SEQUENCE STRATIGRAPHY AND FACIES ANALYSIS OF THE ROLLINS SANDSTONE MEMBER (MOUNT GARFIELD FORMATION) AND RE-EXAMINATION OF THE CONTACT BETWEEN THE MOUNT GARFIELD AND WILLIAMS FORK FORMATIONS (LATE CRETACEOUS)

BY

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ABSTRACT

The Cretaceous Rollins Sandstone Member (Mount Garfield Formation) is the youngest marine sandstone deposited within the Sevier foreland basin in Colorado. The Rollins Sandstone Member is a complicated stratigraphic unit that consists of four progradationally stacked sequences. These sequences were deposited as a result of high-frequency changes in sea level. Each sequence initiates with an incised valley fill and contains a single parasequence within the highstand systems tract. Parasequences within highstand systems tracts contain offshore to marine-shoreface deposits. The top of the Rollins Sandstone Member is a surface that results from the progradation of a single strandline. This surface can be used as a regional datum. This new datum indicates there is no upward-climbing geometry at the top of the Mount Garfield Formation, and the Rollins Sandstone Member and the Cameo Wheeler coal zone (of the Williams Fork Formation) are not time-equivalent units. The marine-shoreface deposits within the Rollins Sandstone Member represent high-energy shorefaces. These shorefaces had daily wave heights of 1-2 m and Nor'easter-scale storms occurring several times a year. These high-energy conditions produced a straight coastline along the western edge of the Cretaceous Western Interior seaway.

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CHAPTER ONE

Introduction

The purpose of this study is to produce a detailed sequence-stratigraphic correlation of the Rollins Sandstone Member of the Mount Garfield Formation and a hydrodynamic facies interpretation of shoreface sandstones within the Rollins Sandstone Member. Controversy exists as to the nature and geometry of the contact between the Mount Garfield Formation and the Williams Fork Formation; this study proposes a new interpretation for this contact as well as an interpretation of the internal stratigraphy of the Rollins Sandstone Member. The Rollins Sandstone Member contains marine-shoreface sandstones, and unlike most shoreface deposits within the Sevier foreland basin, these units have not been interpreted in great detail. This study interprets these shoreface sandstones in terms of the hydrodynamic conditions that occurred at the time of deposition. This facies interpretation improves our understanding of these deposits, and the nature of the environment during the deposition of the shoreface.

The Mount Garfield Formation is made up of three sandstone members, from oldest to youngest, Corcoran Sandstone, Cozzette Sandstone, and Rollins Sandstone members. The sandstone members are by tongues of Mancos Shale. These units were originally described by Hancock (1925). The lower two members of the Mount Garfield Formation have been described and documented (Madof, 2006; Zater, 2005). These studies produced sequence-stratigraphic correlations of these units. Correlations of the Rollins Sandstone Member have been done by Kirschbaum and

Hettinger (2004) and Gill and Hail (1975), but these correlations were done on a regional scale. Chapter Two focuses on the sequence-stratigraphic interpretation of the Rollins Sandstone Member and the contact between the Rollins Sandstone Member and Cameo-Wheeler coal zone. This chapter will discuss the geologic problems with the previous interpretations of the Rollins Sandstone Member and offer an alternative interpretation based on the sequence-stratigraphic approach of this study. Chapter 2 also describes the internal stratigraphy of the Rollins Sandstone Member and interprets the history of change in sea level during the deposition of this member.

The Rollins Sandstone Member contains a thick marine-shoreface sandstone that is a cliff-forming unit of the Book Cliffs east of Grand Junction, Colorado. Chapter Three contains a detailed facies interpretation of this marine-shoreface sandstone. The facies interpretation focuses on the hydrodynamics along the shoreface (wave height, storm intensity etc). Detailed descriptions of each sub-environment within the shoreface succession (upper shoreface, lower shoreface, etc) were used to make comparisons to deposits described in modern settings. Using flow-regime concepts and comparisons to modern settings, sub-environments of the shoreface were interpreted, and approximate values for wave height and storm intensity were assigned.

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CHAPTER TWO

Sequence Stratigraphy of the Late Cretaceous Rollins Sandstone Member (Mount Garfield Formation) and Re-Examination of the Mount Garfield and Williams Fork Formation Contact, Piceance Basin, Colorado

INTRODUCTION

The Rollins Sandstone Member (Late Campanian) is the youngest member of the Mount Garfield Formation and records the last pulse of marine sedimentation within the Sevier foreland basin (SFB) (Figure 1). The Cameo-Wheeler coal zone is the oldest unit within the overlying Williams Fork Formation. The formation contact marks the transition from marine-dominated deposition in the Mount Garfield Formation to fluvial-dominated deposition in the overlying Williams Fork Formation. A published correlation of the Rollins Sandstone Member and Cameo-Wheeler coal zone portray the contact between the two formations as an upward-climbing surface with a stair-stepped geometry (Figure 2) (Kirschbaum and Hettinger, 2004). This interpretation of the formation contact is based on a correlation of the Rollins Sandstone Member that interprets the unit as multiple progradationally stacked parasequences (Figure 2). A stair-stepped geometry along this formation contact implies a genetic and temporal relationship between the Rollins Sandstone Member and the Cameo-Wheeler Coal zone, i.e. time lines should cross the formation contact (Figure 2). Patterson (2003) interprets this contact to be unconformable in nature. An unconformity along the formation contact makes the upward-climbing geometry difficult to explain. The purpose of this research is to produce a detailed sequence-stratigraphic analysis of the Rollins Sandstone Member, which will resolve these issues.

The lower two members of the Mount Garfield Formation are well studied and interpreted in a detailed sequence-stratigraphic framework (Madof, 2006; Zater, 2005). A detailed sequence-stratigraphic study of the Rollins Sandstone Member, however, is lacking. The Rollins Sandstone Member has a complex internal stratigraphy with current interpretations showing parasequence boundaries that terminate within the Rollins Sandstone Member (Hettinger and Kirschbaum, 2002) with no explanation for the complexity. A detailed sequence-stratigraphic interpretation explains these stratal complexities and allows for more accurate correlations of the underlying (Cozzette Sandstone Member) and overlying (Cameo-Wheeler coal zone) stratal units. The Cameo-Wheeler coal zone is a fluvial-dominated unit with no internal surfaces on which to correlate, so the top of the Rollins Sandstone Member is used as a datum for correlation of this interval. Analysis of the Rollins Sandstone Member, using a sequence stratigraphic framework, establishes the history of relative changes in sea level that occurred during the deposition of the strata and how these changes produce the complex stratigraphic architecture of this member.

GEOLOGIC SETTING

The Mount Garfield Formation and Cameo-Wheeler coal zone of the Williams Fork Formation were deposited within the Sevier foreland basin (SFB), approximately 200 km east of the Sevier thrust belt (Cole and Cumella, 2003; Hettinger and

Krischbaum, 2002) and approximately 150-200 km west of the forebulge. Current interpretations place the forebulge in central Colorado (DeCelles, 2004; DeCelles and Coogan, 2006). Strata of the Mount Garfield Formation and Cameo-Wheeler coal zone are exposed discontinuously from the Colorado and Utah state line to approximately 10 km east of Grand Junction, Colorado. These strata dip into the subsurface to the north and east of Grand Junction. Outcrop exposures of the Rollins Sandstone Member and Cameo-Wheeler coal zone were analyzed along the Colorado section of the Book Cliffs near Grand Junction, Colorado (Figure 3).

METHODS

This is an outcrop-based study supplemented by subsurface data. Six sections were measured along the dip-oriented outcrop exposure of the Rollins Sandstone Member. Sections were measured on a bed-by-bed basis. Facies were defined and described based on grain size, grain-size trends, and internal sedimentary structures. Facies were then interpreted based on depositional environment, and parasequence and sequence boundaries were identified in each section based on facies stacking patterns. Six well logs were also correlated both parallel to and down-dip from the outcrop. Well-log facies were based upon gamma-ray trends, indicating the amount of sand/shale within a succession, and upon porosity trends. Interpretation of well-log facies was based on analogy to adjacent surface successions. Each section was correlated to the next measured section or well log using a floating datum. In order to strengthen the correlation of the Rollins Sandstone Member, the sequence stratigraphic correlation of the Cozzette Sandstone Member from Madof (2006) was used in this correlation and extended into the subsurface using the well-log data in this study (Plate 1).

DEPOSITONAL FACIES

In outcrop, the Rollins Sandstone Member consists of upward-coarsening packages, up to 40 m in thickness, representing marine-shoreface deposits, and thinner successions, less than 20 m, of stacked marginal marine deposits. Marginal marine deposits consist of thin (less than 6 m) sandstone-and mudstone-dominated intervals in both upward-coarsening and upward-fining genetic packages. The Cameo-Wheeler coal zone contains abundant, thick coals (1-11 m) interbedded with fluvial sandstones (1-6 m thick) and overbank deposits (up to 20 m thick).

Upward-coarsening HCS, cross-stratified, and planar-bedded facies

This facies is found within the Rollins Sandstone Member and consists of upward-coarsening sandstone-dominated packages ranging in thickness from 30 to 40m. Individual upward-coarsening packages grade from interbedded siltstone and silty mudstone at the base to fine-grained quartz-rich sandstone at the top. The base of each succession consists of interbedded thin (cm scale) siltstones and silty mudstones. These fine-grained sediments are typically slope formers. The interbedded siltstone and mudstone grade vertically into hummocky cross-stratified (HCS) sandstone beds interbedded with silty mudstone (Figure 4 and 5). Interbedded HCS sandstones and silty mudstones grade vertically into amalgamated (meter scale) beds of hummocky cross-stratified sandstone. Amalgamated HCS beds are overlain by a 0.5-2 meter succession of bioturbated sandstone containing abundant *Ophiomorpha* (Figure 6).

This bioturbated interval grades into 8-9 m of trough and wedge-shaped cross-stratified sandstone (Figure 7). The top of the succession consists of low-angle planar-bedded sandstone.

The described vertical succession is similar to the vertical profile of wave-dominated shoreface successions interpreted for other foreland basin sandstones (Figure 8) (Brown et al., 1986; Cole and Cumella, 2003; Hettinger and Kirschbaum, 2002; Kamola and Van Wagoner, 1995; Kirschbaum and Hettinger, 2004; Patterson, 2003; Plint et al., 1988; Power, 1988; Van Wagoner, 1990; Varban and Plint, 2008). These thick, upward-coarsening successions represent deposition during progradation of wave-and storm-dominated marine shorefaces (Clifton, 2006; Kamola and Van Wagoner, 1995; Schwartz and Birkemeier, 2004; Reinson, 1984). Interbedded siltstones and silty mudstones at the base of the succession are offshore transition deposits (Figure 8). Thin beds of siltstone within the offshore-transition deposits represent the distal parts of storm beds. Silty mudstones that are interbedded with distal storm beds represent fair-weather deposits (Clifton, 2006; Kamola and Van Wagoner, 1995; Schwartz and Birkemeier, 2004). Beds of HCS sandstone represent storm deposits in the lower shoreface developed by combined-flow (oscillatory and unidirectional) currents. These combined-flow conditions are generated during large storms along the shoreface (Clifton, 2006; Duke et al., 1991; Swift et al, 1983; Reinson, 1984)). Bioturbated sandstones above the lower shoreface deposits are interpreted as middle-shoreface deposits, and most likely represent preservation of the trough of a bar on a barred shoreface (Davidson-Arnott and Greenwood, 1974; Howard and Reinech, 1981; Reinson, 1984; Schwartz and Birkemeier, 2004). Cross-stratified sandstone records the migration of three-dimensional bedforms formed by daily wave action in the upper shoreface (Clifton, 2006; Reinson, 1984; Kamola and Van Wagoner, 1990; Reinson, 1992). Low-angle, planar-bedded sandstones were deposited in the swash zone and represent foreshore deposits (Clifton, 2006; Kamola and Van Wagoner, 1990; Reinson, 1984; Schwartz and Birkemeier, 2004). Individual progradational marine sandstones form a single parasequence (Kamola and Van Wagoner, 1995; Van Wagoner, 1990).

Laminated mudstone facies

This facies consists of 2-4 m thick successions of siltstone and mudstone. This fine-grained facies is typically a slope former, and is poorly exposed within the field area. These successions show a slight upward-coarsening trend and grade from mudstone at the base to interbedded siltstone and mudstone at the top (Figure 9). Mudstones are laminated to very thinly bedded (mm to cm scale bedding). Beds of siltstone are continuous across the outcrop exposure and contain wave-ripple cross-stratification. This facies typically overlies regional erosional surfaces.

This fine-grained facies represents deposition in a protected low-energy setting such as an estuary, embayment, or lagoon. Laminated mudstone and siltstone represent suspension fall out in a low-energy setting. Wave ripple cross-stratification indicates some wave energy within this environment. These finer-grained deposits represent bay-fill mudstones similar to the central-basin facies described by Dalrymple et al. (1992).

Heterolithic (interbedded sandstone and mudstone) channel-fill facies

This facies consists of upward-fining, sandstone-dominated successions ranging from 2-6 m in thickness (Figure 10). Sandstone grades from fine-grained sandstone at the base to very-fine-grained sandstone at the top of a succession. Individual upward-fining successions have erosional (scoured) bases. Bedding thickness decreases vertically and ranges from 40 cm at the base to a few cm thick at the top of the succession. Bedding at the top of the succession consists of thin (cm scale) heterolithic strata of interbedded sandstone and mudstone. Sandstones contain medium- to thickly-bedded (15-40cm scale) trough and wedge-shaped cross-stratification and planar-tabular cross-stratification with abundant mud drapes, double mud drapes, and reactivation surfaces (Figure 11 and 12). Planar bedding, as well as current-ripple and wave-ripple cross-stratification are present within thinner sandstone beds at the top of the succession and occur interbedded with larger-scale cross-stratification. Flaser bedding is common within ripple bedded sandstone. Locally, larger-scale cross-bedding is interbedded with current-ripple cross-stratification where foreset lamina of the ripples dip in the opposite direction to the foresets of the cross-beds. *Ophiomorpha* is abundant within the facies. These sandstones overlie laminated mudstone deposits.

These upward-fining units represent tide-influenced channel-fill deposits. Upward-fining grain-size trends and erosional (scoured) basal contacts indicate deposition within channels. The medium-scale trough and wedge-shaped cross-stratification formed during the migration of three-dimensional mega-ripples. Planar-tabular cross-stratification formed during the migration of two-dimensional megaripples. Medium-scale cross-stratification, as well as upper-flow-regime planar bedding indicate high-energy events during the early stage of channel deposition. Interbedded medium-scale and current-ripple cross-stratification indicate alternating high- and low-energy conditions, as the channels filled. Mud drapes and double mud drapes record periodic slack water conditions. Mud drapes within cross-stratification, flaser bedding, and heterolithic strata indicate alternating tractive and non-tractive flow within the channel, and are diagnostic of tidal environments (Clifton, 2006; Dalrymple, 1992). Opposing dip directions on cross-straitification indicate bi-modal flow direction. Bi-modal cross-stratification most likely records both the ebb and flood tidal currents within the channels. Marine influence is indicated with the presence of *Ophiomorpha* (Frey and Howard, 1990; Kamola, 1984; Pemberton et al., 1992).

