominated by shale with interbedded limestone (Hayes, 1982). The gamma ray signature of the Rierdon Formation is serrated and irregular to dirtying-up or increasing in API units, while the resistivity curve displays moderate to high values (Figure 28). The SP curve is totally vertical with no excursions

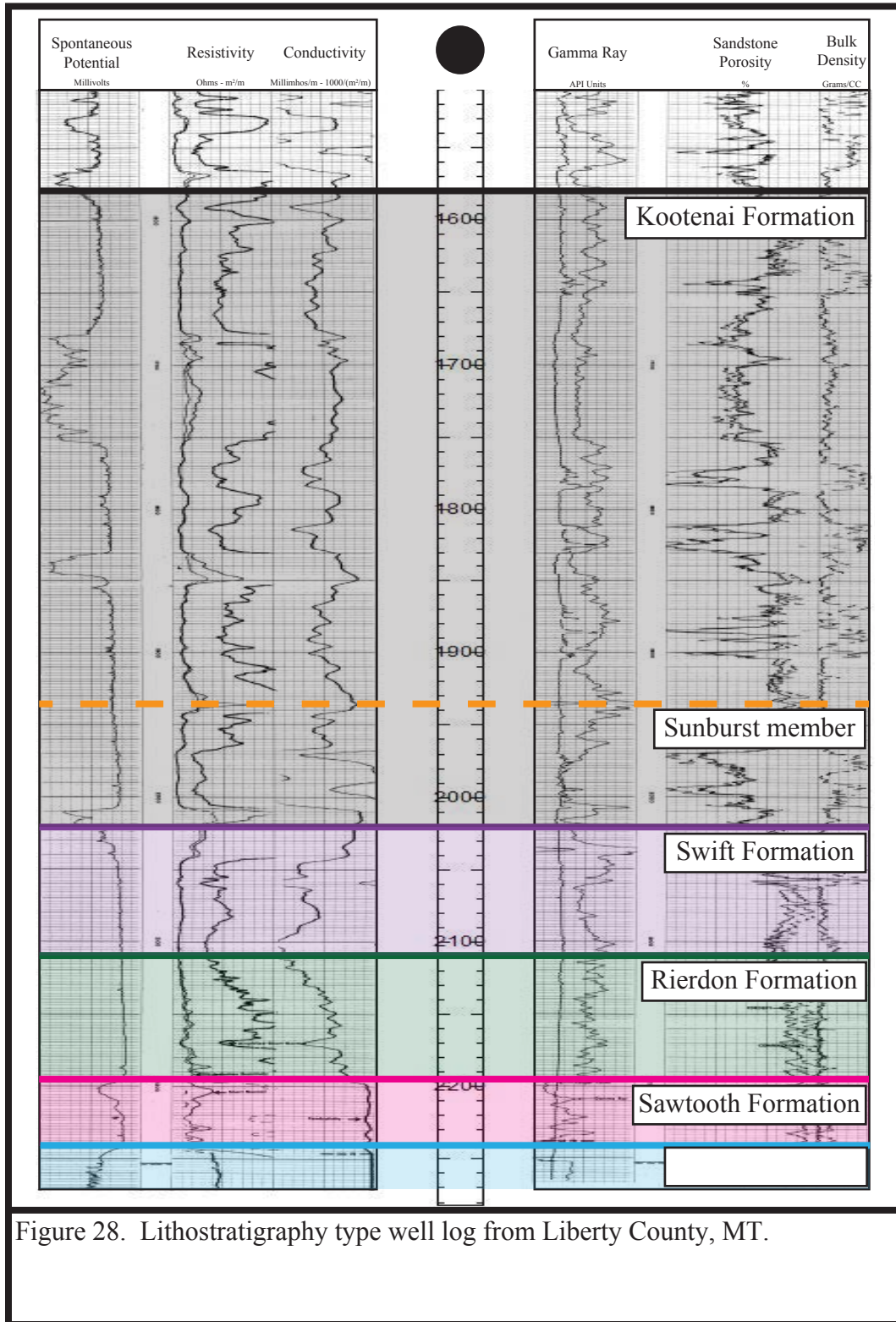


Figure 28. Lithostratigraphy type well log from Liberty County, MT.

due to the lack of significant porosity and fluids. The top of the formation is picked where high resistivity values significantly decrease and where gamma ray API values are at their highest.

Significant thick and thin trends observed on the Rierdon Formation isochore map (Figure 29):

1. The Rierdon is thickest in the northeastern portion of the study area and thins to the southeast and more dramatically to the west.
2. A thick located in 32N 1E trends northeast into 34N 2E and separates two distinct zones of regional thinning.

Thinning in the west-northwest portion of the isochore is likely due to the presence of a paleotopographic positive. The positioning of the thinning is congruent with the location of the Sweetgrass arch. Deposition of the Rierdon Formation would have been minimal across the arch and thickened to the east and likely to the west. The thinning in the southeastern portion of the study area may be related to the Pendroy Fault zone, which has been shown by McMannis (1965) and O'Neill and Lopez (1985) to have influenced Jurassic period deposition. However, the exact location, extent, and timing of movement on the Pendroy system is unclear in the study area.

Swift Formation:

No outcrop section of the Swift Formation was described in this project, but two drill cores (E891 & R744) were described and calibrated to available well log curves. The Swift Formation is recognized as the final marine transgression of the Jurassic Period followed by a slight outbuilding of the Jurassic shoreline, due to increased clastic input

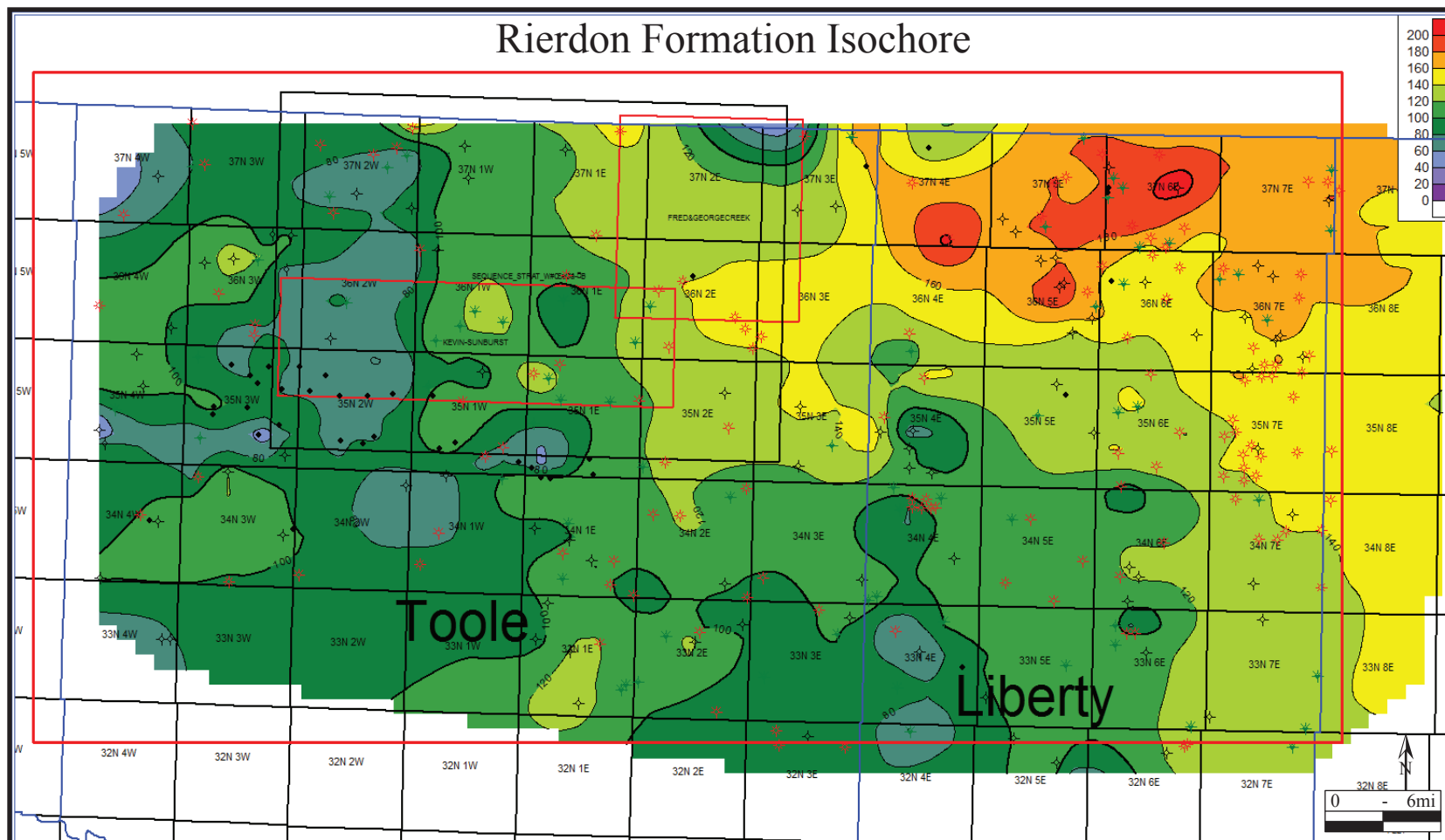


Figure 29. Jurassic Rierdon Formation isochore map.

from the west. (Hayes, 1982). At the base of the Swift Formation the gamma ray displays variable API units with moderate resistivity values (Figure 28). The gamma ray curve then cleans-upward and resistivity values slightly decline. The top portion of the Swift is highly irregular where medium- to coarse-grained sandstone bodies from 0.6-4.6m (2-15ft) thick are encased in shale. The resistivity curve often shows spikes where fluids are trapped in these sandstone bodies. Throughout the Swift Formation, the SP curve remains nearly vertical with slight deflections where thicker sandstone bodies with fluids are present. The top of the formation is picked at the base of a thick succession of medium- to coarse-grained sandstone, which appears as a boxcar or blocky trend on the gamma ray curve. This blocky well log motif represents the top of the Swift Formation, as well as, the sub-Cretaceous unconformity. Where sand bodies of the Swift Formation are in contact with the overlying Sunburst member, the distinction between Jurassic and Cretaceous aged strata can be quite difficult to determine.

Significant thick and thin trends observed on the Swift Formation isochore map (Figure 30):

1. The Swift Formation thickens slightly to the east and west away from the center of the study area.
2. A north-northwest trending thinning occurs between ranges 2E and 5E. The trend becomes more extensive northward.

The previous topographic high of the Sweetgrass arch, prevalent during deposition of the Rierdon Formation, appears to have slightly subsided by the time strata of the Swift Formation was being deposited. Limited thickening toward the east and

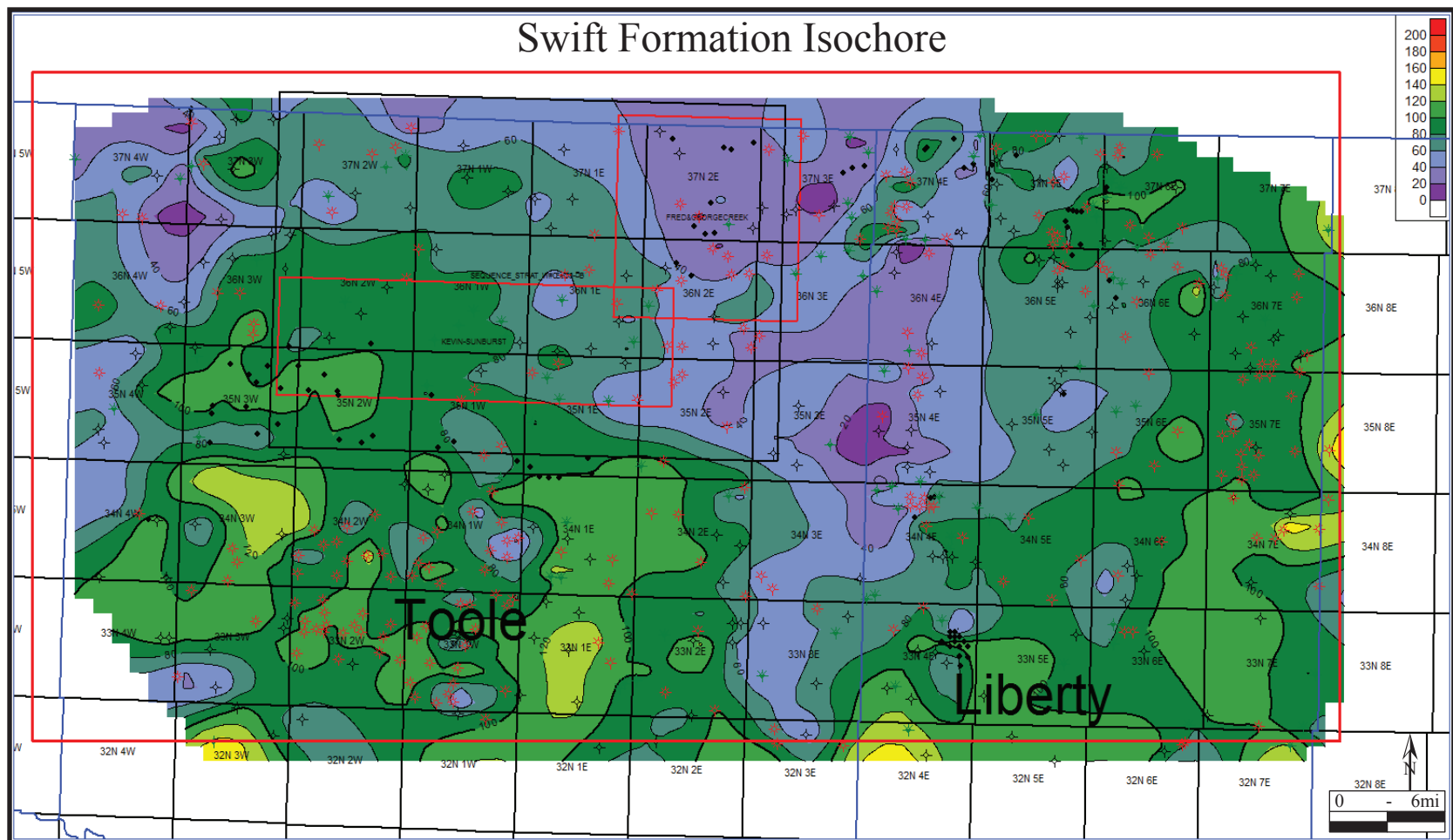


Figure 30. Jurassic Swift Formation isochore map.

west, or more widespread deposition, provides evidence for this interpretation. Post-Jurassic erosion masks the true thickness of the Swift Formation making the presence or absence of the Sweetgrass arch difficult to determine. The north-northwest trending thinning was similarly identified by Hayes (1982) and was interpreted to be a valley-fill system that incised into the Swift Formation. The name for the valley-fill system in this study is the Sunburst incised valley-fill system, described in Chapter 5.