Fine-grained ripple-bedded sandstone and laminated siltstone facies

Deposits of this facies are composed of upward-coarsening successions of sandstone and siltstone ranging from 2-6 m in thickness (Figure 13). This facies is poorly exposed compared to the more sandstone-dominated facies in the field area. A single upward-coarsening package grades from laminated mudstone and siltstone at the base to very fine-grained sandstone at the top. Laminated siltstones and mudstones at the base of the succession grade vertically into interbedded very-fine-grained sandstone and mudstone containing wavy to lenticular bedding and wave-modified current-ripple cross-stratification (Figure 13). Sandstone bed thickness increases vertically through the succession and ranges from centimeter-scale to 0.25 m in thickness. Sandstone beds at the top of each succession contain current-ripple cross-stratification. Flaser bedding is found locally. Traces include *Ophiomorpha* and *Arenicolites*. *Arenicolites* is found primarily in the lower half of the succession while *Ophiomorpha* is found near the top of the succession. This facies is laterally associated with the heterolithic channel-fill facies and commonly overlies laminated mudstone deposits.

These upward-coarsening successions are interpreted as small-scale deltas that prograded into a protected body of water such as an estuary or lagoon. The overall upward coarsening as well as the vertical increase in sandstone-bed thickness indicate that these were progradational successions. *Ophiomorpha* and *Arenicolites* are considered marine to marginal-marine indicators and indicate this facies had some marine influence (Frey and Howard, 1990; Kamola, 1984; Pemberton et al., 1992). Wavy, lenticular, and flaser bedding as well as lateral association with tidally influenced channels indicate tidal processes within this environment (Dalrymple, 1992). Wave-modified current ripples indicate some wave energy, but a lack of abundant wave-formed structures indicates this environment was protected. This facies is similar to thin progradational successions described by Dalrymple et al. (1992) as bay-head deltas. The laminated mudstone facies overlain by heterolithic channel-fill facies or fine-grained ripple-bedded sandstone and laminated siltstone facies make up an estuarine facies succession.

Cross-stratified channel-fill facies

This facies is found within the Cameo-Wheeler coal zone and consists of laterally discontinuous, upward-fining sandstones. These sandstones have concave-up, erosional lower contacts and grade from fine-grained sandstone at the base to very-fine-grained sandstone at the top. Sandstones contain lateral-accretion surfaces that extend from the top to the base of the sandstones. Individual sandstone beds contain small-scale (10-15 cm scale) planar-tabular cross-stratification and current-ripple cross-stratification. Planar-tabular cross-stratification is found primarily at the base of each bed while current-ripple cross-stratification is more common at the top of an individual bed. Climbing-ripple cross-stratification is found locally. Rip-up clasts are common at the base of sandstones and along lateral-accretion surfaces. *Teredolites* and *Ophiomorpha* are present, but are not common (Figure 15). Sandstones are single story and have a maximum thickness of 6 m and a lateral continuity of 10’s-100’s of m across the outcrop exposure (Figure 16).

These discontinuous, upward-fining sandstones represent fluvial channel-fill deposits. Upward fining and erosional (scoured) basal contacts indicate deposition within channels. Lateral accretion surfaces indicate these were meandering channels in a low-gradient fluvial system (Allen, 1963; Bridge, 2006; Maill, 1996). Sandstone beds with a vertical decrease in scale of cross stratification record individual depositional events in the fluvial system. The occurrence of *Ophiomorpha* and *Teredolites* indicates that some of these fluvial channels had some connectivity with marine waters (Frey and Howard, 1990; Kamola, 1984; Pemberton et al., 1992).

Organic-rich mudstone and siltstone facies

This facies consists of successions of mudstone and siltstone within the Cameo-Wheeler coal zone. These mudstones and siltstones are laterally associated with the cross-stratified channel fill facies. Mudstones and siltstones are poorly laminated or structureless. The lack of any visible internal structures may be a result of poor exposure. The siltstones and mudstones range in color from dark brown to black. Organic material and carbonaceous plant fragments are common within the facies, and rooting is found locally.

Siltstones and mudstones associated with meandering fluvial channel-fill sandstone deposits are interpreted as overbank and flood-plain deposits (Allen, 1963). The dark brown to black color of these mudstones is caused by preserved organic material and indicates deposition in a poorly drained floodplain (Potter et al, 2005).

Coal

Coal beds are found within the Rollins Sandstone Member and the Cameo-Wheeler coal zone. Those within the Rollins Sandstone Member are thin (few cm to 25cm), poorly exposed, and occur interbedded with heterolithic channel-fill and fine-grained ripple-bedded sandstone and laminated siltstone facies. These thin coals represent the preservation of organic material at the top of individual facies successions.

Coal beds within the Cameo-Wheeler coal zone are interbedded with cross-stratified channel-fill and organic-rick mudstone and siltstone facies. These coals typically range from 1-4 m in thickness but can reach 11 m in thickness. Coal beds cannot be traced from one measured section or well log to the next and are interpreted to be laterally discontinuous. In some locations, thick coals (4-11 m) directly overlie the contact with the Rollins Sandstone Member (Figure 17). Contacts between coal beds and the underlying and overlying strata are sharp. Coals within the Cameo-Wheeler coal zone are clean, containing little to no sediment. Thick, siltstone-free coal beds within the SFB have been interpreted as raised mires (McCabe and Parrish, 1992; McCabe, 1984). The discontinuous coal beds within the Cameo-Wheeler coal zone represent isolated mires (McCabe, 1984).

Well-log facies

Facies interpretations based on the outcrop exposures were carried into the subsurface. Well-log facies were interpreted using gamma ray, neutron, and density porosity data where available. Well-log facies identified within the Rollins Sandstone Member and Cameo-Wheeler coal zone include upward-cleaning mudrock-sandstone successions, interpreted as progradational marine sandstones (marine shoreface sandstones), clean sand grading into shale, interpreted as channel-fill sandstones, low gamma, high apparent porosity beds interpreted as coals, and intervals with variable gamma-ray intensity and apparent porosity interpreted as interbedded sandstone and mudstone facies. These well-log facies were identified based on analysis of well-log curves as well as comparison with outcrop exposures (Table 1).

REGIONAL CORRELATION AND SEQUENCE STRATIGRAPHY

The Rollins Sandstone Member contains strata from four depositional sequences (Figure 18; Plate 1). Only the middle two sequences occur entirely within the Rollins Sandstone Member; part of the youngest and oldest depositional sequences occur in the underlying member and overlying formation, respectively (Figure 18; Plate 1). The sequence-stratigraphic nomenclature used in this study was inherited from previous studies of the Mount Garfield Formation (Madof, 2006; Zater, 2005) (Figure 18). Sequences within the Mount Garfield Formation are named for the member in which the sequence initiates. Sequences in each member are given a prefix: for example CZ = Cozzette Sandstone Member and R = Rollins Sandstone Member. Sequences within each member are then numbered from base to top with subscripts (e.g. R_1, R_2, etc.). Sequences consist of an incised-valley fill and a highstand systems tract. Incised-valley fills (IVF) in each sequence are labeled for the sequence in which they occur (IVF-R_1, IVF-R_2 etc). Parasequences (PS) within the highstand systems tract of each sequence are also labeled based on the sequence in which they occur (R_1-PS1, R_2-PS1, etc.). This method is made complicated when the location of the basal sequence boundary of a depositional sequence is unknown (for example sequence R_1).

Due to the internal stratigraphic complexity of the Mount Garfield Formation, a single thorough-going surface (i.e datum) does not exist. A floating datum, therefore, is used to correlate measured sections and well logs. The floating datum is picked in a number of ways. Whenever possible, the foreshore of a marine-shoreface deposit within a parasequence is used. The top of the foreshore of a marine shoreface deposit within sequence R_2 was used where it wasn’t eroded. In sections where the top of sequence R_2 was eroded the top of a foreshore of a marine shoreface deposit within sequence CZ_1 was used. This method does not work in locations where shoreface deposits have been eroded. In one location (Farmers Mine), the tops of incised-valley-fill deposits were used to correlate from one section to another.

Sequence stratigraphic analysis allows for interpretation of the magnitude and history of sea-level change that led to the deposition of strata. It also provides a means to trace the history of shoreline movement through time. To trace shoreline movement through time, the terms depostitional and transgressive shoreline are distinguished. These terms are used to describe the marine shoreline at different stages during the deposition of the Rollins Sandstone Member. The transgressive shoreline is a short-lived feature that develops during rising sea level and is not preserved in the rock record. The transgressive shoreline consists of a relatively thin, temporary sand sheet that is reworked and pushed landward through the process of washover. A thin lag deposit, an erosional surface (ravinement surface) or simply a parasequence boundary may be all that is left of the transgressive shoreline (Clifton, 2006; Van Wagoner, 1990). Examples of modern transgressive shorelines are found along the east coast of the United States. The depositional shoreline succession is a depositional feature that develops during sea-level still stands or when sediment supply outpaces any rise in sea level, and the shoreline progrades basinward. Depositional shoreline successions have a high preservation potential and often are preserved in the highstand systems tract of a depositional sequence (Van Wagoner, 1990).

Estimates of the minimum amount of sea-level fall are made by measuring the maximum amount of incision within incised valleys. This can be underestimated if the exposed section is located on the margin of the incised valley, and not along the axis of the valley. In modern environments, such as the Mississippi River, the base of a channel can be below sea level (Aslan, 1999). Incision estimates will be accurate only if the base of the valley is a subaerial exposure surface. If not, the distance between the top of the valley (e.g. the flooding surface at the base of the highstand systems tract) and the lowest subaerial exposure surface is used to determine the magnitude of sea-level fall. The range of sea-level falls for the Rollins Sandstone

Member is estimated between 15-23 m. The details of sea-level change for the Rollins Sandstone Member will be discussed in this section.

The lower two sequences within the Rollins Sandstone Member (CZ_2 and R_1) are poorly exposed and relatively thin compared to the overlying sequence (R_2). These lower two sequences (CZ_2 and R_1) consist primarily of fine-grained sediment. The basal sequence boundary of sequence CZ_2 is a regional erosional surface that truncates marine shoreface deposits of the underlying sequence (Plate 1). The erosional surface is overlain by thin (2-4 m thick) successions of tide-influenced channel-fill and bay-head delta deposits. Tide-influenced channel-fill deposits overlying lower shoreface deposits represents a basinward shift in facies. This facies relationship is observed at Farmers Mine. Truncation of strata as well as a basinward shift in facies indicate this erosional surface is a sequence boundary. The tide-influenced channel-fill and bay-head delta deposits of sequence CZ_2 are interpreted as the fill of an incised-valley. The incised-valley fill is overlain by approximately 8-10 m of distal marine shoreface deposits (lower shoreface and offshore transition facies). Marine strata of sequence CZ_2 were deposited during the progradation of a shoreline and are interpreted as a highstand deposit.

Sequence boundary SB-CZ_2 has both erosional and interfluve expressions (Figure 18; Plate 1). Where sequence boundary SB-CZ_2 has an erosional expression (Hunter Canyon, Coal Canyon, and Farmers Mine), valley incision is present, and this surface incises into shoreface deposits of the underlying sequence (Sequence CZ_1). At least 17 m of relief occurs along this surface, indicating a minimum of 17 m of sea-level fall. Where sequence boundary SB-CZ_2 has an interfluve expression, the surface occurs as an abnormal subaerial exposure surface. This exposure surface is abnormal because marine shoreface deposits, which form in several meters of water, underlie it. During the subsequent sea-level rise, fluvial systems in the valley deposited sediment in response to the base-level rise. As sea level continued to rise, incised valleys became flooded, tides influenced the river systems, and the valleys become estuaries. Sediment trapped within estuaries is recorded as aggradationally stacked successions of marginal marine deposits within the incised valley. As the valley is filled, the transgressive shoreline migrated landward over the top of the valley fill, resulting in a parasequence boundary above the incised-valley deposits. This surface marks the end of marginal-marine deposition within the lowstand and transgressive systems tracts of the sequence. When sediment supply outstripped sea-level rise, the shoreline became a depositional shoreline and prograded basinward. Progradation of the shoreline and deposition of parasequence CZ_2-PS1 signaled the beginning of the highstand deposition. The depositional shoreline of sequence CZ_2 did not prograde through the field area, and only the offshore equivalent facies of this shoreline were deposited from Hunter Canyon eastward (Figure 18; Plate 1).

The sequence boundary at the base of sequence R_1 (SB –R_1) truncates strata from the highstand systems tract of sequence CZ_2. The entire highstand systems tract of sequence CZ_2 is erosionally removed between Coal Canyon and Hunter Canyon (Plate 1). In these locations the sequence boundary is overlain by successions of marginal-marine deposits interpreted as the fill of an incised-valley (IVF-R_1). The incised-valley fill of sequence R_1 is overlain by 8-15 m of offshore transition and lower shoreface facies. These offshore transition and lower-shoreface deposits accumulated during the progradation of a shoreline and are interpreted as a highstand systems tract.

The history of the relative change in sea level of sequence R_1 is similar to that of sequence CZ_2. Progradation of the shoreline was followed by a relative fall in sea level that produced the sequence boundary at the base of sequence R_1 (SB-R_1). Sequence boundary SB-R_1 has both erosional and interfluve expressions. The sequence boundary (SB-R_1) is erosional in the western part of the field area (between Coal Canyon and Hunter Canyon) and has an interfluve expression at Farmers Mine (Figure 18, Figure 19; Plate 1). The amount of sea-level fall associated with this sequence boundary is at least 16 m. After the formation of sequence boundary SB-R_1 sea level began to rise. The subsequent rise in sea level flooded the lower reaches of the valley, making it an estuary. Sediment was deposited in the estuary as sea level continued to rise. This is recorded by the aggradationally stacked successions of marginal marine deposits. While deposition occurred within the estuary, the transgressive shoreline moved landward across the interfluve surface of the sequence boundary. As the rate of sea-level rise began to slow, the rate of sediment supply outstripped sea-level rise, and the transgressive shoreline transitioned to a depositional shoreline that prograded. As with the underlying sequence (CZ_2), the depositional shoreline was located to the west of the field area, and only time-equivalent offshore transition and distal lower-shoreface deposits are present in the study area (Figure 18, Plate 1).

The thickest and best-developed sequence within the Rollins Sandstone Member is sequence R_2. West of Book Cliffs Mine erosion associated with sequence boundary SB-R_2 has removed the highstand systems tract of sequence R_1 and part of IVF-R_1. Sequence boundary SB-R_2 is overlain by successions of marginal marine deposits. These deposits are interpreted as incised-valley fill (IVF-R_2). The extensive erosion along sequence boundaries SB-CZ_2, SB-R_1, and SB-R_2 has resulted in the nesting of up to three incised valleys at Hunter Canyon (Plate 1). The incised-valley fill within sequence R_2 is overlain by a thick (30-40m thick) progradational marine-shoreface succession. These marine strata were deposited during the progradation of a shoreline and are interpreted to be a highstand systems tract. This parasequence is the thickest shoreface succession within the Rollins Sandstone Member and forms a resistant sandstone bed that is the cliff- forming unit at Mount Garfield.