Kootenai Formation

The lower section of the Kootenai Formation was identified in outcrop and in five drill cores (R851, R854, R362, C173, & R685). The deposits, which comprise the lower portion of the Kootenai Formation are interpreted to represent fluvial to estuarine environments, while the upper Kootenai is considered an alluvial plain system. The well log signature of the lower fluvial sandstone is identifiable on the gamma ray curve by a 1-25m (3.3-82ft) thick boxcar or blocky trend of low API units (Figure 28). On the SP curve a significant leftward excursion denotes this basal portion of the Kootenai Formation. The transition from fluvial to estuarine influence is recognized by a dirtying-up trend of the gamma ray curve and a much more irregular trend in resistivity due to thin tidal sandstone interbedded with estuarine mudstone. The upper Kootenai has significant well log variability as expected for an alluvial plain system with multiple depositional processes.

Significant thick and thin trends observed on the Kootenai Formation isochore map (Figure 31):

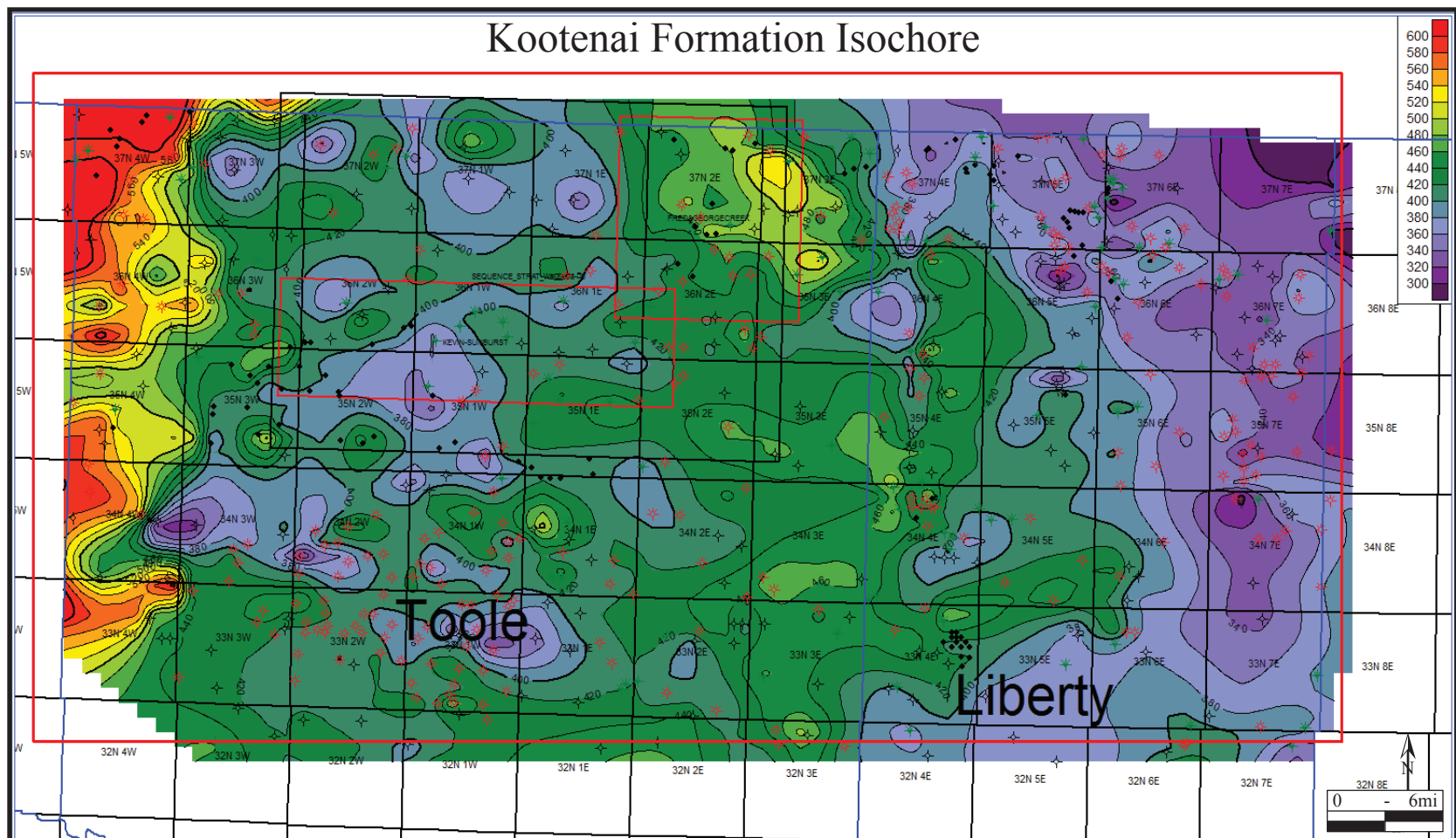


Figure 31. Cretaceous Kootenai Formation isochore map.

1. An abrupt thickening starts at range 3W and continues to the western margin of the study area.
2. A thickening of the Kootenai Formation occurs in the same geographic extent as the north-northwest trending thinning of the Swift Formation. The trend is thickest toward the north.

Thickening of the Kootenai Formation in the extreme west of the study area is related to the Cut Bank valley-fill system, which incised nearly all of the Swift Formation and portions of the Rierdon Formation. The subsequent valley-fill, which includes the Cut Bank member, adds 30.5-45.7m (100-150ft) of thickness to the Kootenai Formation. A less abrupt north-northwest thickening in the center of the study area is related to post-Jurassic erosion and valley development, which caused thinning of the Swift Formation. Numerous isolated thicks in the western portion of the study area are likely related to tributary rivers draining into the aforementioned Sunburst incised valley-fill system or into the western Cut Bank incised valley-fill system.

Sequence Stratigraphy

Introduction:

Sequence stratigraphy is a useful method with which to develop a chronostratigraphic framework through the examination of facies relationships and stratal architecture (Catuneanu et al., 2009). Sequence stratigraphy was developed in the late 1970's by geoscientists in the Exxon Production Research Company (Figure 32). The seminal work by Van Wagoner et al. (1990) provided extensive definitions of

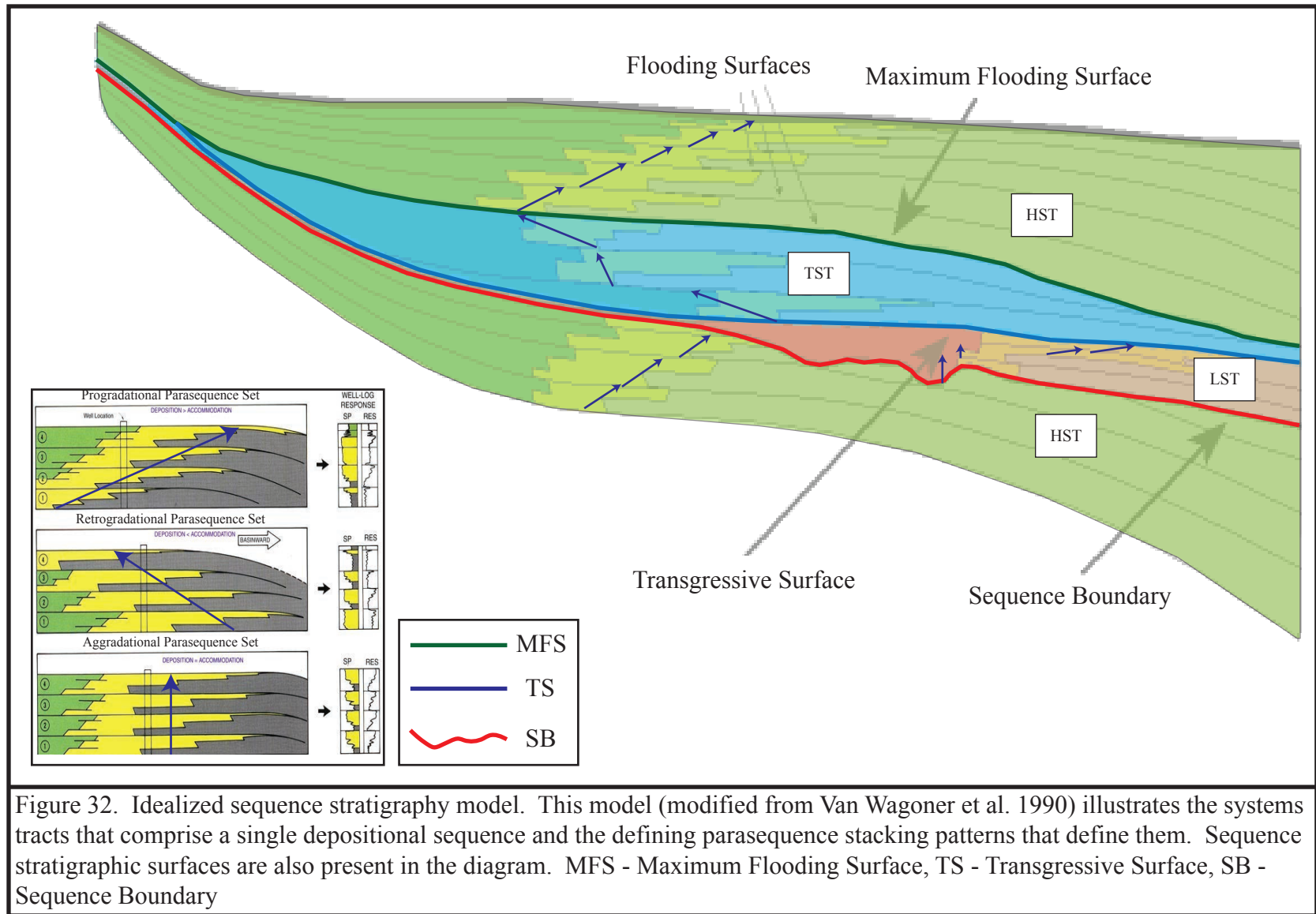


Figure 32. Idealized sequence stratigraphy model. This model (modified from Van Wagoner et al. 1990) illustrates the systems tracts that comprise a single depositional sequence and the defining parasequence stacking patterns that define them. Sequence stratigraphic surfaces are also present in the diagram. MFS - Maximum Flooding Surface, TS - Transgressive Surface, SB - Sequence Boundary

nomenclature and specific examples in marginal marine siliciclastic rocks where sequence stratigraphy could be applied. Shanely and McCabe (1994) furthered the value of sequence stratigraphy concepts by provided evidence that it's concepts could be applied to continental strata. The following sections will detail the foundations and nomenclature of sequence stratigraphy followed by the application of these guidelines to strata in this study.

Depositional Sequence

A depositional sequence original defined by Mitchum et al. (1977) is “a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities.” This definition emphasizes the importance of the unconformity or sequence boundary as a time significant surface, which separates younger strata from genetically unrelated older strata following a period of non-deposition or erosion (Van Wagoner et al., 1988). An unconformity represents a non-depositional hiatus, sediment bypassed or eroded, or the degradational vacuity – volume and time of rock removed, and is preserved as a time significant surface (M. H. Gardner, personal communication, 2014). More simply stated, unconformities represent gaps in time where stratigraphic layers are missing due to erosion or non-deposition and as stated by Weimer (1984) must signify a major break and generally be traceable over large distances.