Sequence boundary SB-R_2 formed due to a relative fall in sea level. Valley incision occurred in the western part of the field area (Hunter Canyon and Corcoran Mine) (Figure 22). At least 23 m of sea-level fall is documented. The incised valley of sequence R_2 filled in a manner similar to the incised valleys of sequences CZ_2 and R_1. After the valley filled with sediment marine waters flooded landward over the top of the valley. Total sea-level rise from the base of the valley to the top of the highstand shoreline is approximately 59 m. This includes 23 m of sea-level rise to inundate the valley, and 36 m to produce the accommodation for shoreface deposits of the overlying parasequence within the highstand systems tract. After almost 60 m of relative sea-level rise, the rate of sea-level rise slowed and sediment input outstripped sea-level rise. The transgressive shoreline became a depositional shoreline, and prograded through the field area. This produced the upward coarsening shoreface succession within parasequence R_2-PS1. Shorelines for this time period are interpreted to trend from the northeast to the southwest (Kirschbaum and Hettinger, 2004). Based on these shoreline trends, and the distance covered by the correlation in this study, the shoreface associated with parasequence R_2-PS1 prograded at least 40 km into the basin.

The close stratigraphic spacing of these three depositional sequences produces a complicated internal stratigraphy for the Rollins Sandstone Member. Erosion associated with sequence boundaries results in an incomplete depositional record, as well as nesting of incised-valley fills. In many locations incision has removed the highstand of sequences CZ_2 and R_1 (Figure 18; Plate 1). In these localities there are as many as three nested incised-valley fills (Figure 19). Where valleys are nested it is difficult to determine the boundary of each valley, and thus determine the correct number of sequence boundaries preserved and the amount of incision that took place at the base of each depositional sequence.

The youngest sequence within the Rollins Sandstone Member is sequence R_3. The basal sequence boundary of sequence R_3 (SB-R_3) truncates highstand deposits of sequence R_2. Locally the highstand systems tract of sequence R_2 is incised into and replaced by multi-story channel-fill sandstones (heterolithic channel-fill facies) interpreted to be incised-valley fill of sequence R_3 (Figure 18; Plate 1). Unlike the lower three sequences, sequence R_3 contains no marine strata. While the incised valley at the base of sequence R_3 occurs within the Rollins Sandstone Member, the remainder of the sequence occurs within the overlying Cameo-Wheeler coal zone. The incised-valley fill of sequence R_3 (IV R_3) is overlain by successions of thick coals, fluvial sandstones, and overbank deposits. These thick coals, fluvial sandstones, and overbank deposits are interpreted to be the highstand strata of sequence R_3.

Evidence for the last sea-level fall affecting deposits within the Rollins Sandstone Member is observed in the sequence boundary (SB-R_3), along the contact between the Rollins Sandstone Member and the Cameo-Wheeler coal zone. Sequence boundary SB-R_3 has erosional and interfluve expressions. Erosion and valley incision is seen in HC, BCM, and FM (Figure 18). In these locations up to 15 m of incision is documented. The incision surface is interpreted as a subaerial exposure surface, and at least 15 m of a relative fall in sea level is interpreted for these exposures. Valley incision was followed by a rise in sea level. As sea level rose, the valley flooded, forming an estuary. During this transgressive event, the valley filled with tide-influenced channel-fill deposits. The shoreline never transgressed across the study area. Where sequence boundary SB-R_3 has an interfluve expression (i.e. where the incised valley fill does not occur), the upper surface of sequence R_2 corresponds to the top of a progradational shoreface succession within parasequence R_2-PS1 (Figure 18, Plate 1). This surface is also the lithostratigraphic contact between the Mount Garfield and Williams Fork formations.

DISCUSSION

The complicated internal stratigraphy of the Rollins Sandstone Member cannot be interpreted from a single vertical succession. Many of the lateral stratigraphic relationships cannot be resolved without correlation of the measured sections. For example, marginal marine strata are found at the same stratigraphic horizon as, and juxtaposed to, offshore transition facies. This juxtaposition of facies is observed between the Corcoran Mine and Book Cliffs Mine localities as well as between the Coal Canyon and Farmers Mine localities (Plate 1). Using a sequence-stratigraphic approach, the marginal-marine deposits are identified as an incised-valley fill, and an erosional surface (i.e. sequence boundary) is identified to separate the marginal-marine facies from the underlying offshore transition facies. Erosion of lower shoreface and offshore-transition deposits and subsequent deposition of marginal-marine strata within these valleys accounts for the juxtaposition of offshore transition and marginal marine deposits. Published cross-sections show a stratigraphic pinch out of these marginal-marine units into offshore transition facies but do not interpret this relationship (Figure 2) (Kirschbaum and Hettinger, 2004).

The sequence boundaries within the Rollins Sandstone Member are not always easily recognizable in the field. To the east of the field area sequence boundaries occur as interfluve surfaces (Figure 20). These interfluve surfaces are non-descript, with little facies offset on either side of the surfaces. Due to the lack of facies offset and poor outcrop exposure in these localities, the Rollins Sandstone Member resembles a single upward-coarsening succession (Figure 20). For example, Gill and Hail (1975) originally interpreted the Rollins Sandstone Member exposed in Coal Canyon as a single progradational succession. Later Cole and Cumella (2003) interpreted it as three stacked parasequences containing marine shoreface facies. Neither of these interpretations recognized the interfluve expression of sequence boundaries. These interfluve surfaces are only recognized when correlated from the top of incised-valley fills (Figure 18, Figure 20; Plate 1).

The top of the Rollins Sandstone Member is a surface that results from the progradation of a single strandline, within parasequence R_2-PS1, and as a result this surface can be used as a datum. Where this surface has been incised by sequence boundary SB-R_3 and basinward of the seaward limit of shoreline progradation within parasequence R_2-PS1, this surface is not a good choice for a datum.

Published correlations for the study area portrays the top of the Rollins Sandstone Member as a progressively upward-climbing contact (stair-stepped geometry; Figure 2) (Kirschbaum and Hettinger, 2004). The interpretation of an upward-climbing geometry at the top of the Rollins Sandstone Member implies that the Rollins Sandstone comprises multiple, progradationally stacked parasequences. This interpretation is not supported by the results of this study (Figure 18; Plate 1). Because the top of the Rollins Sandstone Member is not an upward-climbing surface, a reevaluation of the Mount Garfield Formation and Williams Fork Formation contact is necessary. The contact between the Williams Fork Formation and overlying Paleocene to Eocene Wasatch Formation, as interpreted by previous authors, mimics the upward-climbing geometry of the Mount Garfield Formation and Williams Fork Formation contact. The upper contact of the Williams Fork Formation mimics the Mount Garfield Formation and Williams Fork Formation contact in order to preserve the thickness of the Williams Fork Formation (Gill and Hail, 1975; Kirschbaum and Hettinger, 2004). If the contact between the Rollins Sandstone Member and Williams Fork Formation is drawn as it is interpreted here, as a planar surface, the overlying contact will also need to drop to reflect this change.

Correlations by Kirschbaum and Hettinger (2004) place intervals of the Cameo-Wheeler coal zone at the same stratigraphic horizon as the top 40 m of the Rollins Sandstone Member. This correlation makes the basal 40 m of the Cameo-Wheeler coal zone up-dip, lateral equivalent strata to the upper 40 m of the Rollins Sandstone Member (Figure 2). This correlation suggests that the lower part of the Cameo-Wheeler coal zone is genetically related to the top of the Rollins Sandstone Member. The strata of the Cameo-Wheeler coal zone that occur in the same stratigraphic interval as the Rollins Sandstone Member would then be interpreted to reflect lateral facies changes. This relationship suggests that the fluvial and non-marine strata of the Cameo-Wheeler coal zone that are laterally equivalent to the Rollins Sandstone Member are the non-marine temporal equivalent of the marine sandstones within the Rollins Sandstone Member. Results of this study show the Cameo-Wheeler coal zone is stratigraphically above the Rollins Sandstone Member and not a genetic time equivalent unit (Figure 18, Plate 1). This is further supported by the recognition of a sequence boundary at the top of the Rollins Sandstone Member (Figure 18; Plate 1).

Patterson (2003) recognized the sequence boundary at the top of the Rollins Sandstone Member, however, this study also portrayed an upward-climbing geometry at the top of the Formation. An unconformity at the top of the Mount Garfield Formation as well as a upward-climbing geometry along this contact indicate this geometry is the result of erosion, and this surface must represent a significant unconformity. The top of the Rollins Sandstone Member, however, is a horizontal surface, and although this surface corresponds to both the interfluve expression of sequence boundary SB-R_2 there is no field evidence that suggests the sequence boundary represents a greater amount of time than any of the other sequence boundaries within the Mount Garfield Formation.

Fluvial successions of the Williams Fork Formation are difficult to correlate due to the lack of internal surfaces that can be used as a datum. Using the top of the Rollins Sandstone Member as a datum allows for more accurate correlation of these strata (Figure 21). Channel-fill sandstones within the Cameo-Wheeler coal zone that occur at the same stratigraphic horizon can now be correctly recognized (Figure 21). A correct datum will also allow for more accurate correlation of thick coals within the Cameo-Wheeler coal zone.

The depositional sequences CZ_2 through R_3 make up a progradational sequence set as defined by Mitchum and Van Wagoner (1991). A sequence set consists of stacked sequences with either a progradational, aggradational, or retrogradational stacking pattern (Mitchum and Van Wagoner, 1991). Sequence stacking patters are defined in a manner similar to that of a parasequence set. The stacking pattern of sequences is determined by the vertical arrangement of systems tracts within successive sequences (Mitchum and Van Wagoner, 1991). In a retrogratational sequence set, systems tracts within successively younger sequences are positioned farther landward in a backstepping pattern. In an aggradational sequence set, systems tracts within successively younger sequences are positioned in approximately the same location. In a progradational sequence set, systems tracts within successively younger sequences are positioned farther basinward. The highstand systems tracts of sequences CZ_2, R_1, R_2 and R_3 are progradationally stacked, and these sequences are interpreted as a progradational sequence set (Figure 18). The decreasing amount of marine influence within progressively younger sequences records the overall regression of the seaway. The overall regression was complex, marked by four cycles of sea-level rise and fall recorded by the four depositional sequences.

The frequency of sequence boundaries within the Rollins Sandstone member cannot be determined because of the lack of biostratigraphic data. Sequence boundaries within the Rollins Sandstone Member occur in close stratigraphic spacing and are most likely high frequency sequences as defined by Mitchum and Van Wagoner, 1991. High frequency sequences record fourth and fifth order cycles of sea-level fluctuation (0.1-0.2 m.y., and 0.01-0.02 m.y.) (Mitchum and Van Wagoner, 1991). The Mount Garfield Formation is interpreted to represent 3.5 m.y. of time (Gill and Hail, 1975; Cobban et al., 2006). There are 9 sequence boundaries within the Mount Garfield Formation. Although there is not enough biostratigraphic data to date each sequence boundary within the formation, the duration of each sequence can be estimated by dividing the amount of time represented by the formation by the number of sequences within the formation. If this age estimate is correct, and the total number of sequences is accurately known, the sequences within the Mount Garfield Formation are high frequency sequences.

The depositional style of the Rollins Sandstone Member, with multiple sequence boundaries in close stratigraphic spacing, is consistent with the depositional style of the lower two members of the Mount Garfield Formation (Madof, 2006; Zater, 2005) as well as the underlying Sego Sandstone Member of the Mancos Shale

(VanWagoner, 1991). The Sego Sandstone Member of the Mancos Shale contains eight high-frequency sequences. Some sequences within the Sego Sandstone Member are less than 8 m in thickness (Van Wagoner, 1991). This is similar to the number of sequences and the observed thicknesses of sequences within the Mount Garfield Formation. Extensive erosion at the base of sequence boundaries within the Sego Sandstone Member often results in the nesting of up to 3 incised valleys (Van Wagoner, 1991). This is similar to what is observed within the Rollins Sandstone Member.

CONCLUSIONS

The Rollins Sandstone Member of the Mount Garfield Formation contains strata from four depositional sequences (oldest to youngest CZ_2, R_1, R_2, and R_3) (Figure 20). These four sequences make up a progradational sequence set. The existence of four sequences within the Rollins Sandstone Member is not obvious in a single vertical section. In the eastern part of the field area (BCM, CCW, CC, and FM) sequence boundaries have interfluve expressions. These surfaces are non-unique and poorly exposed, making them hard to identify in the field. Where sequence boundaries have an erosional expression they incise into the highstand of the underlying sequence and sometimes completely remove it. In these locations, valley fills are commonly nested making the basal sequence boundary of each depositional sequence difficult to distinguish. By correlating the top of each incised valley down-dip to its associated interfluve surface, the correct number of sequence boundaries can be determined.

The four sequences within the Rollins Sandstone Member occur at a high stratigraphic frequency. Although there is not enough biostratigraphic data to date each sequence boundary, sequences within the Mount Garfield Formation are most likely high-frequency sequences. The top of the Rollins Sandstone Member is a surface that represents the progradation of a single strandline, allowing this surface to be used as a datum. There is no evidence to support an upward-climbing geometry at the top of the Rollins Sandstone Member.   The depositional style of the Rollins Sandstone Member is consistent with both underlying members of the Mount Garfield Formation (Corcoran Sandstone Member and Cozzette Sandstone Member)(Madolf, 2006; Zater, 2005;), and underlying formations (Sego Sandstone Member of the Mancos Shale) (VanWagoner, 1991).

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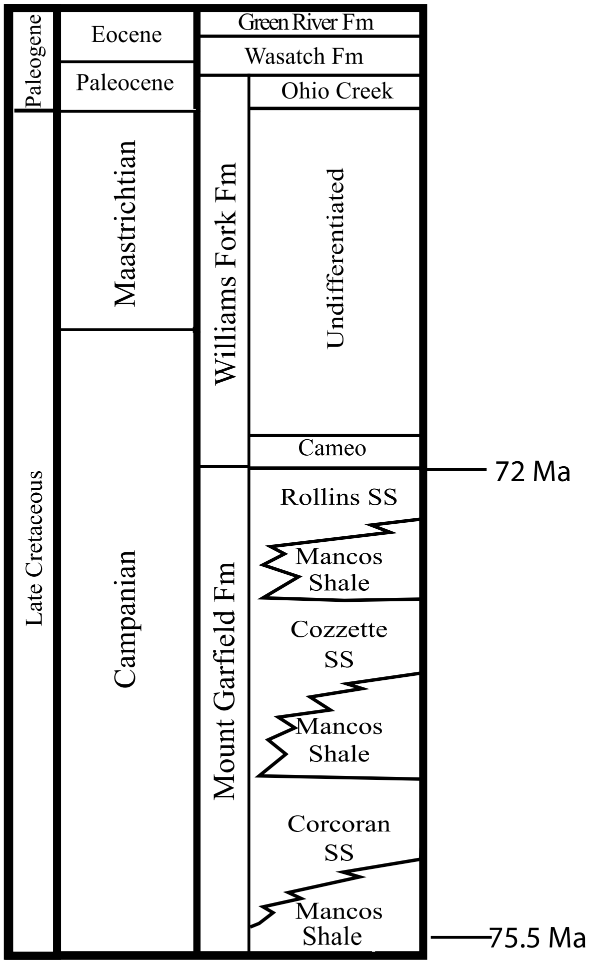


Figure 1. Lithostratigraphic nomenclature and stratigraphic ages for the Upper Cretaceous strata exposed near Grand Junction, Colorado. Ages of the Mount Garfield Formation are constrained using ammonite zones identified by Gill and Hale (1984). ^{40}Ar/^{39}Ar radiometric age dates for ammonite zones are from Cobban et al. (2006). Cameo is an abbreviation for the Cameo-Wheeler coal zone.

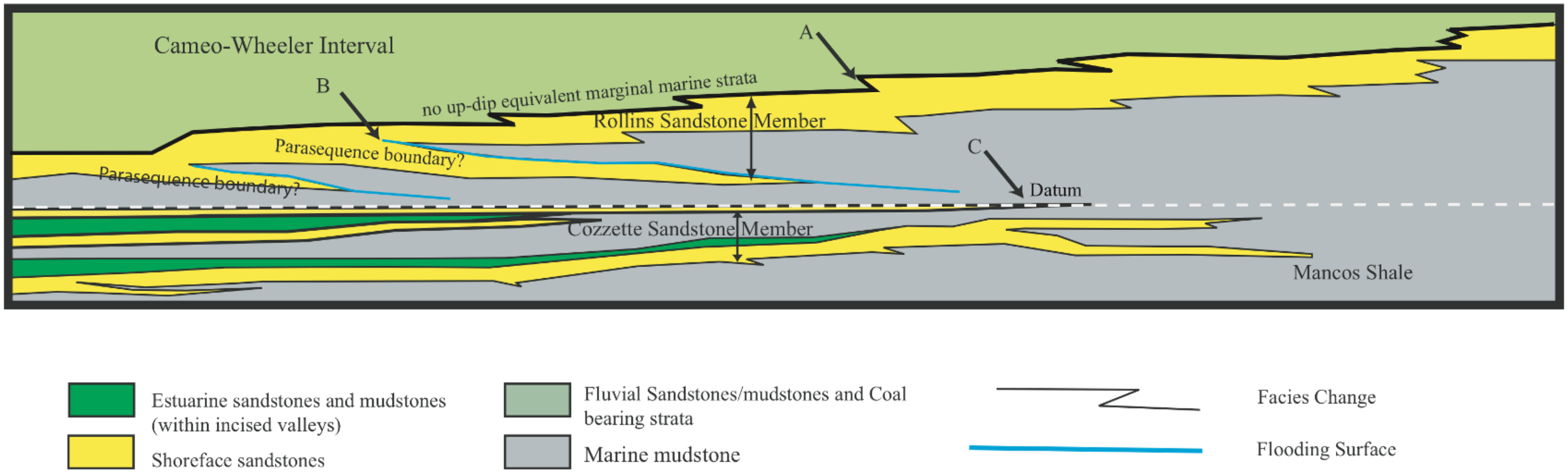


Figure 2. Schematic representation from Kirschbaum and Hettinger (2004) of the correlation of the Corcoran and Rollins Sandstone members, and Cameo-Wheeler Interval. This correlation portrays the upper surface of the Rollins Sandstone Member with a stair-stacked geometry (A). In this interpretation parasequence boundaries (time lines) within the Rollins Sandstone Member terminate abruptly, and do not continue into the Cameo-Wheeler contact (B). The top of the Cozzette Sandstone member was used as a datum. The top of the Corcoran Sandstone Member, however, is a depositional profile which dips basinward, and not a horizontal surface.

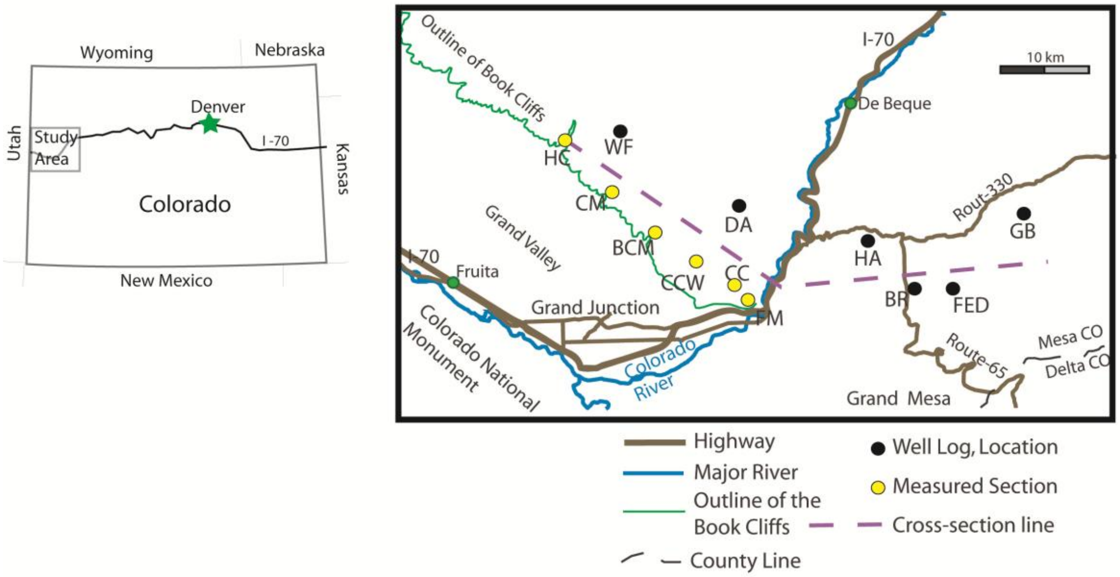


Figure 3. Base map showing the study area near Grand Junction, Colorado. Measured sections along the Book Cliffs are shown in yellow. Well log locations are shown in black. HC = Hunter Canyon; CM = Corcoran Mine; BCM = Book Cliffs Mine; CCW = Coal Canyon West; CC = Coal Canyon; FM = Farmers Mine; WF = Winter Flats; DA = Dome Albertson; HA = Harvey; BR = Brousch; FED = Federal; GB = Gibson.

Figure 4. Upward-coarsening succession of interbedded sandstone and silty mudstone exposed at Farmers Mine. Exposure is approximately 5 m high.

Figure 5. HCS bed (30 cm thick) within the lower shoreface succession of the Rollins Sandstone Member exposed in Corcoran Mine.

Figure 6. Intensely bioturbated, *Ophiomorpha*-dominated interval within the middle shoreface succession of the Rollins Sandstone Member exposed in Coal Canyon. Remnant HCS is found at the base of the interval (bottom of the photo).

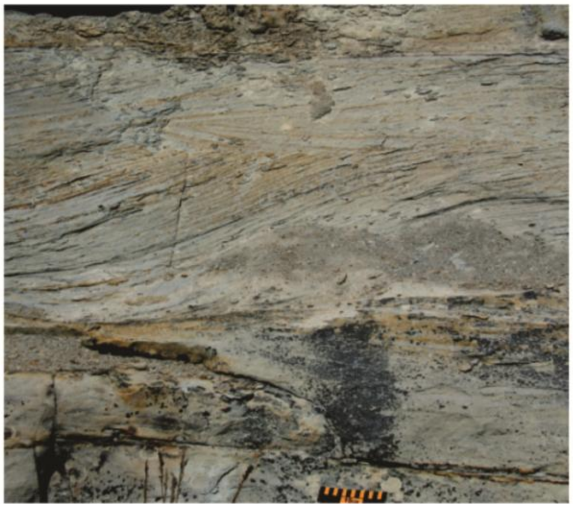


Figure 7. Cross-stratified sandstone within the upper shoreface succession of the Rollins Sandstone Member exposed in Corcoran Mine. The sloping surface of the outcrop exposure give the cross-stratification a large apparent thickness. The true thickness of the cross-stratification is approx. 20 cm. The scale at the bottom of the photo is 15 cm.

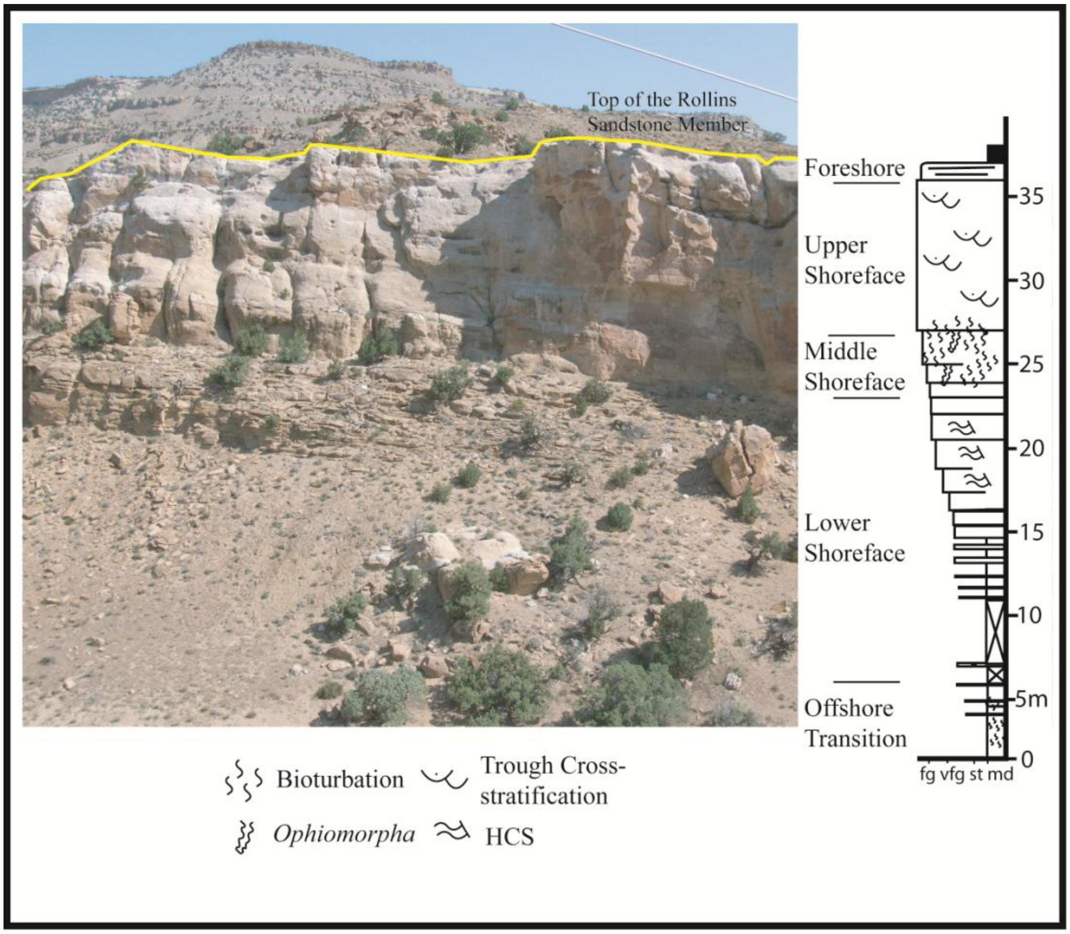


Figure 8. Progradational marine shoreface deposits of the Rollins Sandstone Member are expressed as upward-coarsening packages in Coal canyon (type locality for the Rollins Sandstone Member). fg = fine grained sandstone, vfg = very fine grained sandstone, st =silt, and md = mud.

Figure 9. Laminated mudstone exposed in Hunter Canyon. At this location a slight upward-coarsening trend is observed. The siltstones at the top of the facies contain wave ripple cross-stratification. This succession is overlain by deposits of the heterolithic channel-fill facies (base shown as white line). Scale in the center of the photo is a 1.5 meter Jacob staff.

Figure 10. Stacked, upward-fining successions exposed at Hunter Canyon. White (dotted) lines trace the base of each succession. Triangles indicate individual upward-fining successions (total exposure is approximately 8 m thick)

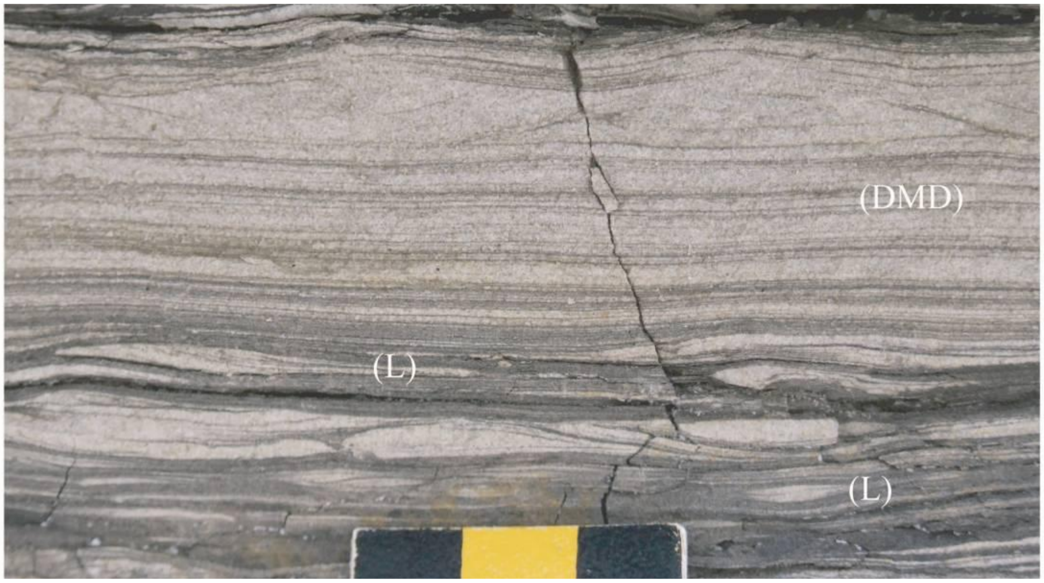


Figure 11. Double mud drapes (DMD) and lenticular bedding (L) are common within the heterolithic channel-fill facies. Scale at the base of the photo is 3 cm.