In this study a major unconformity, or sequence boundary, is present at the base of the Cretaceous and is known as the sub-Cretaceous unconformity. The sub-Cretaceous unconformity represents a period of tectonic and magmatic quiescence from 140-125 Ma

(Leckie, 2008) and can be correlated across the rocky mountain region. The sub-Cretaceous unconformity separates strata of the Jurassic Ellis Group, which is marine in nature from the fluvial to estuarine Sunburst member and alluvial plain deposits of the upper Kootenai Formation. Fuentes et al. (2011) placed a value of 20 m.y. on this regional unconformity. However, the total time value of the sub-Cretaceous unconformity, which is present throughout much of the rocky mountain region, should be considered diachronous (Glaister, 1959), as is inherent to all unconformities (Blackwelder, 1909).

In the Kootenai Formation, a single depositional sequence, bound by the sub-Cretaceous unconformity at its base and built by parasequences and parasequence sets (Van Wagoner et al., 1990), is identified (Figure 33). Within this depositional sequence a simple incised valley-fill system, demarcated by the basal sub-Cretaceous unconformity, has been identified and its valley-fill correlated within the study area. The Sunburst member represents the valley-fill and a portion of the strata that partially overtops the valley. Along the interfluvies where the sub-Cretaceous unconformity was non-erosive, a disconformity occurs. This observation is congruent with the description of incised valley-fill systems presented by Van Wagoner et al. (1990). The thickness of the depositional sequence is highly variable across the study area, but roughly averages 121.9-182.8m (400-600ft) and is divisible into three systems tracts.

Systems Tracts and Surfaces

Within the sequence stratigraphic hierarchy, depositional sequences are subdivided into three ordered systems tracts, a lowstand systems tract (LST), a

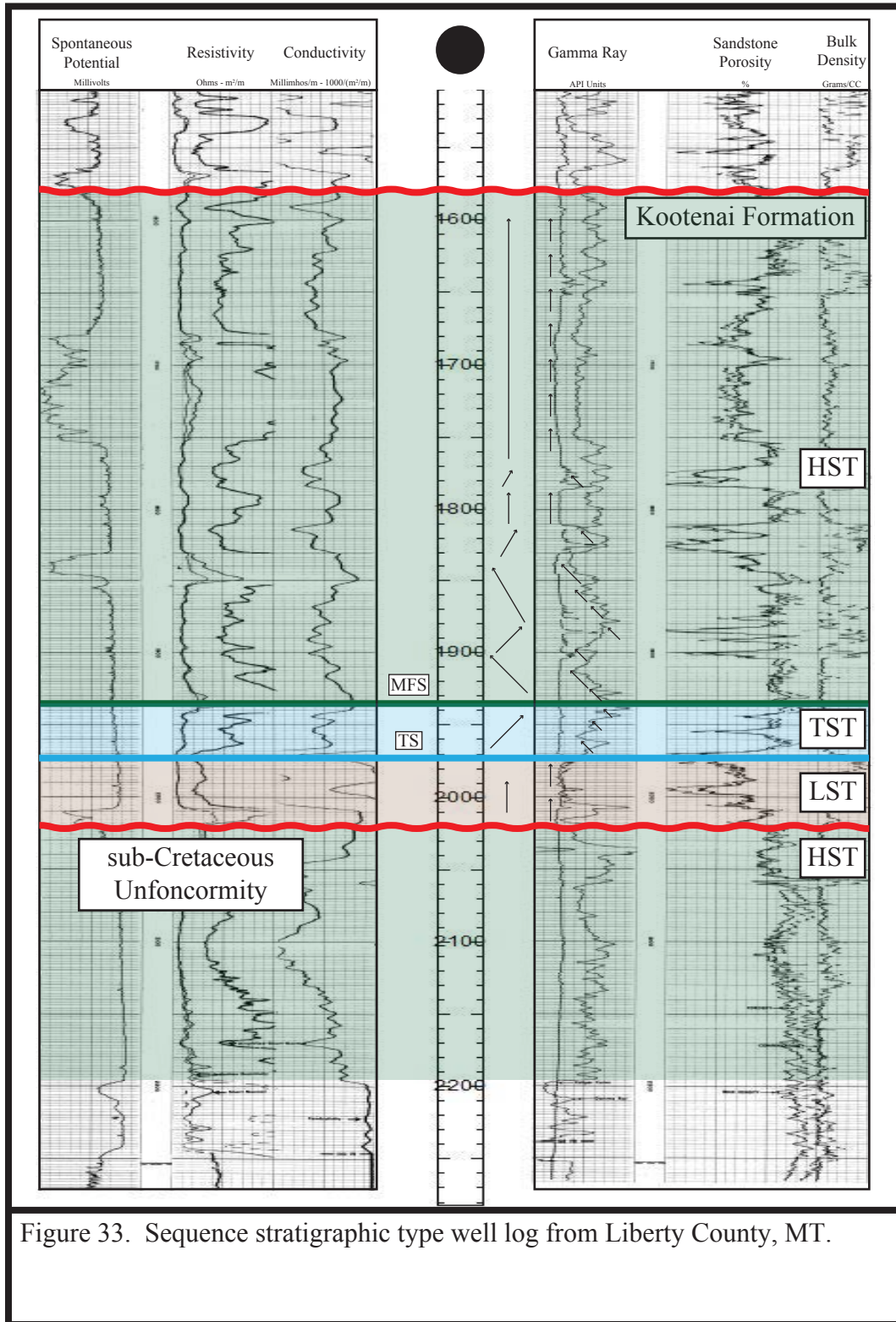


Figure 33. Sequence stratigraphic type well log from Liberty County, MT.

transgressive systems tract (TST), and a highstand systems tract (HST). A systems tract is defined as a “linkage of contemporaneous depositional systems” (Brown and Fisher, 1977; Van Wagoner et al., 1990). Each systems tract can be discerned by its vertical position in relation to the sequence boundary, parasequence set stacking patterns, and the types of surfaces bounding it (Posamentier et al., 1988).

The LST is the first systems tract to be deposited above the sequence boundary. Following Posamentier and Allen’s (1999, p. 33) definition the LST includes “all the deposits accumulated after the onset of relative sea-level fall as well as the initial rise, that is, until the rate of rise exceeds the rate of sediment accumulation”. Parasequence sets on well logs in the LST display a progradational to aggradational stacking pattern (*sensu* Van Wagoner et al., 1990) where overall, the rate of deposition is greater than or equal to the rate of accommodation (Van Wagoner et al., 1990). Bounding the top of the LST is a generally conformable (Catuneanu, 2002) flooding surface termed the transgressive surface (TS) (Posamentier and Vail, 1988). The transgressive surface is the first major flooding surface across the shelf in a depositional sequence (Van Wagoner et al., 1990) and can be identified in the fluvial reach as an abrupt change in fluvial energy (Catuneanu, 2002). The LST in the study area occurs within the fill of the Sunburst incised valley-fill system, which is bounded by the sub-Cretaceous unconformity and a transgressive surface. Fluvial incision of the underlying Jurassic Swift Formation occurred during a period of intense base level fall. Locations where significant erosion did not occur are marked by a correlative conformity discernable by pedogenically altered mudstones (F10) and no fluvial deposition. The LST is represented by the lower

portion of the Sunburst member and is composed of amalgamated fluvial channel sandstone (FA2), which makes up the majority of the valley-fill.

The transgressive systems tract follows the lowstand systems tract and overlies the transgressive surface. Posamentier and Allen (1999, p. 37) define the TST as “compris[ing] the deposits accumulated from the onset of coastal transgression until the time of maximum transgression of the coast, just prior to renewed regression”. This systems tract is a consequence of the rate relative sea-level rise exceeding the rate at which sediment is supplied (Posamentier and Allen, 1999). Parasequence sets in the TST display a retrogradational stacking pattern (*sensu* Van Wagoner et al., 1990) where overall, the rate of deposition is less than the rate of accommodation (Van Wagoner et al., 1990). The TST is bounded by another significant flooding surface termed the maximum flooding surface (MFS). The MFS or downlap surface of Van Wagoner et al. (1988) separates retrogradational strata of the TST with progradational strata of the HST.

The transgressive surface marks the top of the Sunburst member and the beginning of the TST in the study area. This systems tract was initiated when a significant base level rise generated the development of a transgressive estuarine system and back-stepping estuarine bayhead delta deposits, estuarine central basin mudstone, and estuarine mouth sand bodies (FA3, FA4, and FA5). By the end of the TST the estuarine system had overtopped the valley walls and was deposited across the immediate interflaves. In the subsurface study area the TST ranges in thickness from 4.6-9.1m (15-30ft)

The highstand systems tract is the final systems tract deposited in a depositional sequence. This systems tract marks a period that Catuneanu (2002) describes as “the late stage of base level rise during which rates of rise drop below the sedimentation rates, generating a normal regression of the shoreline”. In the continental reach of the system the HST can be characterized by “laterally interconnected, amalgamated channel and meander belt systems” (Shanley and McCabe, 1993; Catuneanu, 2002). Parasequence sets in the HST display a progradational to aggradational stacking pattern (*sensu* Van Wagoner et al., 1990) where overall, the rate of deposition is greater than or equal to the rate of accommodation (Van Wagoner et al., 1990). The HST is bound at the top by the next overlying sequence boundary (Van Wagoner et al., 1990). The preservation of the HST is determined by the subsequent fall in base level and degree of erosion or truncation by the ensuing sequence boundary (Van Wagoner et al., 1990; Catuneanu, 2002). A maximum flooding surface above the Sunburst member marks the end of the TST and the onset of the highstand systems tract. The HST makes up the unnamed upper section of the Kootenai Formation and is comprised of amalgamated channel, meander belt systems, and floodplain deposits of an alluvial plain system.

Sunburst Incised Valley-Fill System

A major objective of this thesis was to delineate the stratigraphic position and architecture of local-scale incised valley-fill systems and to construct a valley-fill model that incorporates environments of deposition interpreted from lithofacies observed in core and analogous outcrop and their position within a sequence stratigraphic framework. A

detailed description of the valley container along with figures illustrating the valley-fill will be presented in order to satisfy the final objective originally presented in the introductory chapter. As previously mentioned in Chapter 5 an incised valley-fill system that satisfies three of the five recognition criteria exists within the study area and is termed the Sunburst incised valley-fill system (See Appendix B). Hayes (1982) describes a valley in the same geographic location and stratigraphic interval, which he called the Whitlash valley. However, due to Hayes' (1982) focus on regional stratigraphy and as a consequence lower resolution mapping suggesting a connection between the two interpreted valleys could be flawed.

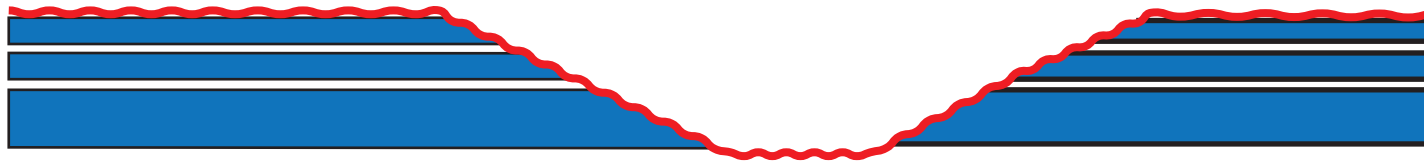
Within the subsurface study area the Sunburst incised valley-fill system can be described as a simple valley-fill system (*sensu* Dalrymple et al., 1994), composed of a single incisional valley and its fill and appears to be relatively narrow and slightly dendritic. The Sunburst incised valley-fill system is bound by the regionally extensive sub-Cretaceous unconformity. The incised valley-fill system can be traced across nine different townships for nearly 65km (40.4mi) and has an average width of roughly 2.86km (1.78mi). Several lobes deviate from the main valley axis and trend north-northwest. The lobes are generally less thick than the main valley-fill and are interpreted to be tributary channels. The dimensions of these lobes are rough estimates as well control is limited due to the lack of significant hydrocarbon production.

The valley-fill of the incised valley-fill system is a single overall fining-upward cycle. Interpreted sequence stratigraphic surfaces provide additional evidence that the incised valley-fill system is a single sequence as opposed to the multi-sequence systems

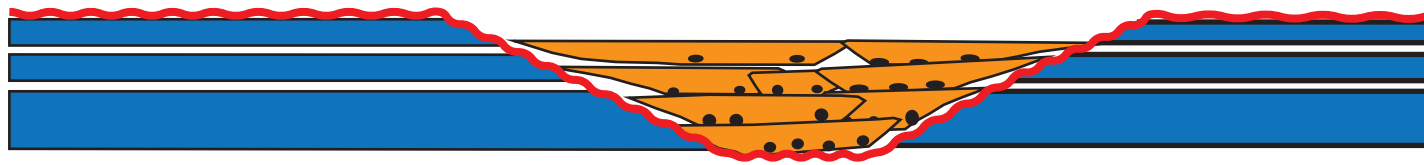
described by Ardies et al. (2002), Lukie et al. (2002), and Zaitlin et al. (2002). The thickness of the valley-fill consistently ranges from 10.7-18.3m (35-60ft). Due to the lack of available core, the fill of the incised valley-fill system will be described using the electrofacies presented in Chapter 4 followed by an interpretation of the depositional environments present based on the lithofacies and lithofacies associations observed in analogous outcrop. The valley-fill and strata immediately overlying the valley is divided into three sections based on observed electrofacies and their associated gamma ray trend.

The first electrofacies present, following incision into shoreface deposits, is a stack of clean coarse- to medium-grained sandstone (Ea) (Figure 34). This sandstone immediately overlies the sub-Cretaceous unconformity. Very rarely, minor fine-grained sandstone with minor interbedded siltstone (Eb) is present. This basal stack of sandstone has a boxcar or blocky gamma ray curve and ranges from 1.8-19.8m (6-65ft) thick.

The basal sandstone is interpreted to be amalgamated fluvial channels (FA2), which were interpreted from core and outcrop. Individual channels near the base of the valley are lined with a flattened mud-clast conglomerate (F1). Ardies (1999) indicates that similar conglomerates were likely sourced from the bank due to upper bank failure and toe scouring near the base of the bank. Proportionally, the succession is dominated by trough cross-stratified and massive coarse- to medium-grained sandstone (St & Sm). All of the production from the Lower Cretaceous Kootenai Formation comes from strata deposited within the LST. However, thin section analysis and production tests indicate that the entire succession isn't always productive. This is likely due to differential porosity throughout the sandstone (Figure 35).



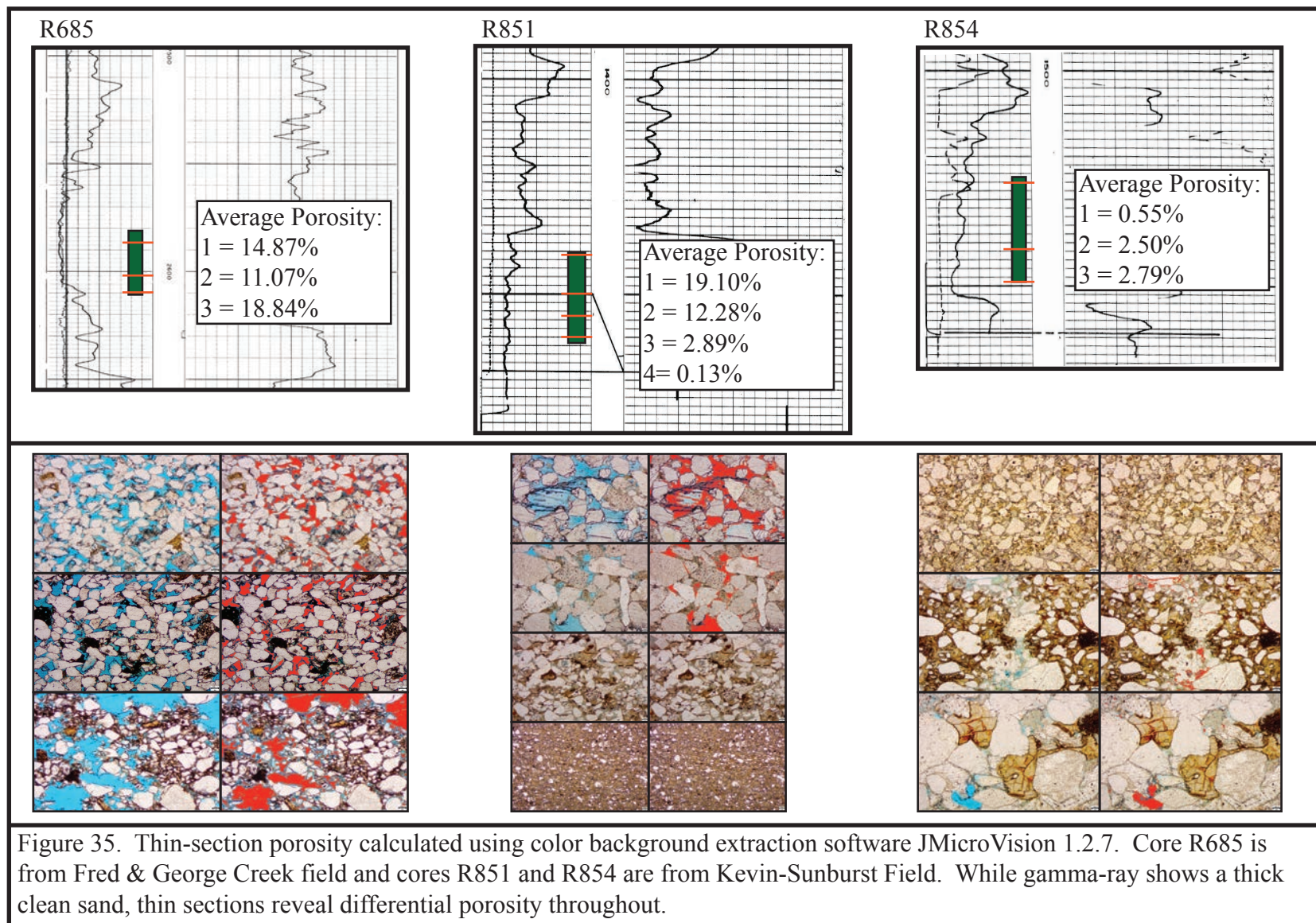
Shoreface (Lower - Lower Middle):
FA1: Sr, Sh, SFh, & Fm



Fluvial Channel Fill
FA2: Cnglm., St, Sm, Fm



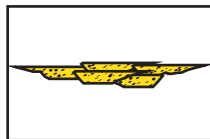
Figure 34. The first event in the evolution of an incised valley system is the creation of the valley container by fluvial incision during base level fall. When the rate of base level falls decreases fluvial deposition FA2 commences.



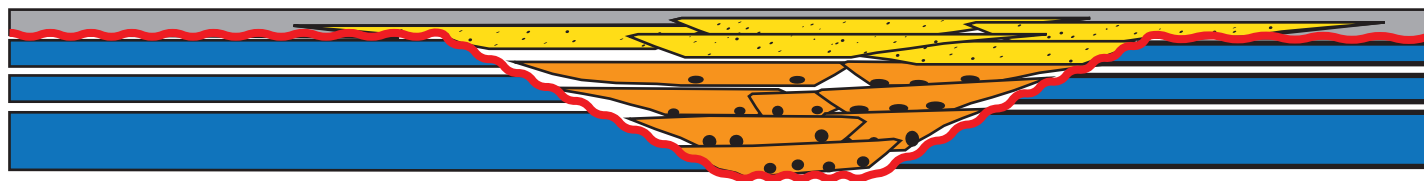
Directly above the basal sandstone is a section composed dominantly of fine-grained sandstone with minor interbedded siltstone (Eb) and thin beds composed entirely of siltstone (Ec). This unit has an overall dirtying-up gamma ray trend and was deposited at the top of the valley and onlaps the interfluves. A bed of organic-rich mudstone (Ed) caps the second section.

The depositional environments of the second unit within the valley-fill are interpreted to be bayhead delta deposits (FA3), central basin mudstone (FA4) (Figure 36), and estuarine mouth sand bodies (FA5) (Figure 37). A single core was recovered from the lower section of this interval, requiring outcrop observations to be relied on heavily for depositional environment interpretations.

The last deposits of the estuarine system (estuarine mouth sand FA5) overtop the valley and are no longer confined to the valley walls. Tidal flat facies (FA6) are deposited next (Figure 37), which would have required a lateral shift in environments rather than continued base level rise as tidal flats would have been adjacent to the estuary system. Finally, the rate of base level rise wanes and the highstand systems tract begins. During this time progradation and aggradation of an alluvial plain system dominates (Figure 38). Flood plain deposits (FA7) and meandering channel deposits (FA8) begin to accumulate. The depositional sequence is complete following the highstand systems tract (Figure 39).



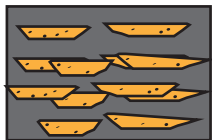
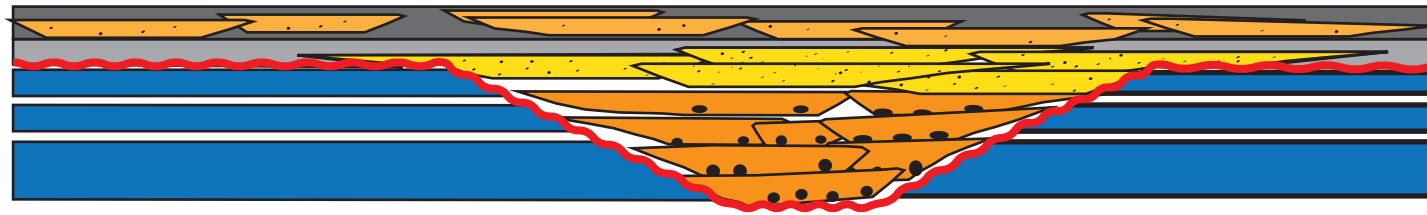
Estuarine System
Bayhead Delta
FA3: St, Sr, & SFh



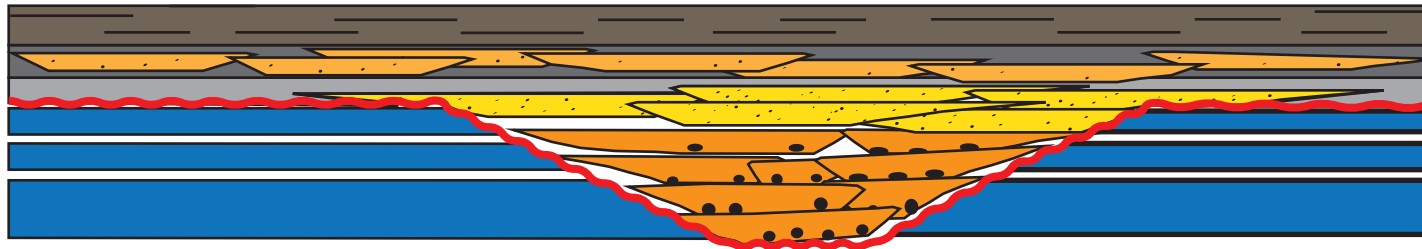
Estuarine System
Central Basin
FA4: Fm, & Sr



Figure 36. A change in depositional environments from fluvial to estuarine signifies a rise in base level. Fluvial style from braided to meandering can also be an indicator of base level rise, but this could not be determined in this study. The deposition of the estuary system is comprised of three environments defined by overall energy (Dalrymple et al., 1992). First is bayhead delta sand dominated by tides or fluvial currents. In the central basin mud is deposited as the energy of the fluvial system is at its lowest, but waves and tides are not particularly strong yet.



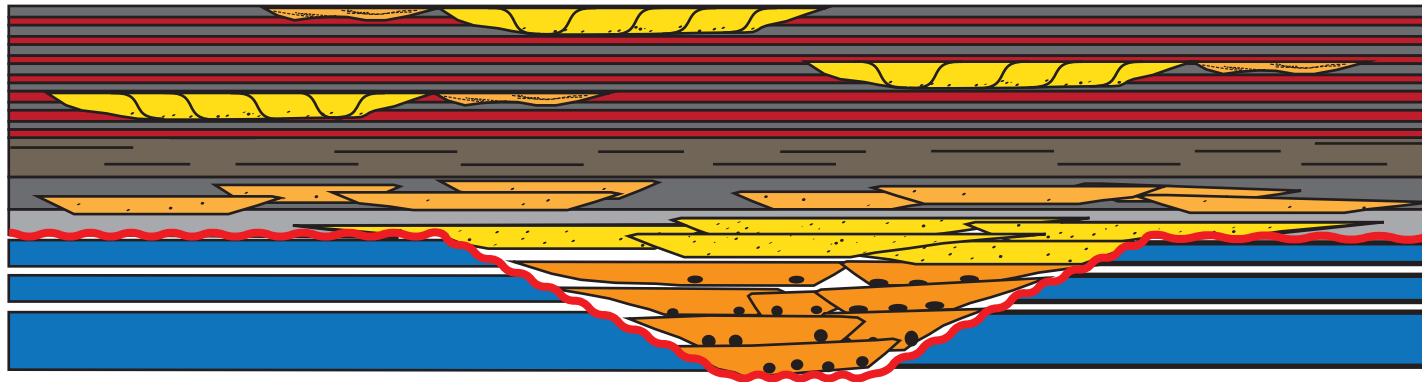
Estuarine System
Mouth Sand Bodies
FA5: Sp & Fm



Tidal Flat
FA6: Sp, Sr, SFh, & Fm



Figure 37. After central basin muds are deposited the waves and tide currents dominate during the deposition of estuary mouth sand bodies. At this point base level is still continuing to rise. A lateral shift in facies deposition is observed as tidal flat deposits occur next in the succession.



Alluvial Plain System
FA7 & FA8



Figure 38. Finally, the rate of base level rise begins to slow and an alluvial plain system begins to prograde. The alluvial plain is made up of flood plain deposits and channel deposits in meander belts with crevasse splays.