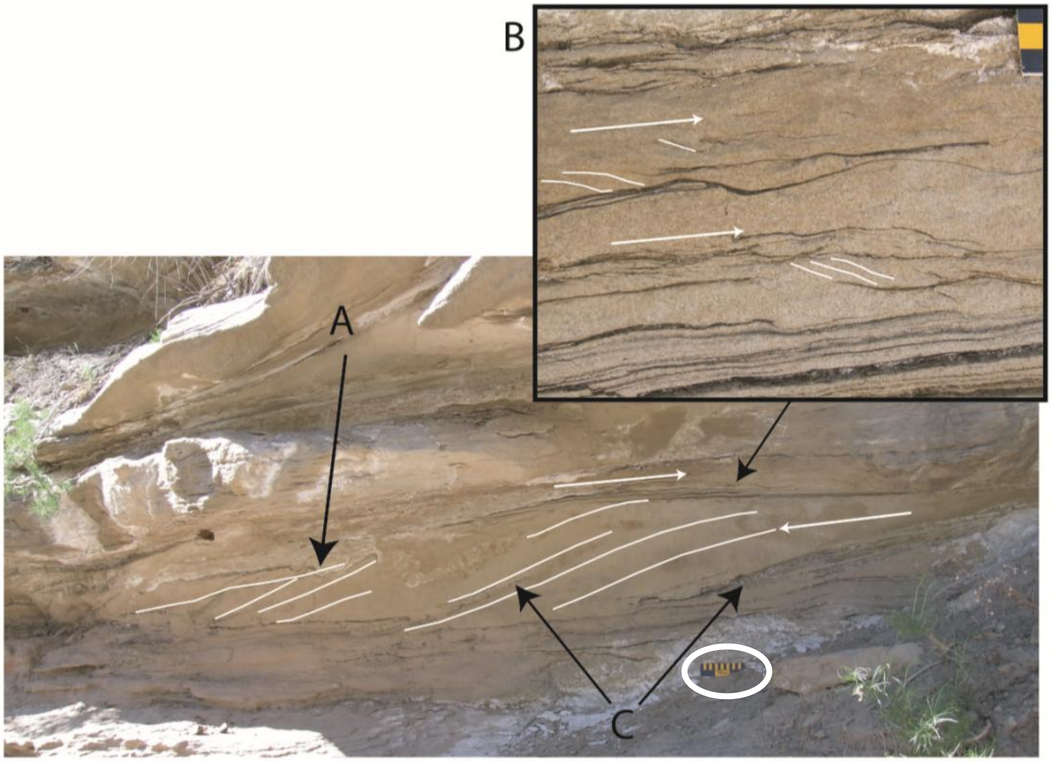


Figure 12. Multiple scales of cross-stratification within the heterolithic channel-fill facies are exposed in Hunter Canyon. Large-scale cross-stratification is truncated by a reactivation surface (A). Current-ripple cross-stratification with opposite flow direction of larger-scale cross-stratification is found locally (B). Abundant mud-drapes are common within larger-scale cross-stratification (C). White arrows indicate flow direction of cross-stratification. White lines trace significant surfaces in order to highlight cross-stratification and reactivation surfaces. The scale at the bottom of the photo is 15 cm (highlighted by a white circle). The scale at the top right of the inset photo is 3 cm.

Figure 13. Upward-coarsening succession (4 m thick) exposed in Coal Canyon, the base of the succession is not exposed. The scale in the right of the photo is 1.5 m high.

Figure 14. Wavy to lenticular bedding and wave-modified current ripples (see arrow) within the fine-grained ripple-bedded sandstone and laminated silstone facies exposed in Hunter Canyon.

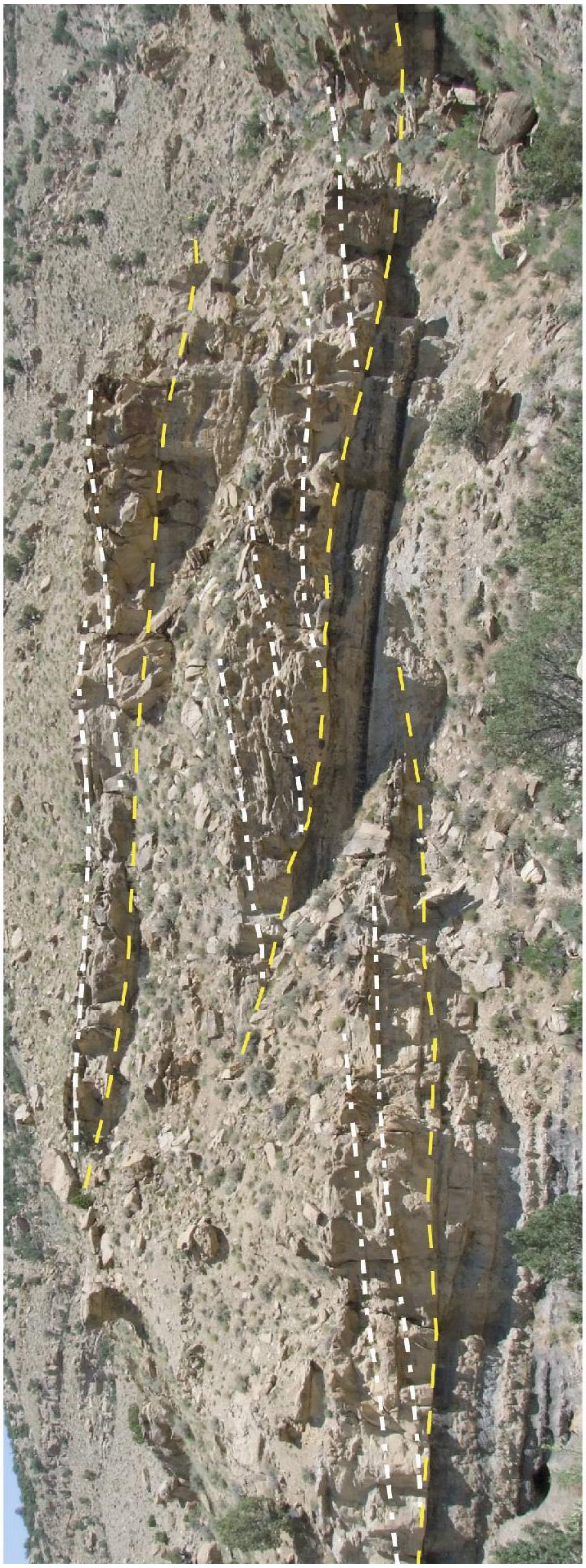


Figure 15. Cross-stratified channel-fill facies within the Cameo-Wheeler coal zone exposed in Coal Canyon. The base of the channels is shown in yellow and accretion surfaces are shown in white. Channels are approximately 6 m thick. The contact between the Rollins Sandstone Member and the Cameo-Wheeler coal zone is 8 m below the lowest channel-fill.

Figure 16. *Teredolites* at the base of a sandstone bed within the Cameo-Wheeler coal zone. Scale is 3 cm.

Figure 17. Thick (11 m) coal within the Cameo-Wheeler coal zone directly overlies the Rollins Sandstone Member in Book Cliffs Mine. White bar in the lower left of the photo is approximately 1 m.

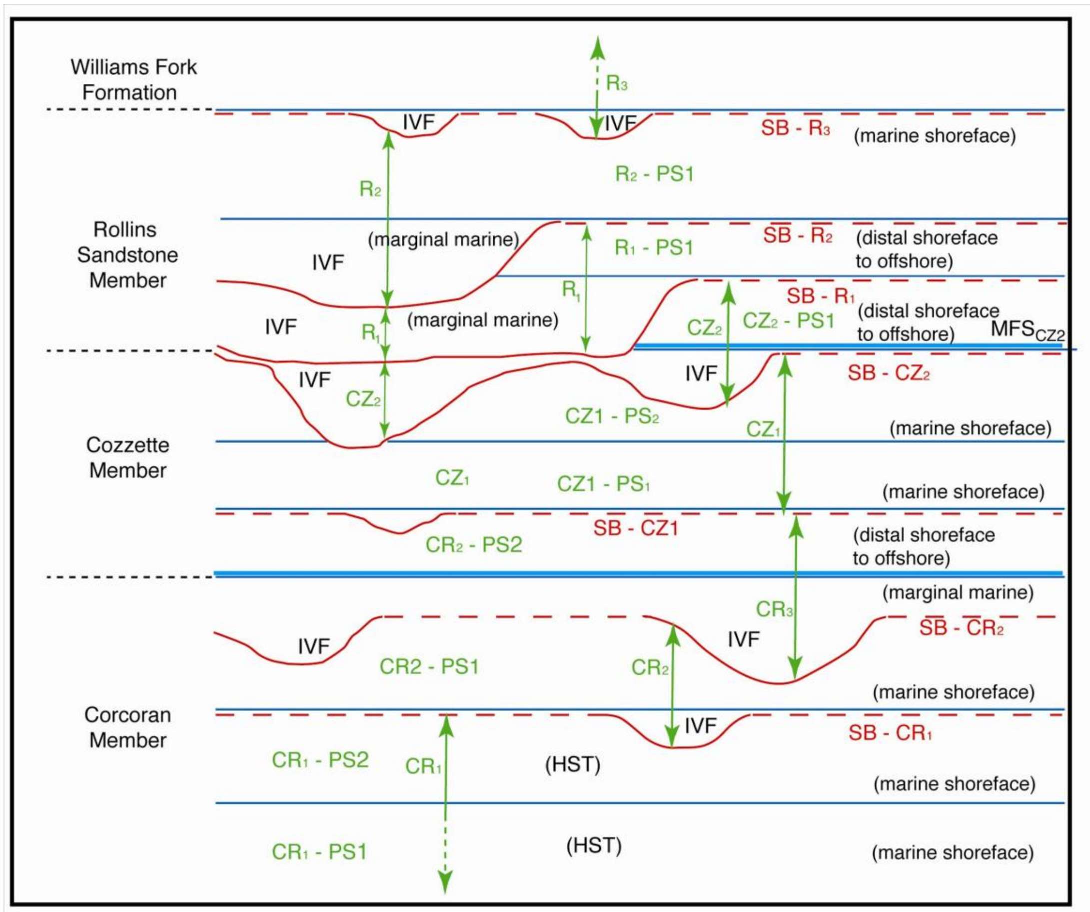


Figure 18. Schematic diagram of the sequence stratigraphy of the Mount Garfield Formation. IVF = incised valley fill; HST = highstand systems tract; CR = prefix for Corcoran; CZ = prefix for Cozzette; R = prefix for Rollins; PS = parasequence; SB = sequence boundary. Modified from Kamola et al., 2007.

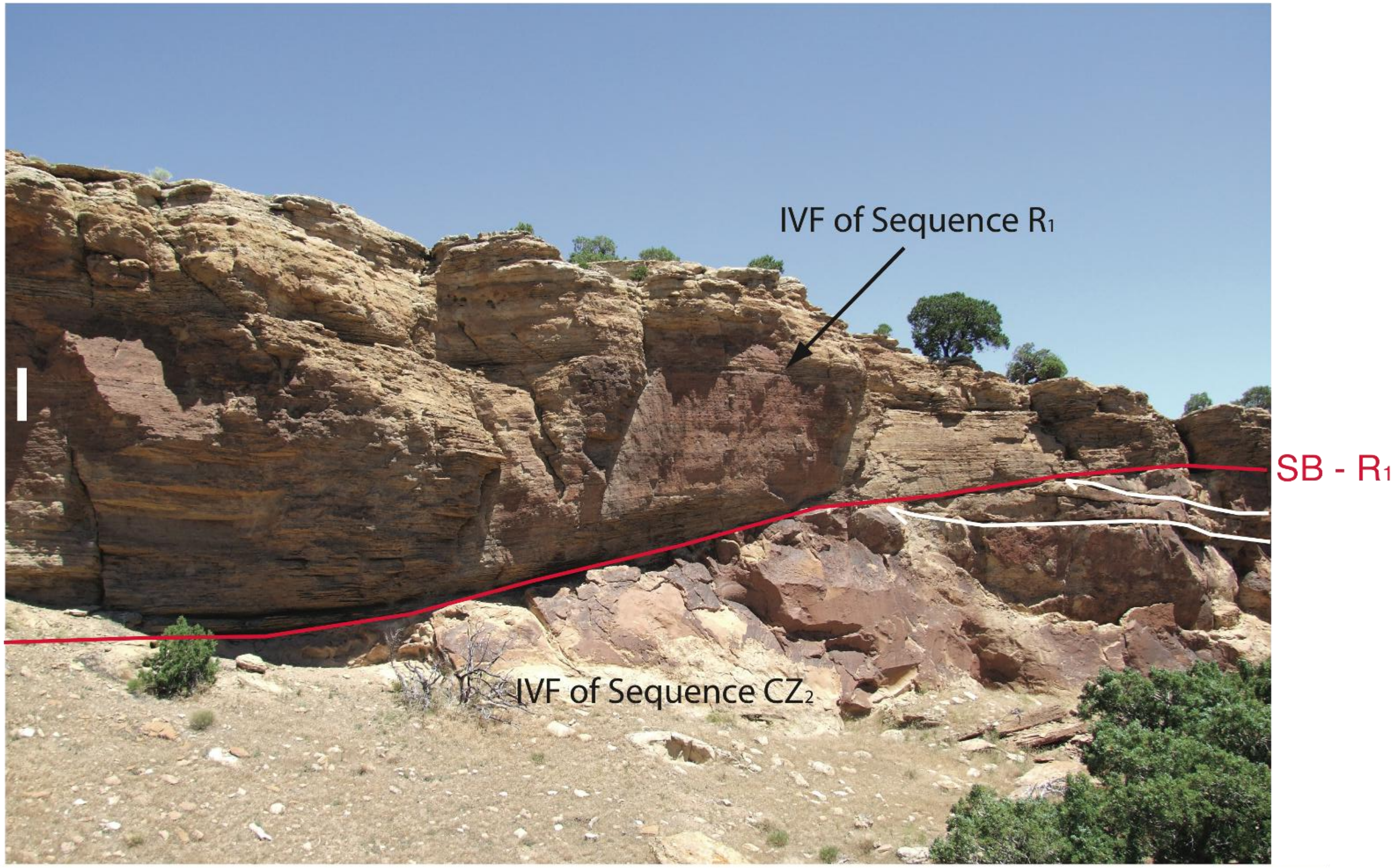


Figure 19. Interpreted photograph of two nested incised valleys at the base of the Rollins Sandstone Member near Coal Canyon West. In this location sequence boundaries SB-CZ_2 and SB-R_1 are erosional. Erosion associated with SB-R_1 is so extensive that the entire highstand parasequence of the underlying depositional sequence (sequence CZ_2) has been removed and the valley fills from sequences R_1 and CZ_2 are nested. Bedding within the incised valley fill of sequence CZ_2 (white lines) is truncated by SB-R_1. The white bar to the left of the photo is approximately 1 meter.