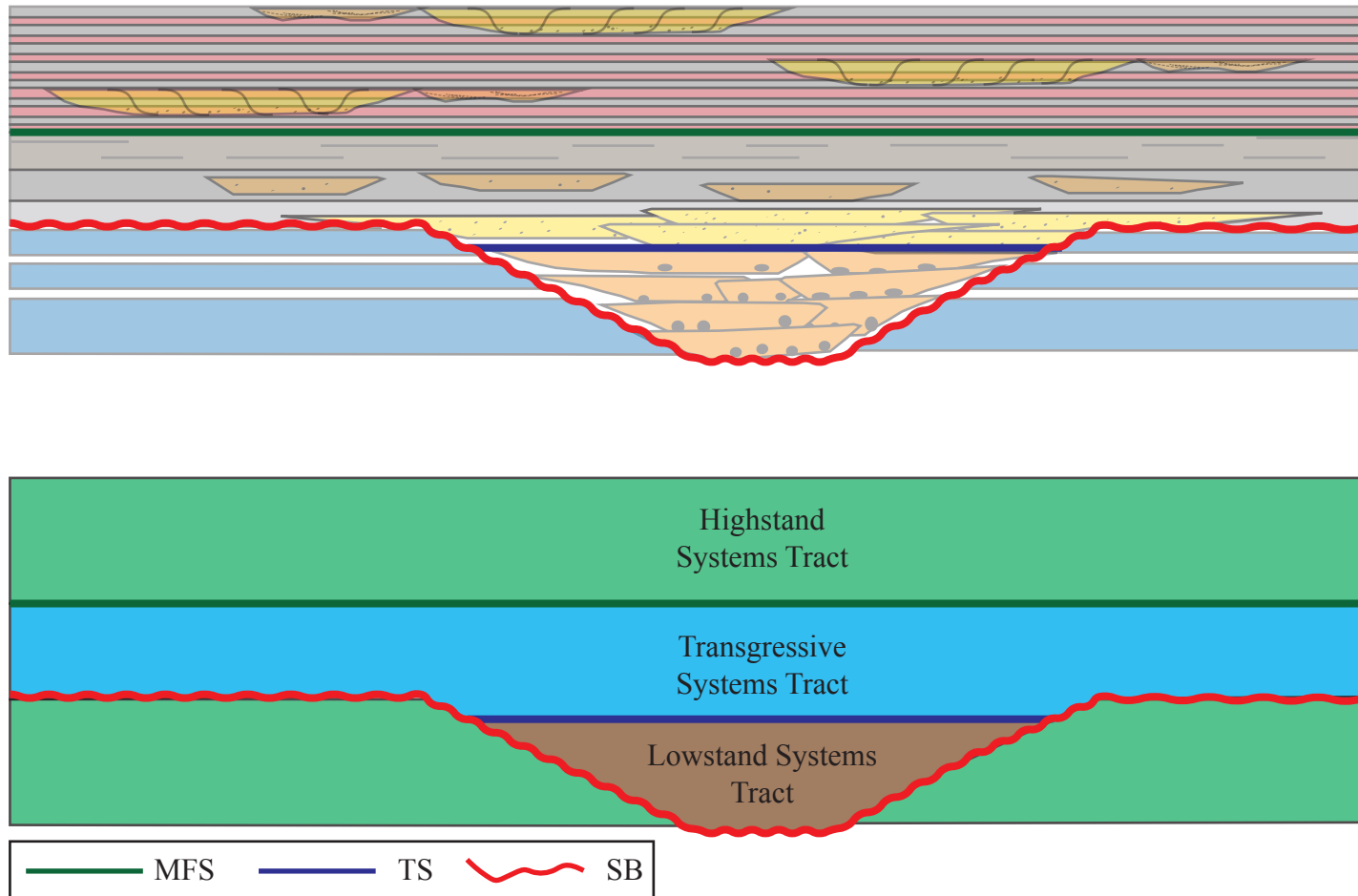
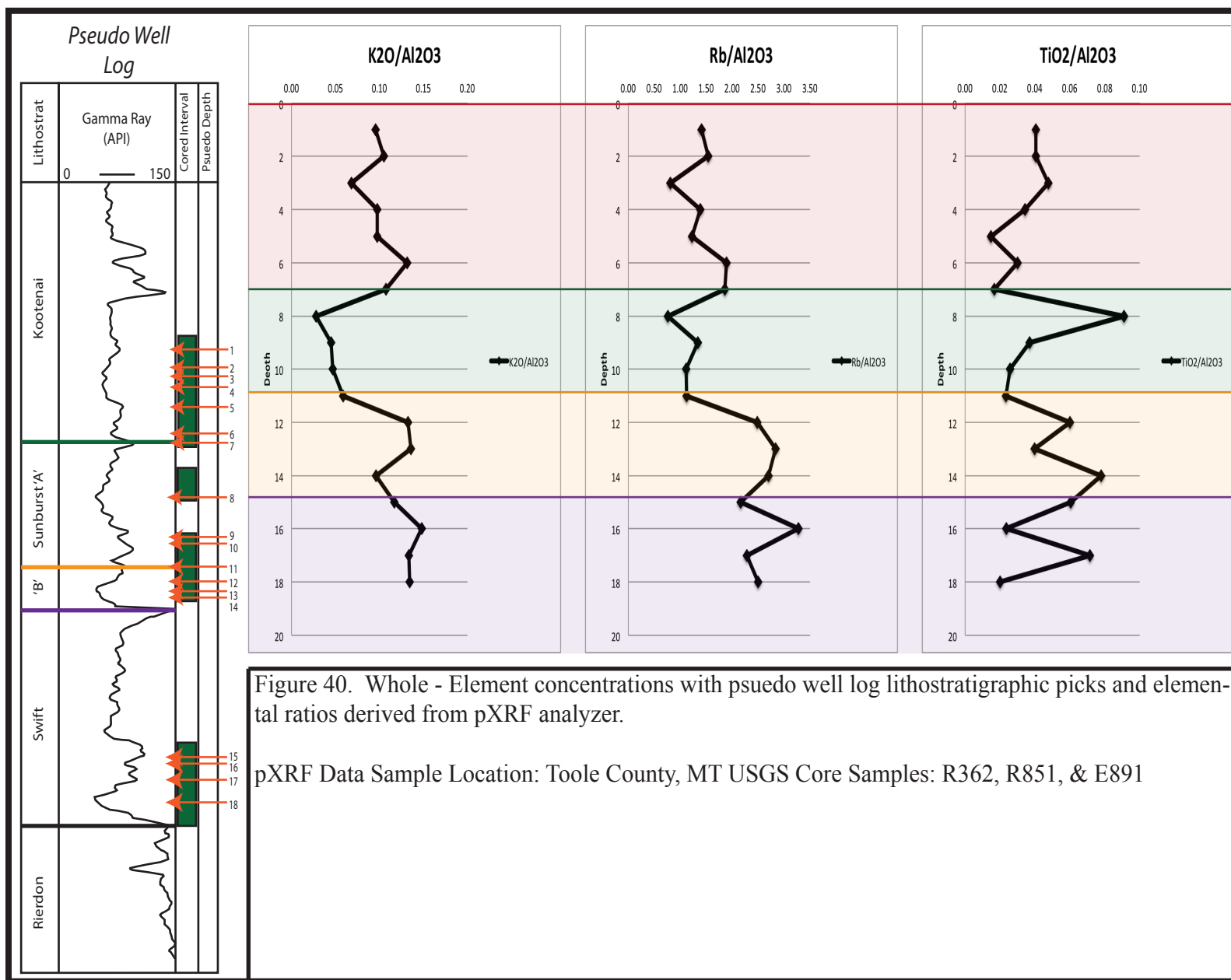


Figure 39. Described Facies Associations are interpreted within a sequence stratigraphic framework where systems tracts are defined by their vertical position in relation to the sequence boundary, parasequence set stacking patterns, and the types of surfaces bounding it (Posamentier et al., 1988). Facies Association 2 (fluvial channel fill) is the only productive FA observed in the study area and is contained within the lowstand systems tract.

Chemostratigraphic Subdivision of
Lower Cretaceous – Upper Jurassic Units

Similar, to the work of Hildred et al., (2010) a preliminary chemostratigraphic analysis was conducted in order to determine if significant differences in the geochemical signal of units with similar lithology could be parsed out. Due to the limited selection of data a number of assumptions were fostered (discussed in Chapter 3), but ultimately variations in K_2O/Al_2O_3 , Rb/Al_2O_3 , and TiO_2/Al_2O_3 ratios accurately delineated between marginal marine strata, fluvial valley-fill, estuarine valley-fill, and channel deposits on an alluvial plain (Figure 40). While a more extensive collection of physical rock data tied to well logs would need to be analyzed and tested, it is the authors opinion, that this method could be used correlate between discreet units that share similar lithologies and well log signatures. A discussion on the practical application and an outline for future studies that incorporate this method will be included in the future work section of the final chapter.



CHAPTER 7

PETROLEUM SYSTEM

Introduction

For any interval of strata to be a successful hydrocarbon play a number of key elements termed the petroleum system need to be satisfied. These elements include the: (1) source rock (2) reservoir rock, (3) seal rock, (4) formation of a trapping mechanism (structural, stratigraphic, or some combination), and finally, (5) generation, migration, and accumulation of petroleum. Numerous petroleum system schemes have been devised (Meissner et al., 1984; Ulmishek, 1986; Magoon and Dow, 1994), but each ultimately reflects these key elements. The following sections outline the Cretaceous Petroleum system for this study area (Figure 41).

Source Rock:

A stratigraphic interval where hydrocarbons can be produced, or a source rock can be considered the most important element of the total petroleum system. Without the source rock there will be not hydrocarbons present rendering the subsequent elements inconsequential. Dyman (1987) noted the “dark grey phosphatic shale beds of Jurassic Formations” as a significant source rock associated with the Upper Jurassic to Lower Cretaceous oil and gas play. Dolson and Piombino (1994) indicate that hydrocarbons from the Mississippian/Devonian Bakken Shale, which migrated nearly 80km (50mi) eastward from the fold and thrust belt footwall, charge the Lower Cretaceous strata of the

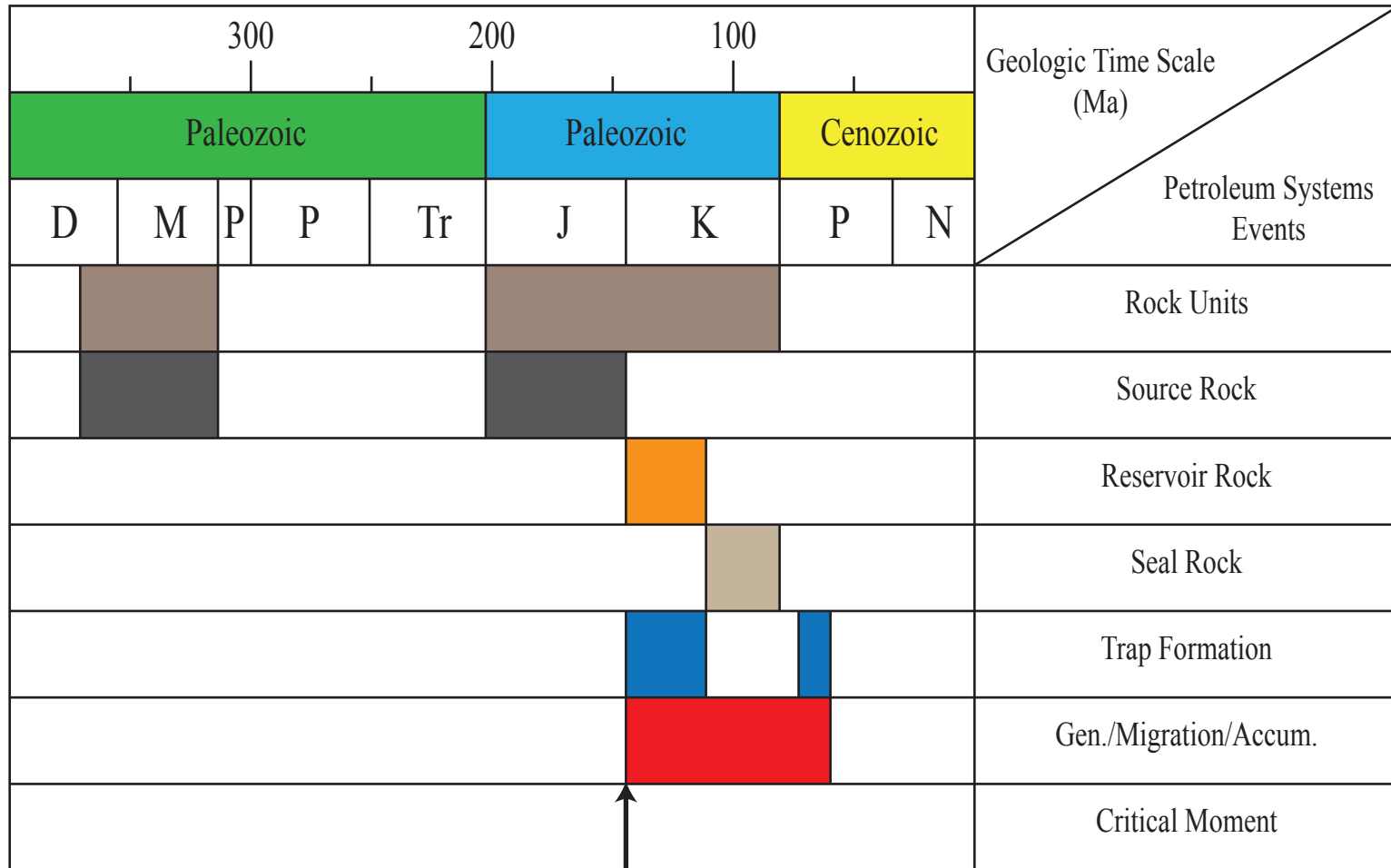


Figure 41. Petroleum system diagram of Cretaceous interval in northwestern Montana. (modified from Magoon and Dow, 1994).