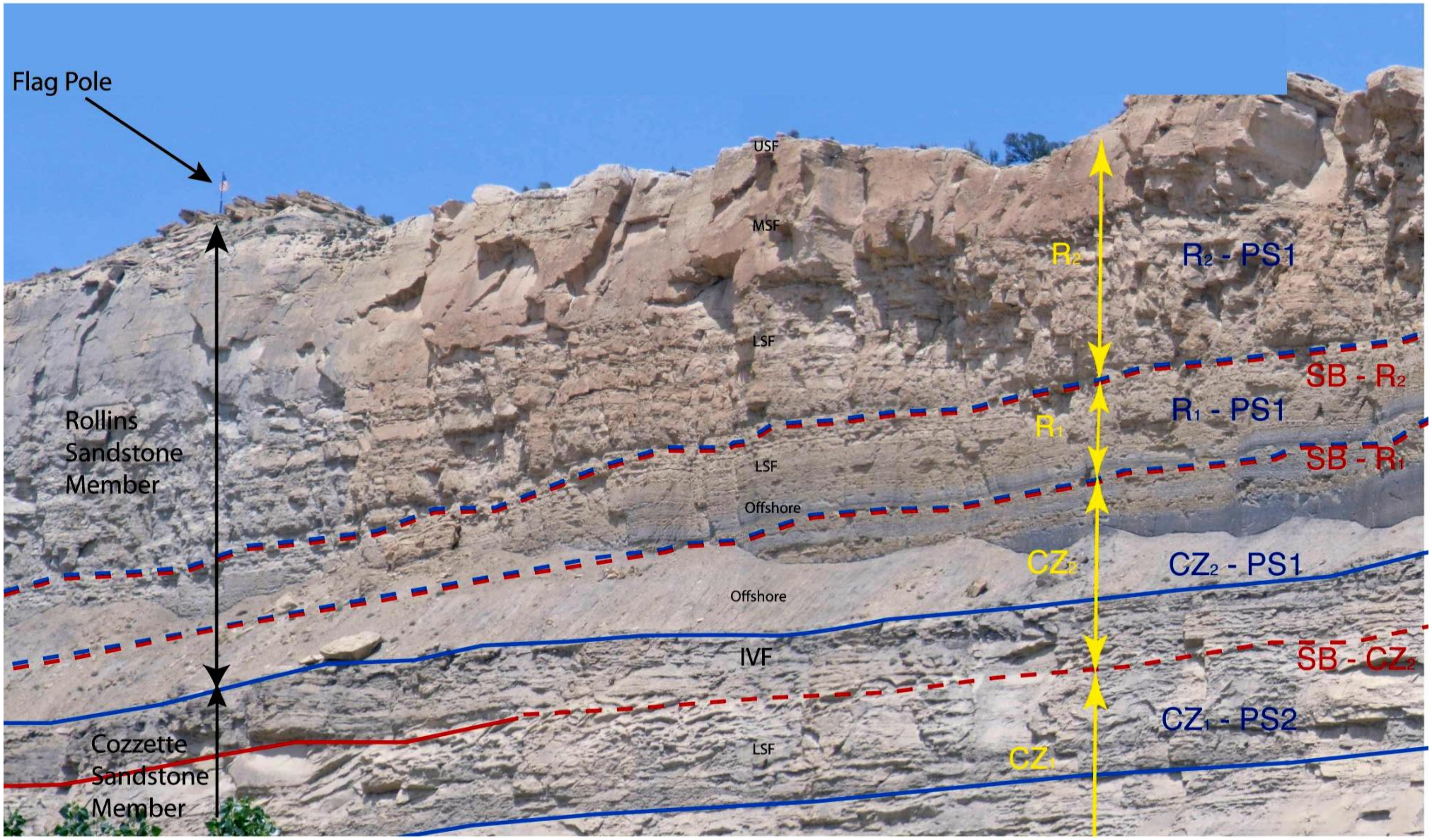
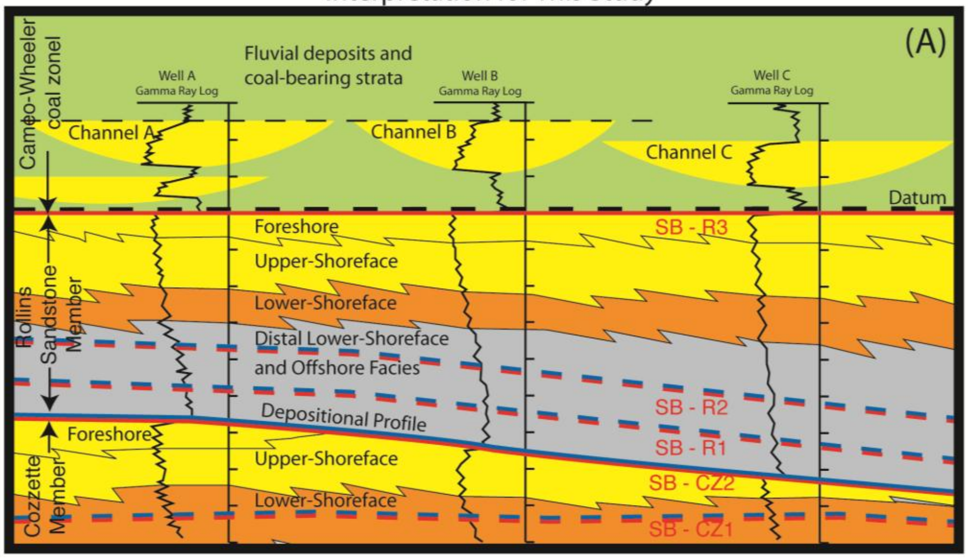


Figure 20. Interpreted photograph illustrating the 4 sequences within the Rollins Sandstone Member exposed along I-70 approximately one mile west of Farmers Mine. In this location sequence boundaries SB-R_1 and SB-R_2 have interfluv expressions making them difficult to recognize; because of this the Rollins Sandstone Member appears to be a continuous upward-coarsening succession. LSF = lower shoreface; MSF = middle shoreface; USF = upper shoreface; IVF = incised valley fill.

Interpretation for This Study



Previous Interpretation

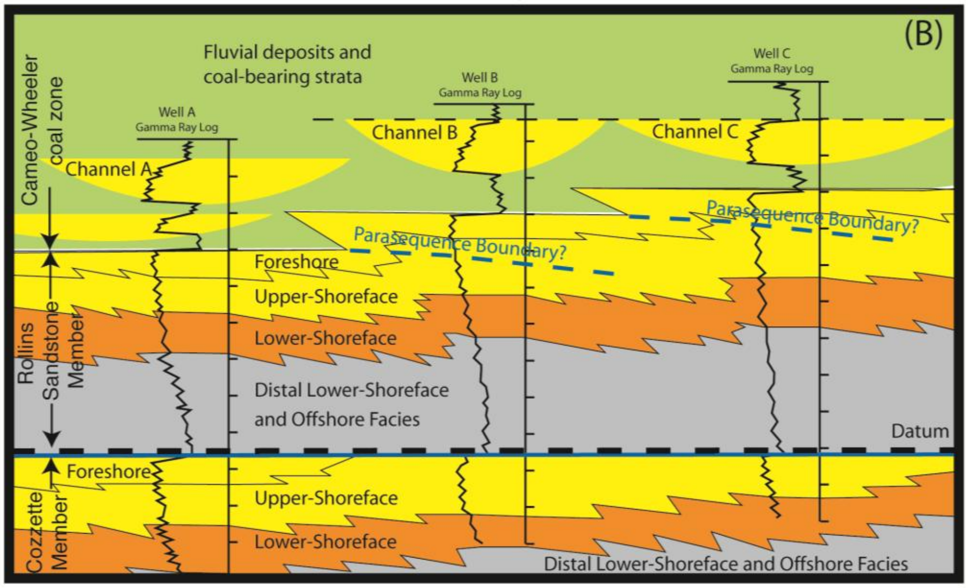


Figure 21. Schematic Representation of three well logs through the Cozzette Sandstone Member, Rollins Sandstone Member, and Cameo-Wheeler coal zone correlated based on the results of this study (A) and the current interpretation by Kirschbaum and Hettinger (2004) (B). The results of this study (A) interpret the top of the Rollins Sandstone Member as a horizontal surface, which can be used as a regional datum. No evidence is found in the field to support an upward-climbing geometry at the top of the member as interpreted by Kirschbaum and Hettinger (2004) (B). This study preserves the depositional profile at the top of the Cozzzette Sandstone Member. If the Cozzette Sandstone Member is used as a datum, lower shoreface and upper shoreface deposits sit at the same stratigraphic horizon as foreshore deposits (B). A correct datum allows for proper correlation of fluvial channel-fill sandstones within the Cameo-Wheeler coal zone.

Table 1. Well-log facies identified within the Rollins Sandstone Member and Cameo-Wheeler coal zone.

Facies	Description	Interpretation
Progradational marine sandstones	Thick (40 meter) packages with gradual, upward-decrease in gamma-ray signature. These are found within the Rollins Sandstone Member.	Gradual decrease in gamma-ray response represents a decrease in clay content and an increase in quartz content (interpreted as an upward-coarsening trend from mudstone to sandstone) (Pirson, 1979). This facies represent progradational, wave-dominated shoreface deposits.
Channel-fill sandstones	Genetic packages initiating with a relatively low gamma-ray response. These packages have a blocky gamma-ray signature, and a vertical increase in gamma-ray response. This facies is found within the Rollins Sandstone Member and Cameo-Wheeler coal zone.	These packages represent channel-fill sandstones. These are correlative to the tidally influenced channel-fills within the Rollins Sandstone Member, and the fluvial channel-fill sandstones within the Cameo-Wheeler Interval.
Coal	This facies has a low gamma-ray response, and an off-scale neutron response. This facies is found within the Rollins Sandstone Member and Cameo-Wheeler coal zone.	Low gamma-ray response and high apparent neutron and density porosity indicate coal (Doveton, 1994)
Interbedded Sandstone and Mudstone	This facies consists of a saw-tooth well log pattern, with alternating high and low gamma-ray readings. This facies is found within the Rollins Sandstone Member.	The alternating high and low gamma-ray readings are interpreted to indicate interbedded sandstones and mudstones (Pirson, 1979). These are correlative to the bay-head delta and bay-fill mudstone facies within the Rollins Sandstone Member.

CHAPTER THREE

Hydrodynamic Interpretation of high-energy wave-dominated shoreface successions, Cretaceous Mount Garfield Formation, Colorado

INTRODUCTION

Marine shoreface deposits are abundant and well exposed within the Cretaceous Sevier Foreland basin (SFB) of North America. Studies of wave-dominated shoreface successions within foreland basins are numerous (Brown, 1986; Clifton, 2006; Cole and Cumella, 2003; Harms et.al, 1982; Kamola and Van Wagoner, 1995; Kirschbaum and Hettinger, 2002; Kirschbaum and Hettinger, 2004; Power, 1988; Plint et al, 1988; Reinson, 1984; Van Wagoner, 1995; Varban and Plint, 2007). The facies model for these shoreface succession is characterized by four sub-units, (1) a thick lower-shoreface interval consisting of hummocky cross-stratified sandstones and burrowed siltstones, (2) a middle-shoreface interval consisting of interbedded burrowed and laminated sandstone, (3) a thick and well-developed upper shoreface succession containing thick, approximately 8 m, sets of trough cross-stratification, and (4) a foreshore interval composed of seaward-inclined parallel-to sub-parallel-bedded sandstone. Although detailed facies interpretations exist, the storm intensity and daily wave energy of preserved shorefaces has yet to be quantified.

This study focuses on shoreface deposits within the Campanian Rollins Sandstone Member of the Mount Garfield Formation (75.5-72 Ma) (Cobban et al., 2006; Gill and Hale, 1984) to help understand and quantify the hydrodynamics of high-energy, wave-dominated shorefaces that developed within the SFB. The Rollins Sandstone Member is the youngest member of the Mount Garfield Formation and is well exposed along the Colorado portion of the Book Cliffs north of Grand Junction, Colorado (Figure 1 and 2). The Rollins Sandstone Member was deposited at a time of high-frequency sea-level change and contains strata from three depositional sequences (Figure 3) (Chapter 2). Each sequence within the Rollins Sandstone Member contains an incised-valley fill overlain by a single parasequence within the highstand systems tract. This study focuses on the highstand systems tract of the youngest sequence within the Rollins Sandstone Member. The shoreface succession within the highstand systems tract was used for this study because the exposed shoreface deposits are representative of shoreface deposits within the SFB, and because it contains the most complete shoreface succession within the Mount Garfield Formation.

The purpose of this study is to interpret the hydrodynamics of a shoreface succession within the SFB, including daily wave height and period, an estimate of storm intensity, and calculations of water depth for the sub-units of the shoreface. A detailed facies analysis will also help to interpret shoreface morphology and the geometry of the shoreline at the time of deposition.

METHODS

Six sections were measured through the Rollins Sandstone Member near Grand Junction, Colorado (Figure 1). Each section was measured on a bed-by-bed basis, documenting sedimentary structures, grain size, the geometry of individual sandstone beds, and the nature of the contacts between beds. Vertical trends in grain size or sedimentary structures were also noted. Sub-units of the shoreface were distinguished based on grain size and sedimentary structures, and interpreted in terms of the hydrodynamic conditions that occurred at the time of deposition.

Interpretation of the hydrodynamics of each sub-unit is based on comparison with modern shorefaces. Information gathered through this comparison includes daily wave height and period, storm intensity, and water depth. Daily wave height was estimated by comparing the upper shoreface deposits of the Rollins Sandstone Member with upper shoreface deposits along modern coastlines. Daily wave height is estimated from flow velocity, which is calculated by analyzing thickness of cross-bed sets and grain size within the deposits. Storm intensity is interpreted by comparing the size and type of sedimentary structures as well as grain sizes within the lower shoreface deposits of the Rollins Sandstone Member with modern environments.

Water-depth estimates for each sub-unit are based on the thickness of the stratigraphic succession above the sub-unit. This estimate assumes foreshore deposits (the top of the succession) were deposited at or near sea level. For example, the upper shoreface interval occurs between 1 and 8 m below the top of the shoreface succession and is thus interpreted to have been deposited in water depths of 1-8 m.

Compaction of sediment and subsidence that occurred during and soon after deposition of the shoreface must be taken into consideration before making these estimates. Water depth will be underestimated if the compacted thickness is less than the true thickness, however, for this calculation compaction will be ignored. The shoreface succession is a sandstone-dominated interval, and strata in this part of the Piceance Basin has a shallow burial history (less than 3,000 ft of overburden), and thus compaction will be minimal (Johnson and Nuccio, 1986; Van Hinte, 1978).

Ongoing subsidence within the foreland basin will result in a continuous increase in accommodation during deposition of the shoreface succession, but this continuous increase in accommodation will be minimal for the amount of time it takes the shoreline to prograde the distance required to deposit the 30-40 m of strata at any measured section locality (see Appendix B). Rates of subsidence for distal parts of foreland basins are between 3 and 10 cm/1000 years (DeCelles, 2004; Fleming and Jordan, 1989; Willis, 2000). Each parasequence within the Mount Garfield Formation represents approximately 0.1-0.25 Ma of time (Appendix B). Each of the 30-40 meter thick vertical successions measured in the study area is interpreted to represent less than 2,500 yrs; and no more than 7-25 cm of accommodation due to depositional subsidence will be added to the stratigraphic succession in that time frame (see Appendix A). This amount of subsidence is minimal, and can be ignored for the purpose of estimating water depth for each sub-unit.

DEPOSITIONAL FACIES

The Rollins Sandstone Member contains both marginal-marine and marine shoreface successions. Within the study area marginal-marine deposits within the Rollins Sandstone Member are found within incised valleys, and marine shoreface deposits are preserved in the highstand systems tract (Figure 3). This study focuses on the marine shoreface deposits. These deposits are thick (up to 40 m), upward-coarsening, sandstone-dominated successions (Figure 4). The base of these successions consists of bioturbated silty mudstone and siltstone (offshore transition interval). The offshore transition interval grades vertically into interbedded silty mudstone and hummocky cross-stratified (HCS) sandstone (lower shoreface interval). Interbedded silty mudstones and HCS sandstones are overlain by amalgamated beds of

HCS sandstone within the lower shoreface succession. Amalgamated HCS sandstones are overlain by bioturbated and burrowed sandstones (middle shoreface interval), followed by a thick succession of cross-stratified sandstones (upper shoreface interval), and eventually, the succession is capped by parallel- to sub-parallel-bedded sandstones (foreshore interval) (Figure 4).