Cut Bank oil and gas field. Whether or not the hydrocarbons could have continued their migration eastward across the Sweetgrass arch into the study area is unknown.

Reservoir Rock:

Depositional environments interpreted from analogous outcrops, thin section analysis, and historical production are all used to evaluate the reservoir attributes of the Fred & George Creek and Kevin-Sunburst oil and gas fields. Production in these fields comes from three different sandstone reservoirs a “ribbon sandstone” of the Jurassic Swift Formation and two sandstone units in the Cretaceous Sunburst member.

The shoreface sandstones of the Swift Formation reservoir are much more productive in the Kevin-Sunburst field than they are in the Fred & George Creek Field. A possible explanation derived from the Swift Formation isochore map suggests deeper incision into the Swift Formation may have removed a more sand-rich upper shoreface section in the Fred & George Creek Field. Quantitative reservoir attributes for the Swift Formation reservoir are un-reported.

Above the Swift Formation in both fields is fluvial channel fill (FA2), which directly overlies the sub-Cretaceous unconformity and was deposited during a lowstand systems tract (LST). This sandstone is composed of fine- to medium-grained moderately sorted, rounded to sub-angular quartz grains with <5% dark black and minor orange chert grains. Reported porosity averages across the Fred & George Creek Field are 28% and 27% by Thompson (1966) and Hughes (2006), respectively. Average porosity calculated from thin section samples taken at different intervals from three drill cores are much lower, but have high variability suggesting porosity is a major control on production

(Figure 35). Permeability is considered extremely variable in the Kevin-Sunburst Field (Jones, 1985) and is estimated at 1,600 millidarcies by Thompson (1966) for the Fred & George Creek Field.

Minimal production in both fields also comes from estuarine system sandstones (FA3 and FA4). However, no cores were available for thin section analysis through this interval and previous field reports did not differentiate these upper estuarine system sandstones from lower fluvial channel sandstone.

It should be noted here that no wells drilled to date have produced from meander belt fluvial sandstone, which was deposited during the highstand systems tract (HST) and observed in outcrop. Thin beds of heterolithic sandstone, siltstone, and mudstone (SFh) are likely barriers that have prevented the migration of hydrocarbons into this interval. On well logs, these meander belt have a deceptive appearance of clean sandstone intervals. Diagenesis may have played a significant role as well in plugging up pore space within this interval and should be considered in future studies.

Trap/Seal Rock:

The traps across the Sweetgrass arch are structurally enhanced stratigraphic traps (Dyman, 1987). The incised valley-fill system described in this study provides a classic example of a stratigraphic trap where migrating hydrocarbons have become effectively trapped within amalgamated fluvial channels that were deposited adjacent to incised marine mudstone of the Swift Formation. Fine-grained estuarine sandstone and mudstone provide a top seal. Other small oil and gas field traps are enhanced by domal

features that are present across the Sweetgrass arch and are most commonly associated with Eocene, alkali-intrusions (Lageson, 1985; Heam et al., 1978; Podruski, 1988).

Generation-Migration-Accumulation:

In order to generate hydrocarbons, organic-rich beds must be put under specific pressure and temperatures (Philippi, 1965; Hunt et al., 2002). This zone of unique pressure and temperature is commonly referred to as the “oil window”. The source rocks described above most likely came into the oil window as lithospheric flexure caused by the loading of stacked thrust sheets to the west forced subsidence in the hinterland and the creation of a foreland basin system. Logically, hydrocarbon generation could have continued throughout the development of foreland basin system as long as organic rich source beds were present. Migration and accumulation would have begun shortly after generation as mobile hydrocarbons began to travel updip until stratigraphic or structural traps were encountered.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND FUTURE WORK

Introduction

The objectives of this thesis were to investigate the Lower Cretaceous Kootenai Formation in northwestern Montana in order to develop a stratigraphic framework and to delineate the stratigraphic position and architecture of any incised valley-fill systems within the study area. The construction of numerous isochore maps and cross-sections, couple with sedimentologic and stratigraphic attributes from analogous outcrop provides a better understanding of the behavior of stratigraphic units and the evolution of incised valley-fill systems. The following statements provide a summary of the findings of this study, conclusions, and thoughts for potential future work.

Summary

1. This study provides details from an investigation of subsurface stratigraphy (Townships 33N-37N, Ranges 4W-7E) coupled with outcrop sedimentology and stratigraphy (Township 21N, Range 5E) in northwestern Montana.
2. Nine lithofacies are identified from both outcrop and minimal drill core. These are grouped into eight facies associations: Shoreface (FA1), Fluvial channel fill (FA2), Estuarine tidal sand (bayhead delta) (FA3), Estuarine central basin mud (FA4), Estuarine mouth sand bodies and mud (FA5), Tidal flat (FA6), Flood plain deposits (FA7), and Channel deposits (FA8).

3. The Kootenai Formation can be subdivided into three ordered systems tracts (lowstand systems tract, transgressive systems tract, and highstand systems tract) of a single depositional sequence (*sensu*, Mitchum et al., 1977). The informal Sunburst member of the Kootenai Formation is contained within the lowstand systems tract and transgressive systems tract of this depositional sequence.
4. The basal sequence boundary of the depositional sequence is commonly known as the sub-Cretaceous unconformity and in the study area separates Upper Jurassic from Lower Cretaceous strata. The time value of the unconformity is contentious, but within the Sunburst incised valley-fill system the surface separates underlying shoreface lithofacies (FA1) from fluvial channel fill (FA2) indicating a violation of Walther's Law and the presence of an unconformable surface.
5. An incised valley-fill system termed the Sunburst incised valley-fill, is orientated east-northeast and is a narrow, shallowly incised 10.7-18.3m (35-60ft), and slightly dendritic, valley-fill system that is filled with both fluvial and estuarine deposits, that indicate the study area is in Segment 2 of the Zaitlin et al. (1994) incised valley-fill system model. The valley-fill system is recognized by three of five criteria: (1) A negative paleotopographic feature bound by a basal sequence boundary and truncation of underlying strata, (2) a non-Waltherian, basinward shift in facies and (3) the confinement of strata to a valley form.
6. The development of a foreland basin system to the west created accommodation for deposition. The preservation of an entire depositional sequence suggests continuously available space for sediment to be deposited, unlike the

accommodation limited sequences of the incised valley-fill systems investigated by Ardies et al. (2002), Lukie et al. (2002), and Zaitlin et al. (2002). Similarly, the available accommodation space throughout the Kootenai Formation's deposition indicates that the Sweetgrass arch would not have been a paleotopographic high influencing deposition by Early Cretaceous time.

7. The valley-fill system is an east-northeast trending entity whose drainage pathway may have been affected by the Pendroy fault zone or related fault generated dislocations (Dalrymple, 2006). Overall paleo-drainage would have been to the north-northwest (Zaitlin et al., 2002). A similar possibly related structural trend known as the Vulcan Low in southwestern Alberta affected the drainage patterns of the incised valley-fill system described by Ardies (1999).
8. The valley-fill is largely contained within the lowstand systems tract, although a thin section of the transgressive systems tract is present within the valley. These observations more closely aligned with the sequence stratigraphic model developed by Van Wagoner et al. (1990) rather than that of Zaitlin et al. (1994).
9. The presence of thick sandstone with low API units on the gamma ray curve are not the only controls for successful hydrocarbon reservoirs. From thin section analysis and outcrop observation, porosity lenses and the position of the strata within the sequence stratigraphic framework are also major controls. Within a single amalgamated fluvial channel porosity ranged from 0.13-19.10%. Similarly clean fluvial channel sands in the highstand systems tract, observed on well logs

in the subsurface, are never productive. Upon observation of analogous strata numerous reservoir baffles and barriers including: (1) heterolithic strata, (2) coal stringers, and (3) a lack of migratory pathway due to transgressive estuarine central basin mudstone and tidal flat deposits between source beds.

10. A preliminary chemostratigraphic investigation using samples from drill core was initiated to determine the viability of this correlations method. While samples were combined from numerous drill cores and compiled into a pseudo well, the comparison of elemental ratios suggests samples of similar lithologies could be differentiated.

Future Work

A combined petrographic and provenance study of the Lower Cretaceous interval on the east flank of the Sweetgrass arch would provide insight as to where sediment was sourced. Understanding sediment provenance would increase the ability to discern the general direction of incised valley-fill systems

A future study building on the chemostratigraphic investigation presented here and by Hildred et al. (2010) could prove chemostratigraphy to be a much more informative method of delineating and correlating between units of similar lithology. Specifically, where Jurassic sandstone is in contact with Cretaceous sandstone or in nested incised valley-fill systems where multiple incisional events have put genetically unrelated sandstone bodies in contact. Due to the lack of drill core, analyzing the vast

amount of drill cuttings available should be considered as a potential project as drill cuttings are much more common and less expensive than drill core.

A seismic survey would be the most useful data set, beyond drill core from new wells, that could enhance the results of this study. While the valley-fill model here could still be incorporated, a much higher-resolution geomorphic expression of the valley system could be identified. Production in this interval is constricted to valley-fill sandstone within the center of the valley, amongst other controls. Seismic mapping would increase the ability to directly target these deposits rather than unproductive interfluvial drilled due to poor well control.

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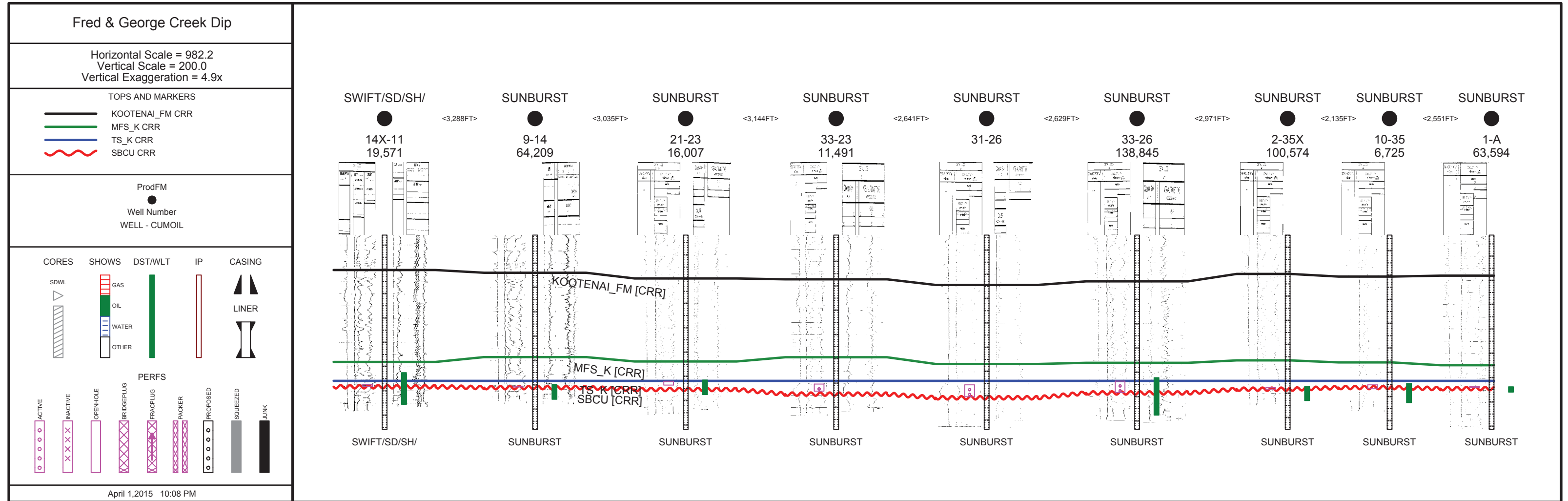
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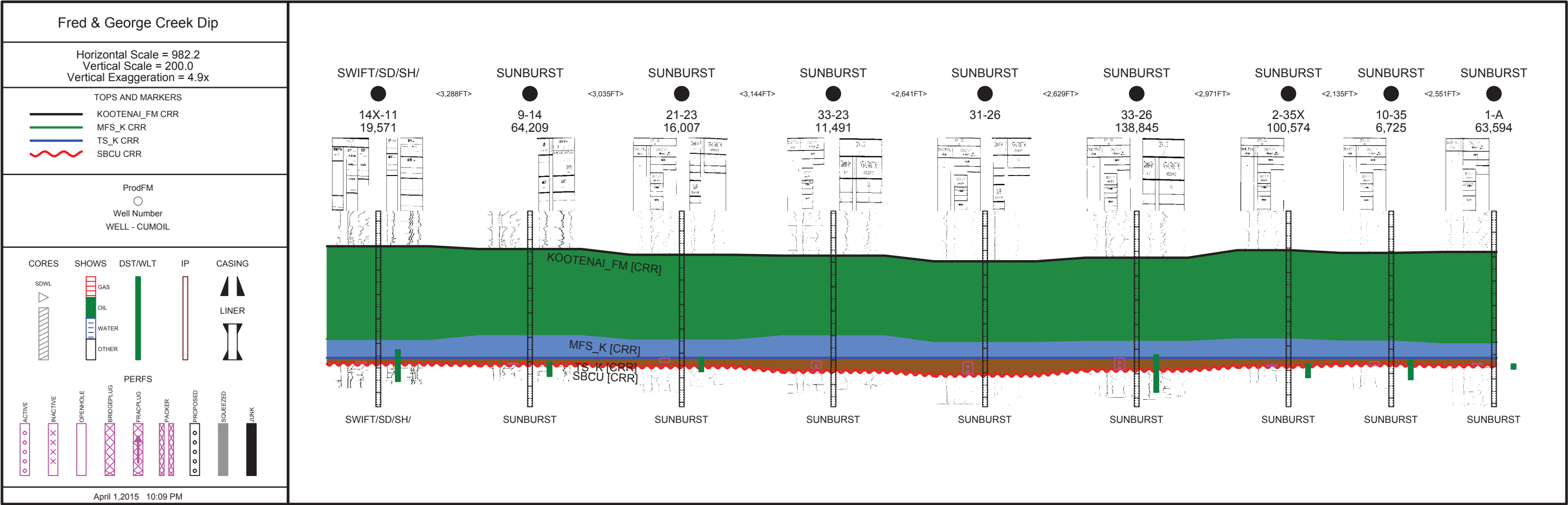
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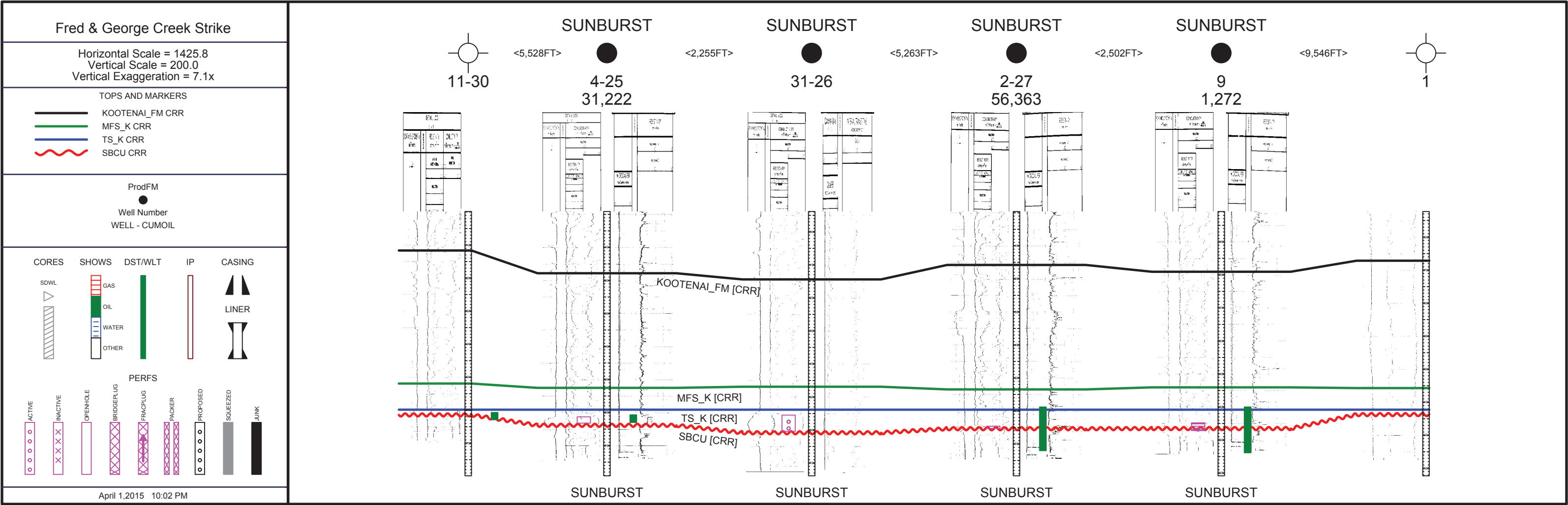
APPENDICES

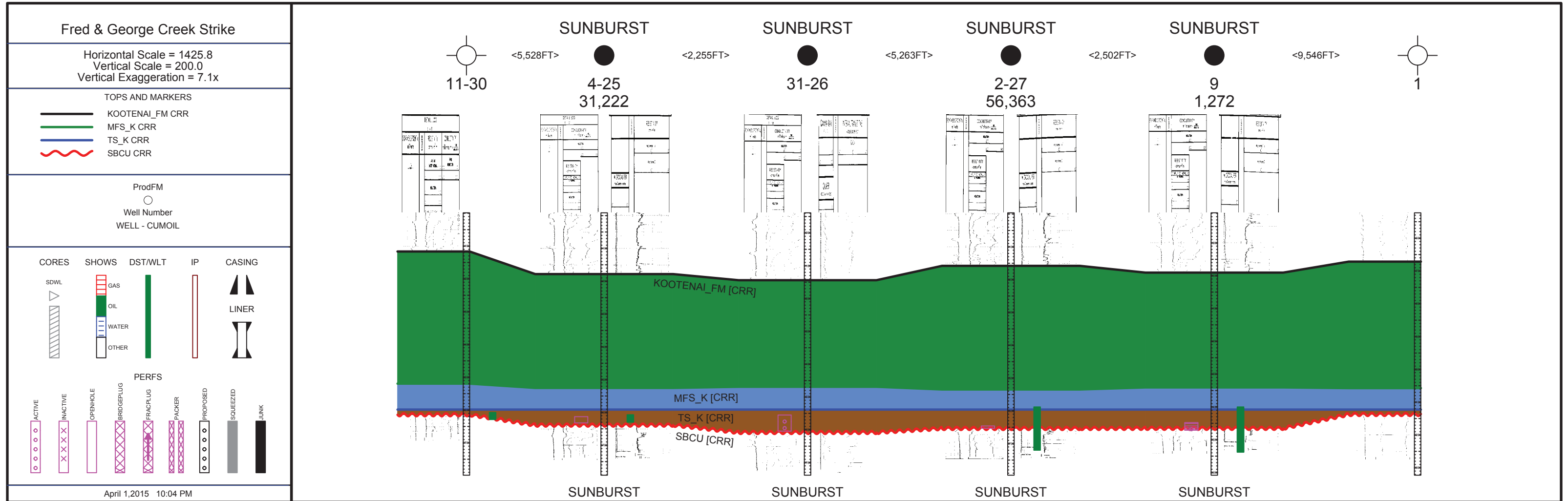
APPENDIX A

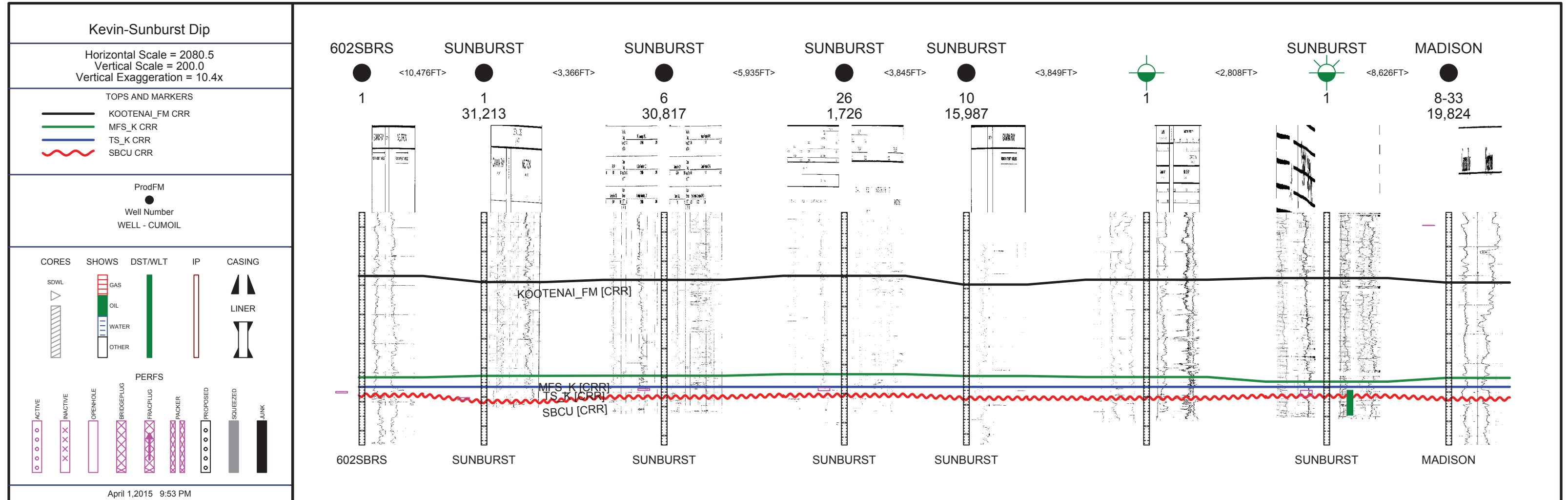
ADDITIONAL FIGURES (INCISED VALLEY FILL-SYSTEM
CROSS-SECTIONS & MAP)