Offshore Transition

Offshore transition deposits are poorly exposed within the field area. This sub-unit is typically a slope-forming interval at the base of the succession. The offshore transition is a silty-mudstone dominated succession consisting of bioturbated silty mudstones interbedded with thin (cm scale) siltstones and very-fine-grained sandstones (Figure 5). Mudstones within this succession represent suspension fall out during fair-weather conditions (Clifton, 2006). Thin sandstones and siltstones represent distal storm deposits. Only the highest intensity storms affect deposition in this portion of the shoreface. Long intervals between storm events allow burrowing organisms to bioturbate these sediments (Pemberton et al., 1992).

Lower Shoreface

The lower shoreface consists of an overall upward-coarsening succession from interbedded, thin (cm scale) sandstones and silty mudstones that grade into 0.25 m - 1.0 m thick amalgamated beds of hummocky cross-stratified (HCS) sandstone (Figure 6, Figure 7). The lower shoreface is 15-20 m thick. Sandstones grade from very-fine-grained sandstones at the base of the sub-unit into fine-grained sandstones at the top. Silty-mudstone beds within this sub-unit represent low-energy conditions, and were deposited as a result of suspension fall out during fair weather conditions (Clifton, 2006). HCS sandstone beds are the result of combined-flow currents developed during high-intensity storms along the shoreface (Harms et al, 1982). During storms, large waves produce oscillatory currents in the lower shoreface. Superimposed on this oscillatory current is a unidirectional, offshore-directed, storm-generated current. The combination of the oscillatory motion from the waves, and the storm-generated current are thought to produce hummocky cross-stratification (Duke et al, 1991; Harms et al, 1982; Myrow and Southard, 1996; Swift et al, 1983). Upward coarsening through the lower shoreface represents progradation of the shoreface profile (Figure 6).

Middle Shoreface

The middle shoreface lies between the lower and upper shoreface intervals and consists of 0.5-2 m (average of about 1.5 m) of fine-grained sandstone. This interval is burrowed to heavily bioturbated. The bioturbation has destroyed most of the original sedimentary structures (Figure 8). *Ophiomorpha* is the dominant structure throughout the middle shoreface. Burrows are robust with walls up to 4 mm thick and burrow size ranging in diameter from 1.5-3 cm (Figure 9). The intensity of bioturbation in this environment is interpreted to reflect the presence of a bar within the shoreface. The bar shadows an associated trough from the energy of shoaling waves. This zone of slightly dampened wave conditions allows organic material to accumulate, and allows organisms to thrive in the trough (Davidson-Arnott and Greenwood, 1974). The accumulation of organics and biota in this protected area results in bioturbation within the trough of the bar. The organisms responsible for *Ophiomorpha* are carnivores that feed on other organisms that thrive in these conditions (Pemberton et al., 1992). Burrowed horizons similar to those observed in the middle shoreface of the Rollins Sandstone Member are found associated with bars in modern settings (Howard and Reinech, 1981; Shipp, 1984; Reinson, 1984; Schwartz and Birkemeier, 2004). The barred shoreface along the Santa Barbara coast, California, contains a bar, approximately 1-1.5 meter high, immediately seaward of the upper shoreface (Howard and Reinech, 1981). Box cores taken from the trough of the bar contain a sand dollar bioturbated interval up to 0.5 m thick. This zone, bioturbated by sand dollars, is analogous to the intervals with a concentration of *Ophiomorpha* and general bioturbation in the middle shoreface of the Rollins Sandstone Member. This barred interval is located at the base of the upper shoreface interval. The littoral processes responsible for producing and maintaining a bar are not well understood, however the presence of the middle shoreface interval throughout the Rollins Sandstone Member indicates that the bar was long lived and not an ephemeral feature on this shoreface.

Upper Shoreface

The upper shoreface interval is deposited as a result of shoaling waves (Clifton, 2006). The upper shoreface interval of the Rollins Sandstone Member consists of 7-8 m of fine-grained sandstone. There is little to no grain-size change throughout the upper shoreface. Sandstones within this sub-unit contain trough and wedge-shaped sets of cross-stratification ranging in thickness from 15-20 cm (Figure 10). There is little to no bioturbation throughout the upper shoreface.

The cross-stratified sandstones within the upper shoreface formed from the migration of three-dimensional megaripples. Bedforms of this scale, in fine-grained sandstone, form due to unidirectional current velocities of 0.5 to 0.8 m/s (Harms et al, 1982). Velocity asymmetry of the oscillatory motion of shoaling waves results in a dominantly unidirectional current in the upper shoreface, which produces the megaripples (Figure 11). For shoaling waves, the landward-directed current is shorter in duration but greater in velocity than the offshore-directed current. Bedload transport is proportional to the cube of the velocity, thus the higher velocity of the onshore-directed current prevails and sediment is transported in a landward direction (Clifton, 2006). Bedforms within this facies will migrate landward to slightly oblique to the shore depending on the direction of approaching waves (Clifton, 2006; Schwartz and Birkemeier, 2004). The daily wave height required to produce these bedforms will be discussed later in this paper.

Foreshore

The foreshore interval of the Rollins Sandstone Member consists of 1- 2 m of fine-grained sandstone. There is little to no grain-size change throughout the foreshore interval. This sub-unit contains sub-horizontal, parallel- to sub-parallel bedding. Locally, sandstones appear structureless due to weathering and rooting at the top of the Rollins Sandstone Member. Millimeter-scale rooting is present at the top of the succession.

The sub-horizontal bedding in the foreshore records deposition due to upper-flow-regime conditions on broad gently sloping surfaces (Harms et al, 1982). These deposits represent the swash zone of the shoreface (Clifton, 2006). The foreshore is the part of the shoreface deposited above the mean low water mark of the intertidal zone (Clifton, 2006). Rooting at the top of the facies is present due to vegetation in coal-forming environments within the overlying Cameo-Wheeler coal zone.

HYDRODYNAMIC INTERPRETATION OF THE SHOREFACE

Analysis of the daily wave height, as well as storm intensity, leads to a better understanding of shoreface dynamics at the time of deposition. An estimate of daily wave height is made by analyzing upper-shoreface strata and comparing them with deposits on modern shorefaces. An estimate of storm intensity is based on a comparison of the lower-shoreface strata with modern storm deposits off the east coast of the United States.

Upper-shoreface deposits within the Rollins Sandstone Member are located between 1 and 8 m from the top of the foreshore and are interpreted to have been deposited in water depths between 1 and 8 m. The daily wave height in these water depths is estimated by analyzing the thickness of individual cross-stratified beds in the upper shoreface interval. To produce cross-stratified beds 15 to 20 cm thick, in fine-grained sandstone, current velocities between 0.5 and 0.8 m/s are required (Harms et al., 1982). These current velocities are produced by the landward-directed motion of shoaling waves (Figure 11). For shallow-water waves, the current-generating orbital velocity is inversely proportional to water depth and directly proportional to both wave height and wave period (Wiberg and Sherwood, 2006). Higher, longer period waves produce larger current velocities at the bed. Wilberg and Sherwood (2006) published a chart relating orbital velocity at the bed with wave height and period (Figure 12). This chart, along with estimates of current velocities for the upper shoreface, were used to calculate a range of wave heights and periods for this sub-unit.

Daily wave heights between 1-2 m are required to produce the cross-stratification observed in the upper shoreface of the Rollins Sandstone Member. Waves larger than 2 m produce velocities that are too high to produce megaripples. These conditions (approximately 0.9 m/s), in fine-grained sand, would produce plane beds (Harms et al., 1982). Waves less than 1 meter do not have sufficient velocity yto produce megaripples (Table 1). The periodicity of waves also affects the current velocity at the bed. Waves that are 1 m high with periods greater than 4 seconds, or 2 m-high waves with varying periodicity (4-14 seconds) are believed to have produced the structures observed within the upper shoreface of the Rollins Sandstone Member (Table 1).

The daily wave height for the Rollins Sandstone Member can also be estimated by comparing stratification in the upper shoreface interval with modern shorefaces. The California coast and the Long Island, New York coast were chosen for this comparison because they are considered high-energy coastlines. Bedforms and stratification of the shoreface south of Santa Barbara, California were described and documented by Howard and Reinech (1981). The upper shoreface of the Santa Barbara coastline consists of fine-grained sand and contains both three-dimensional megaripples and small-scale current ripples. Box cores taken along this interval contain trough cross-bedding ranging from 5-12 cm in thickness in 4-7 m of water (Howard and Reinech, 1981). This size range is slightly smaller than the smallest cross-bedding observed within the upper shoreface of the Rollins Sandstone Member. The upper range of the cross-stratification within the Rollins Sandstone Member is almost double the average thickness of the cross-strata along the California coast.

The California coastline has a daily wave height of approximately 1 meter. The Rollins Sandstone Member is interpreted to have required daily wave heights greater than those along the California coast.

Stratification and bedforms along the Long Island, New York coast were observed and documented by Shipp (1983). The upper-shoreface of the Long Island coast consists of medium-grained sand and contains small-scale wave-ripple bedding, medium-scale three-dimensional megaripples, and planar bedding. The type of bedform that develops along the shoreface is dependent on the current wave conditions along the shoreface. During times of low wave energy only small-scale ripples are produced, however, during higher energy conditions three-dimensional megaripples are formed. Wave heights of 1.25 m with periods of six seconds produce megaripples with amplitudes of 14 to 18 cm in the upper shoreface. Cross-stratification observed from can-cores along the Long Island shoreface ranges from 6-9 cm in thickness. This cross-stratification, like that along the California coast, is smaller than that observed within the Rollins Sandstone Member. The grain-size difference between the Long Island shoreface and the Rollins Sandstone Member must be considered. In medium-grained sand three-dimensional megaripples will form at slightly lower current velocities then in fine-grained sand (0.4 cm/s). Wave heights greater than those observed on the Long Island coast are required to produce the cross-stratification observed within the Rollins Sandstone Member. The lack of bioturbation or burrowing in the upper shoreface is interpreted to indicate that wave energy was present consistently, on a daily basis. If wave height fluctuated from 1-2 m to significantly less than one meter, the upper shoreface would contain burrowed or ripple-bedded horizons.

Waves of 1-2 m in height require a minimum wind speed, duration, and fetch. The conditions needed to produce waves of this height are calculated using a wave prediction chart from the Shoreface Protection Manual (1984) (Figure 13). This chart is typically used to predict the wave height given a known wind speed, duration, and fetch. The wave prediction chart is used here to define wind speed, duration, and fetch for the range of wave heights estimated to produce the cross-stratification observed in the Rollins Sandstone Member. To produce the 1-2 m waves interpreted for the Rollins Sandstone Member, minimum wind speeds of 14-20 m/s are required with a duration of approximately 10-14 hours, and a fetch of 95-190 km (Figure, 13). A fetch of 190 km is possible in the Campanian, as the KWIS extended from western Colorado into central Kansas (approximately 2000 km) (Blakey, 2011). Fetch is one of the key limiting factors for producing large waves. The interpreted wave conditions for the Rollins Sandstone Member (1-2 meter waves) were not limited by fetch, and large waves could be produced under the right wind conditions.

Storms are a major force that rework and re-deposit sediment along the shoreface. To better understand the intensity of the storms at the time of Rollins Sandstone Member deposition, HCS preserved within the Rollins Sandstone Member were compared with HCS deposited along the east coast of the United States. HCS have been identified and described off the inner shelf of Long Island, Maryland, Virginia, and New Jersey by using a combination of vibra-core data and side-scan sonar in water depths up to approximately 30 m (Stubblefield et al,1974; Swift et al.

1978; Swift et al., 1983). These locations have been studied before and after large storms along the east coast to better understand the conditions that produce HCS (Stubblefield et al., 1974; Swift et al., 1978; Swift et al., 1983). Only the largest storms produce currents that will entrain sediment in the lower shoreface, however, very few storms along the east coast produce HCS (Stubblefield et al., 1974; Swift et al., 1978; Swift et al., 1983). Storms capable of producing HCS only occur about 3-5 times per year along the east coast, however, any given location along the east coast may not be affected by every storm. These large storms, called Nor'easters, are known to produce waves up to 8 m in height, and geostrophic currents between 20-60 cm/sec at water depths up to approximately 20 m (Stubblefield et al.,1974; Swift et al., 1978; Swift et al., 1983). Individual HCS beds deposited by these storms reach 30 cm in thickness, however, little is known as to the preservation of the HCS (Swift et al., 1977). Side-scan sonar records do show that hummocky bedforms are no longer visible 2 months after a storm (Swift, 1983). No data is available as to whether these bedforms disappear as a result of being buried in additional sediments or whether they are bioturbated in the 2 months following their formation. The HCS deposited along the east coast of the US are deposited in similar water depths, and are similar in thickness to those preserved within the Rollins Sandstone Member. Storms with approximately the same strength as those observed along the east coast of the US could produce the deposits observed in the Rollins Sandstone Member. HCS beds within the Rollins Sandstone Member contain little to no burrowing, which may be attributed to the high progradation rate of these shorelines. The lack of burrowing within these HCS beds may also indicate a higher frequency of storms along the west coast of the KWIS than what is observed along the east coast of the US.

SHORELINE GEOMETRY

A detailed facies interpretation of the Rollins Sandstone Member allows for re-examination of the Late Cretaceous paleogeography of the shoreline in the study area. A detailed paleogeographic reconstruction by Blakey (2011) shows an irregular shoreline with estuaries, barrier islands, and large river-dominated deltas along the western edge of the KWIS (Figure 14). Data from this study indicates an alternative interpretation, with straight, high-energy, wave- and storm-dominated shorelines. Extensive progradation would have produced a wide strandplain, and the high-wave-energy conditions documented for the study area are usually associated with straight coastlines. The coastline at the time of Rollins Sandstone Member deposition is proposed to be similar to the wave-dominated, progradational coastline present along the western coast of Nayarit, Mexico (Clifton, 2006) (Figure, 15; Figure 16). This interpretation is consistent with other interpretations for the Rollins Sandstone Member (Cole and Cumella, 2003). The Late Cretaceous coastline would have consisted of an extensive strandplain with remnant beach ridges, recording the progradation of the shoreface (Figure 16). River-dominated deltas would not exist in these high-wave-energy conditions, as sediment brought into the seaway by rivers would be reworked quickly by littoral processes (Clifton; 2006). The lack of delta deposits within the Mount Garfield Formation supports the interpretation that these were straight, wave-dominated coastlines and void of any river-dominated deltas.