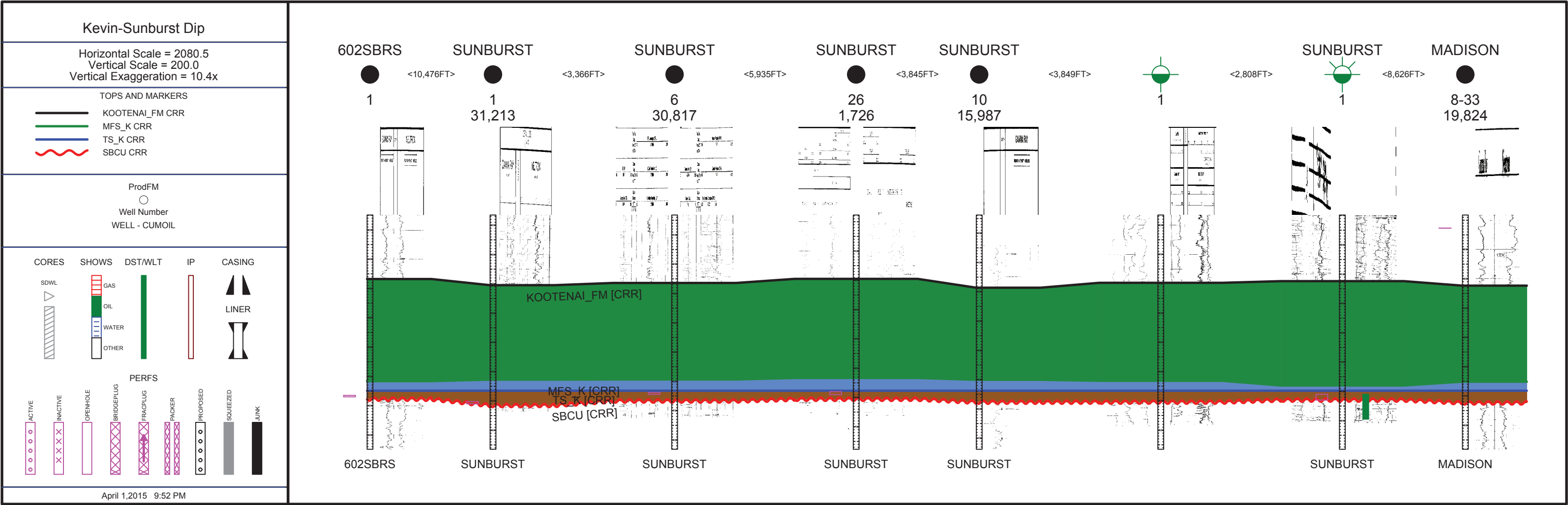


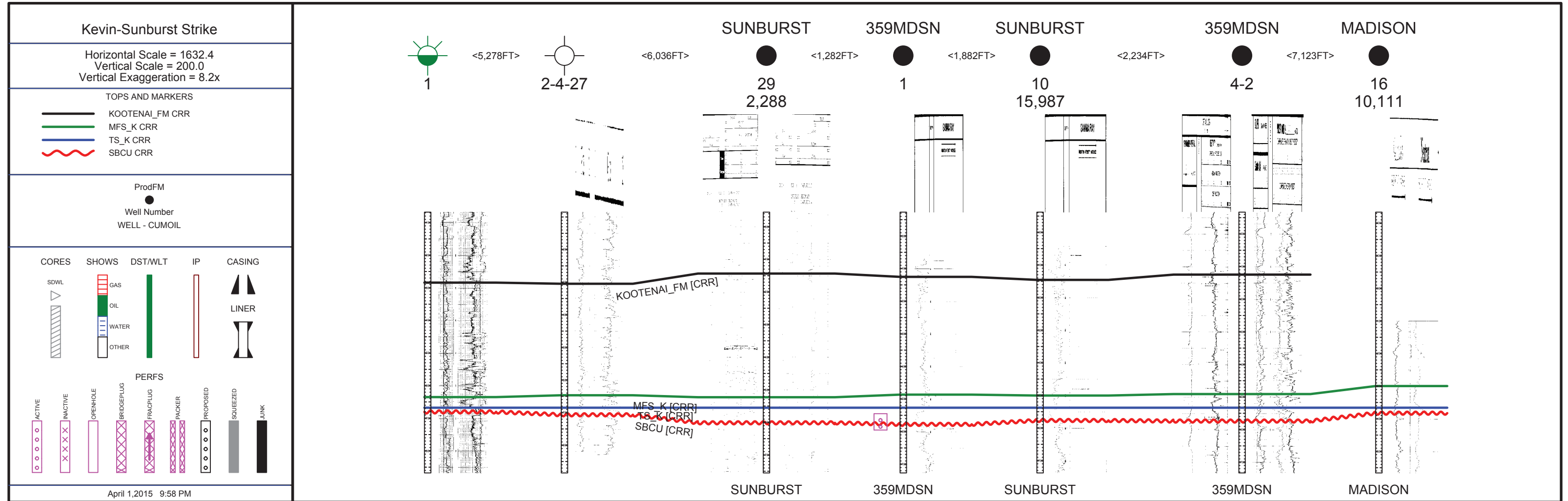


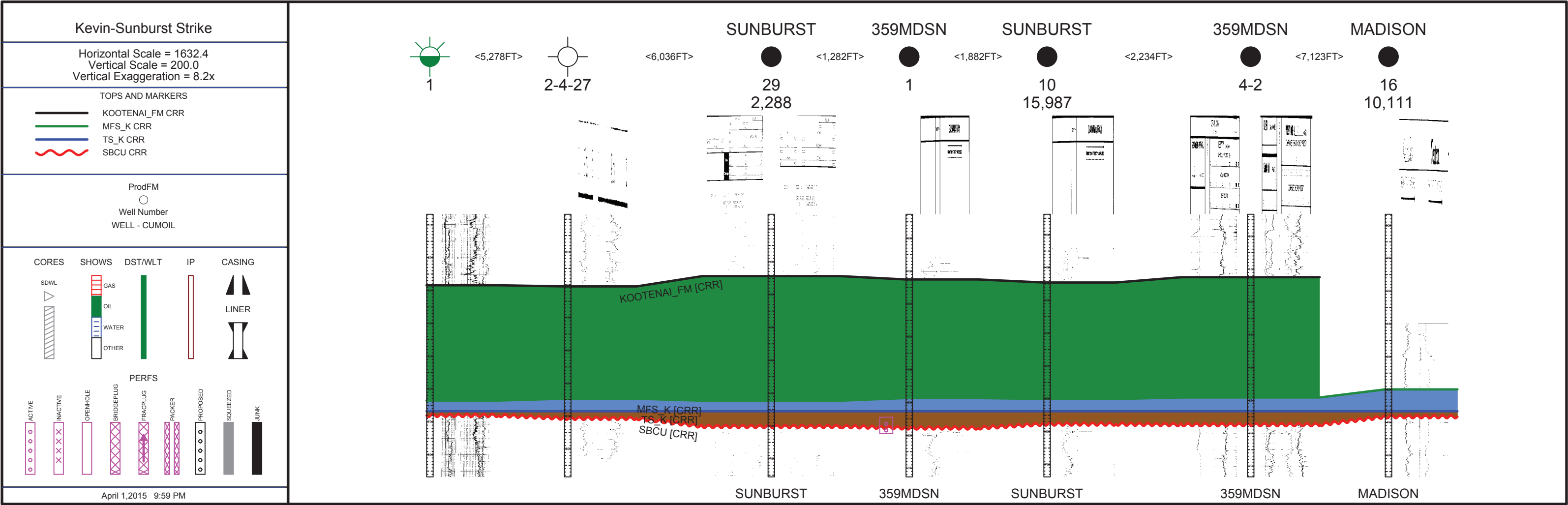




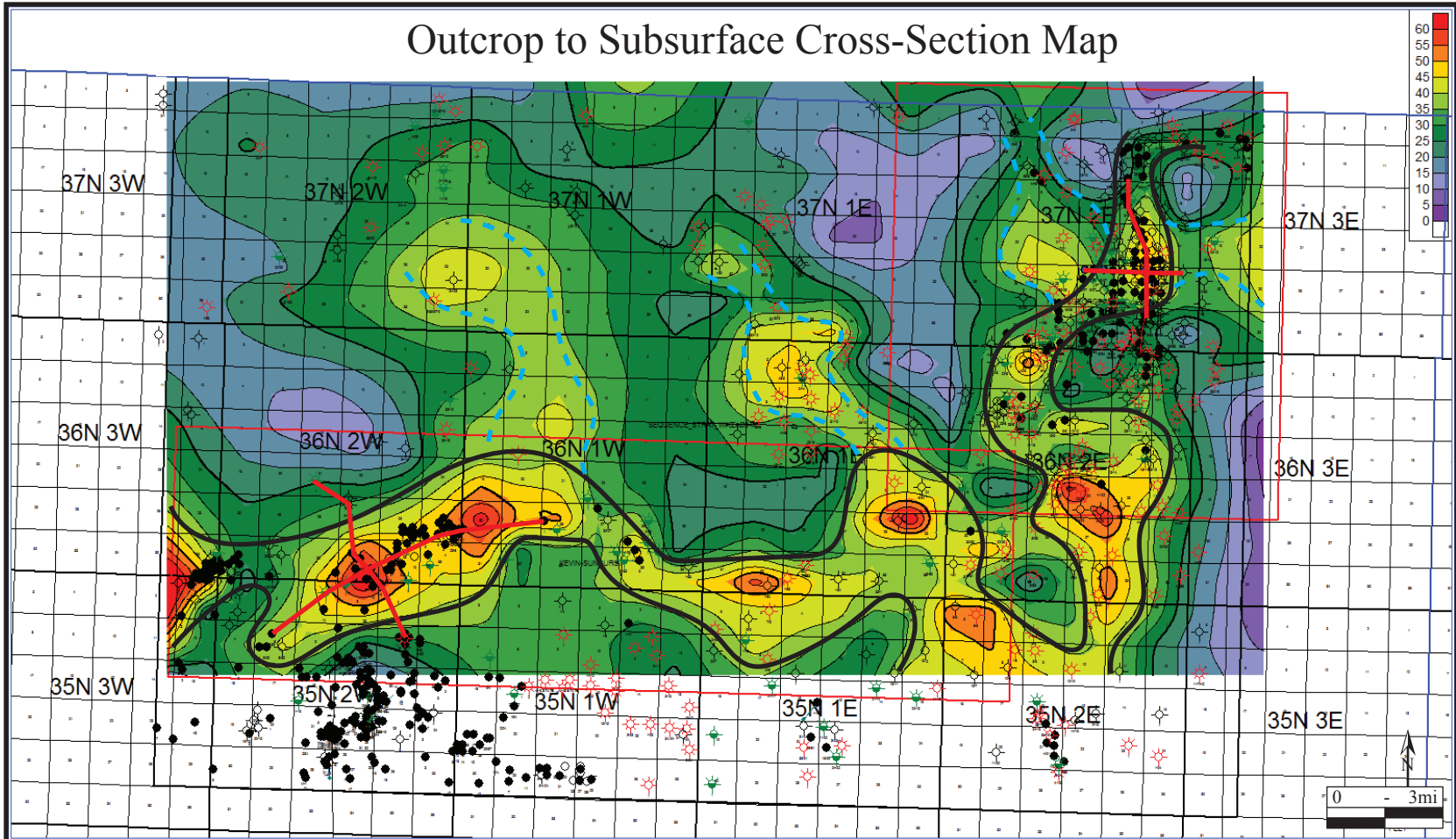








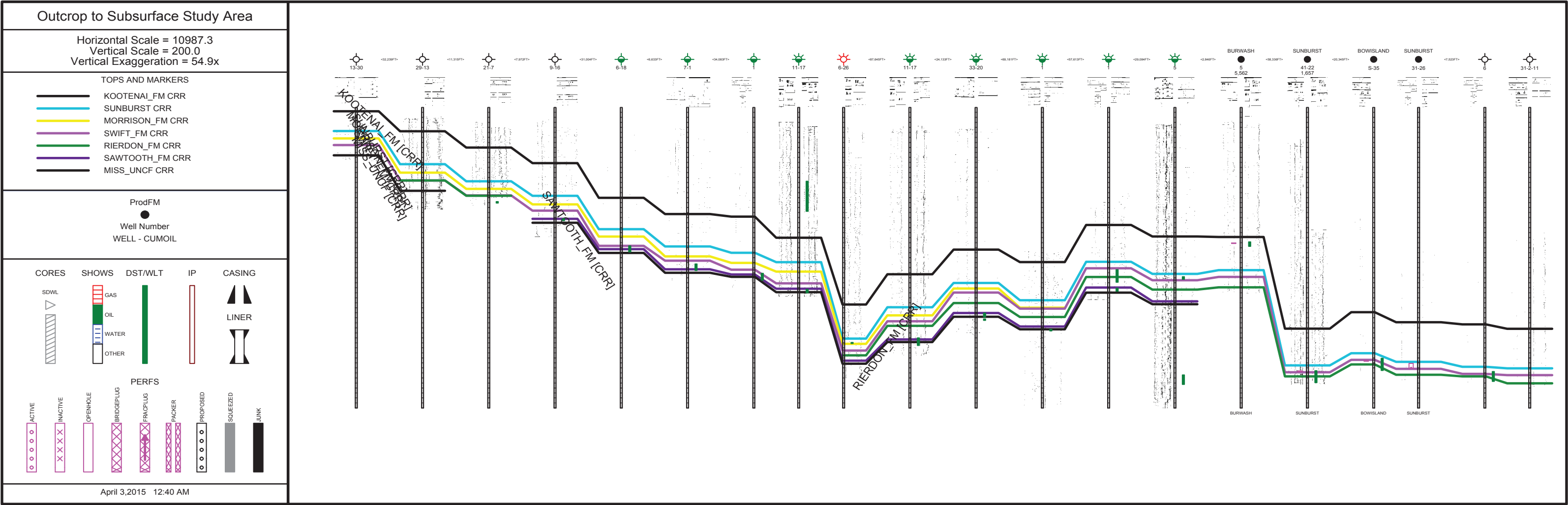
Outcrop to Subsurface Cross-Section Map



Map of wells used in cross-section from near outcrop to subsurface outcrop in the north. Distance is roughly 150km (93mi). Sunburst Incised Valley-Fill System isochore map. Incised Valley-Fill System mapped from sequence boundary to transgressive surface.

APPENDIX B

ADDITIONAL FIGURES (OUTCROP STRATIGRAPHY/CORRELATION)



Characteristics of Facies Associations from Outcrop				
Facies Association (Code, Name, and Color Scheme)	Lithology, Grain Size	Bedding Characteristics	Bed Measurements: m(ft) or cm(in)	Total Outcrop Thickness: m(ft)
FA1: Middle Shoreface	VF-M Sand	Coarsening upward	20cm-1m (7.9-3.3ft)	20m (65.6ft)
	Mud	Beds are tabular to slightly wavy, generally coarsening upward	20-30cm (7.9-11.8in)	
FA2: Fluvial Channel Fill	F-C Sand	Lenticular, Amalgamated, Rarely Fining upward	0.6-2.4m (2-8ft)	6.1-9.1m (20-30ft)
FA3: Estuarine System: Bayhead Delta	F-M Sand	Lenticular	4m (13.1ft)	2-13m (6.5-42.6ft)
	Mud	Thinly interbedded with sandstone	n/a	
FA4: Estuarine System: Central Basin	Mud	Thin planar beds (thickness is estimate, often covered)	2.5-5.1cm (1-2in)	3-6m (12-20ft)
FA5: Estuarine System: Mouth-sand Bodies	F-M Sandstone	Very thick stacked planar cross-bedded sandstones, beds thin near very top	Average cross-bedded set thickness 0.9m (3ft)	7.6-12.5m (25-41ft)
	Mud	Only occurs at very top of stacked succession	n/a	

Characteristics of Facies Associations from Outcrop Cont'd				
Facies Association (Code, Name, and Color Scheme)	Lithology, Grain Size	Bedding Characteristics	Bed Measurements: m(ft) or cm(in)	Total Thickness: m(ft)
FA6: Tidal Flat	Heterolithic: F-M Sand with mud interbedded	Upward fining beds, generally tabular	5-30cm (2-11.8in)	4-4.5m (13-14.7ft)
FA7: Alluvial Plain System: Flood Plain	VF Sand to mud	Tabular sheet geometry, generally fining upward	15cm-2m (5.9in-6.6ft)	21m (70ft)
	Paleosol (pedogenically altered mudstone)	No distinctive bedding surfaces beyond alternating maroon and grey to dark grey colors	Total Thickness: 1-1.5m (3.3-4.9ft) Alternating color: 15.2-30.5cm (6-12in)	
FA8: Alluvial Plain System: Channel	F-M Sand	Highly variable thickness, slightly lenticular to sheet-like, clay-clasts near base of coarsest sand common	0.61-1.5m (2-5ft)	
	Mud	Appears throughout succession, may be slightly laminated, commonly occurs with iron nodules and coal stringers	20.32-30.5cm (8-12in)	