CONCLUSIONS

The marine shoreface deposits that make up the Rollins Sandstone Member represent high-energy, storm- and wave-dominated shorefaces. Cross-stratification preserved within the upper shoreface interval indicates the Rollins Sandstone Member had higher daily wave energy than both the Long Island, New York and southern California coastline. Shorefaces within the Rollins Sandstone Member had daily wave heights of approximately 1-2 m. Thick successions of HCS within the lower shoreface deposits indicate that these were also storm-dominated shorefaces. Storms that produced HCS within the Rollins Sandstone Member are proposed to have been similar in magnitude to Nor'easters along the east coast of the US. The existence of a middle-shoreface interval indicates these shorelines were barred, and that these bars were long lived and not ephemeral features along the shoreface. Due to the high-energy wave climate, the western coast of the KWIS is interpreted as a straight coastline, with extensive strandplain development.

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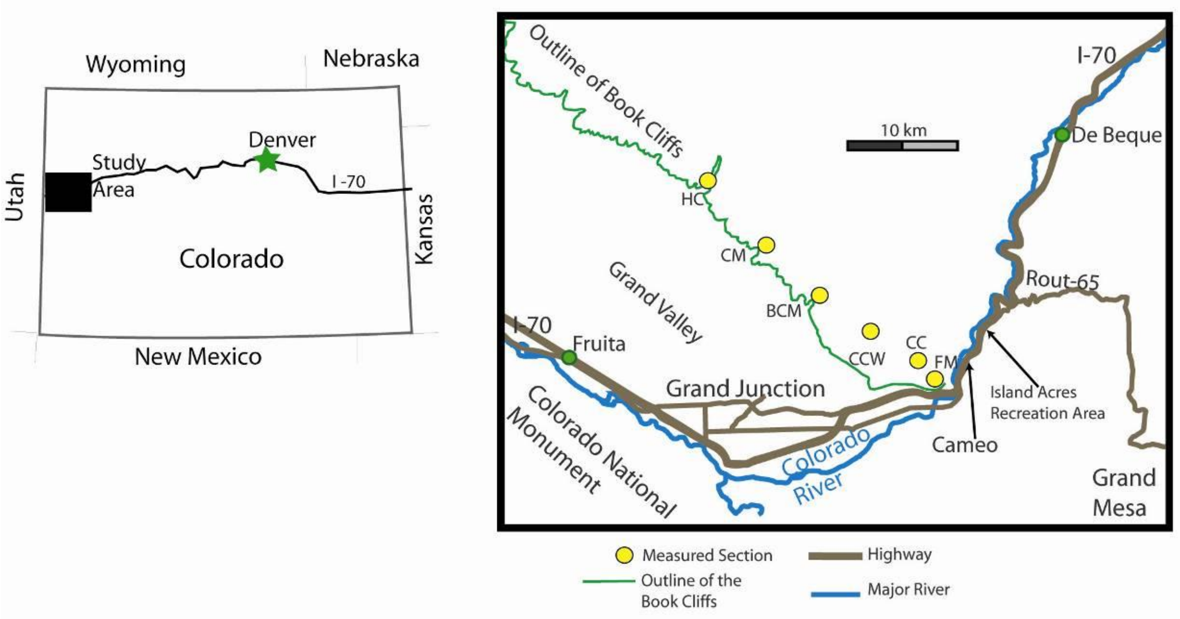


Figure 1. Map showing the study area near Grand Junction, CO. Measured sections along the Book Cliffs are shown in yellow. HC = Hunter Canyon, CM = Corcoran Mine, BCM = Book Cliffs Mine, CCW = Coal Canyon West, CC = Coal Canyon, FM = Farmers Mine.

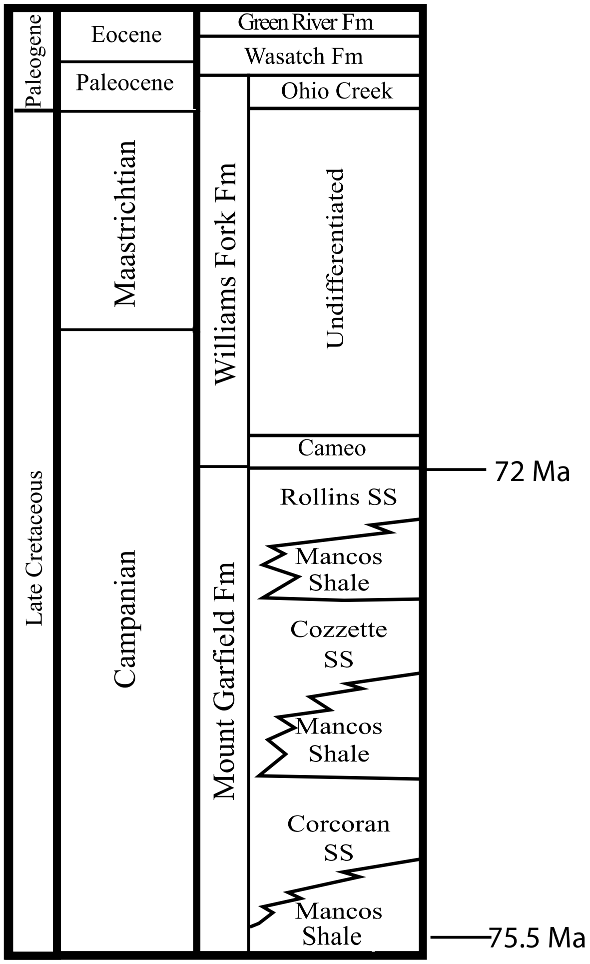


Figure 2. Lithostratigraphic nomenclature and stratigraphic ages for the Upper Cretaceous strata exposed near Grand Junction, Colorado. Ages of the Mount Garfield Formation are constrained using ammonite zones identified by Gill and Hale (1984). ^{40}Ar/^{39}Ar radiometric age dates for ammonite zones are from Cobban et al. (2006). Cameo is an abbreviation for the Cameo-Wheeler coal zone.

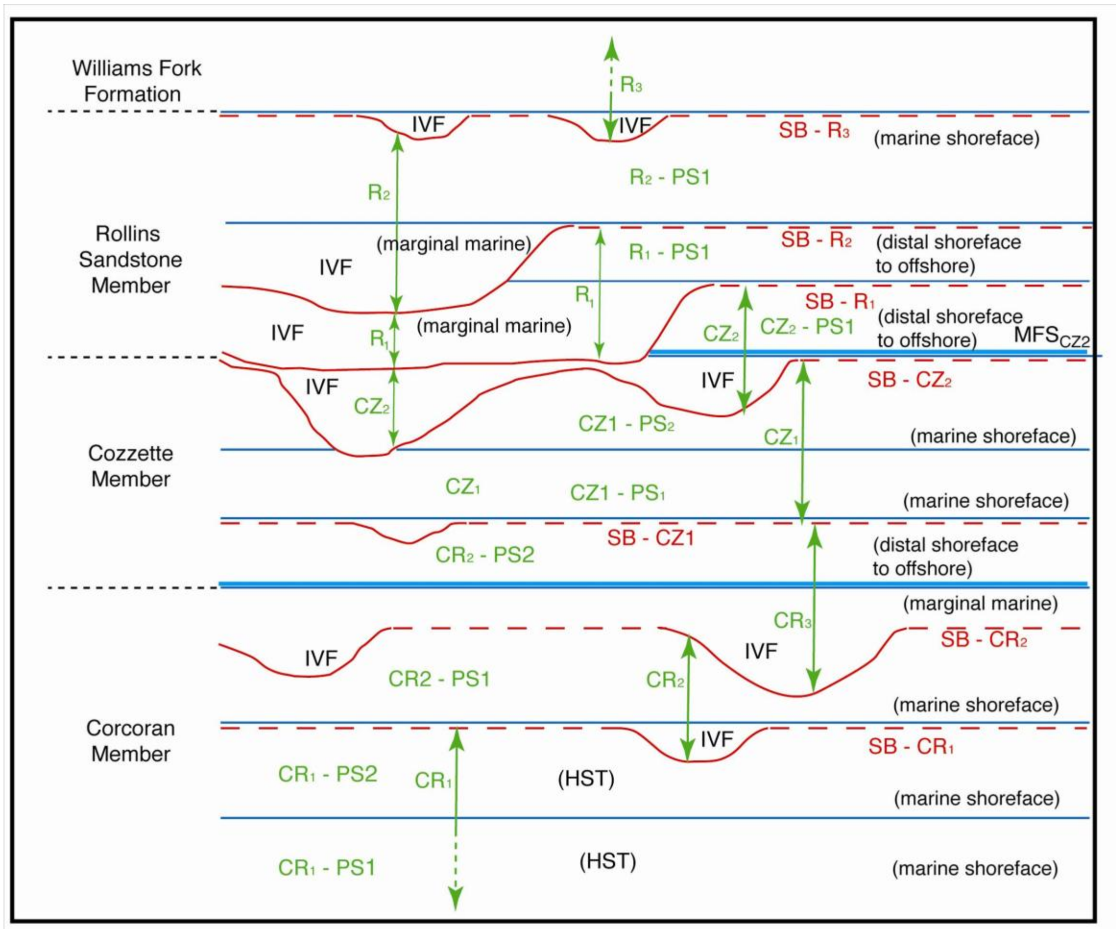


Figure 3. Schematic diagram showing the sequence stratigraphy of the Mount Garfield Formation. R_1 – PS2 is the parasequence which contains the marine shoreface succession which is used for this study. IVF = incised valley fill; HST = highstand systems tract; CR = prefix for Corcoran depositional sequence; CZ = prefix for Cozzette depositional sequence; R = Prefix for Rollins depositional sequence; PS = parasequence; SB = sequence boundary. Modified from Kamola et al. (2007).

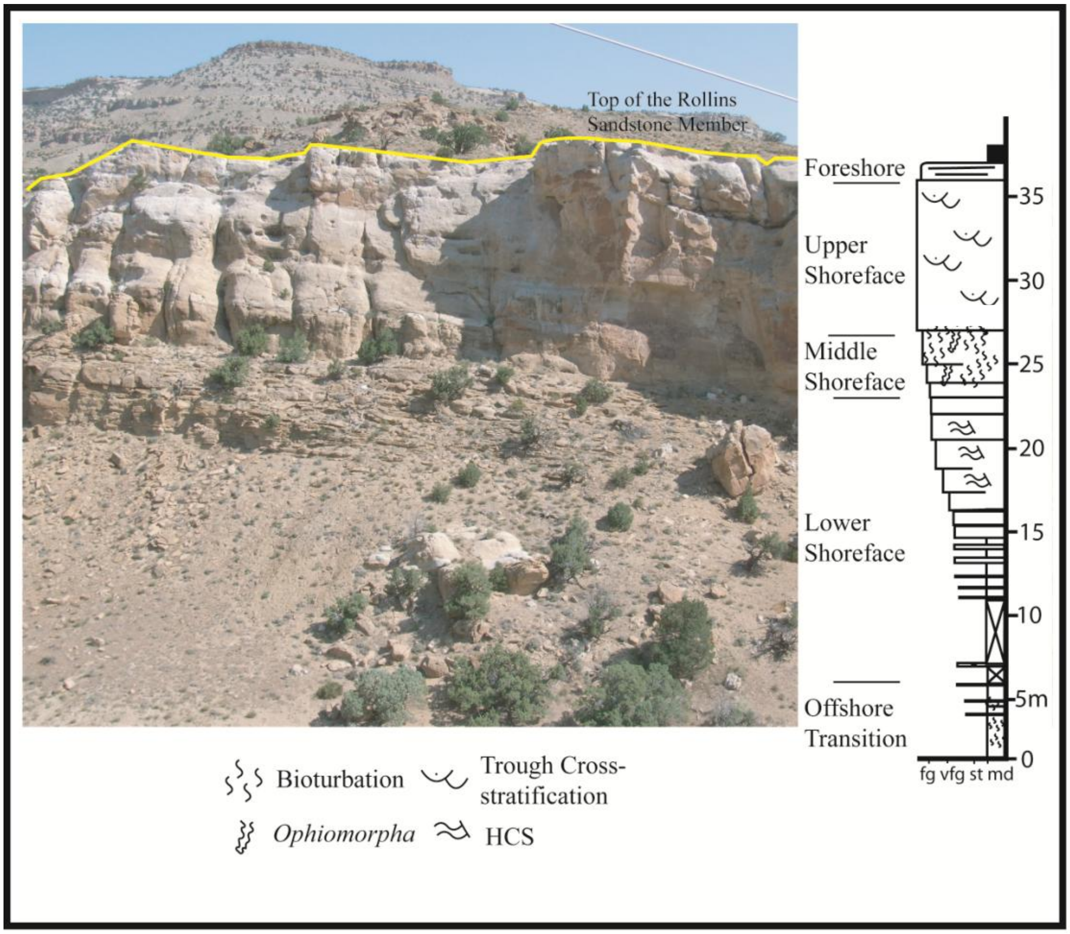


Figure 4. Progradational marine shoreface deposits of the Rollins Sandstone Member are expressed as upward-coarsening packages in Coal canyon (type locality for the Rollins Sandstone Member). fg = fine grained sandstone, vfg = very fine grained sandstone, st =silt, and md = mud.

Figure 5. Bioturbated interbedded silty mudstones and siltstones exposed in Coal Canyon West. These fine-grained deposits are poorly exposed throughout the field area. The jacob staff in the center of the photo is 1.5 m.

Figure 6. Upward-coarsening succession of interbedded sandstone and silty mudstone of the lower shoreface exposed at Farmers Mine. Exposure is approximately 5 m high.

Figure 7. HCS bed (30 cm thick) within the lower shoreface interval exposed in Corcoran Mine.

Figure 8. Intensely bioturbated middle shoreface succession at Coal Canyon. Note the well preserved *Ophiomorpha* (see arrow) and remnant HCS (bottom right) within this facies.

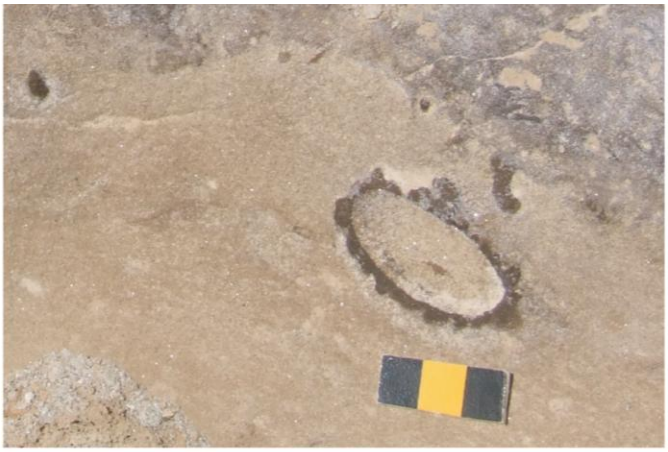


Figure 9. Robust *Ophiomorpha* exposed in the middle shoreface interval at Book Cliffs Mine (3 cm scale at the bottom of the photo).

Figure 10. Cross-stratified sandstone exposed in Corcoran Mine. The sloping surface of the outcrop exposure gives the cross-stratification a large apparent thickness. The true thickness of the cross-stratification in this locality is approximately 20 cm (15 cm scale at the base of the photo).

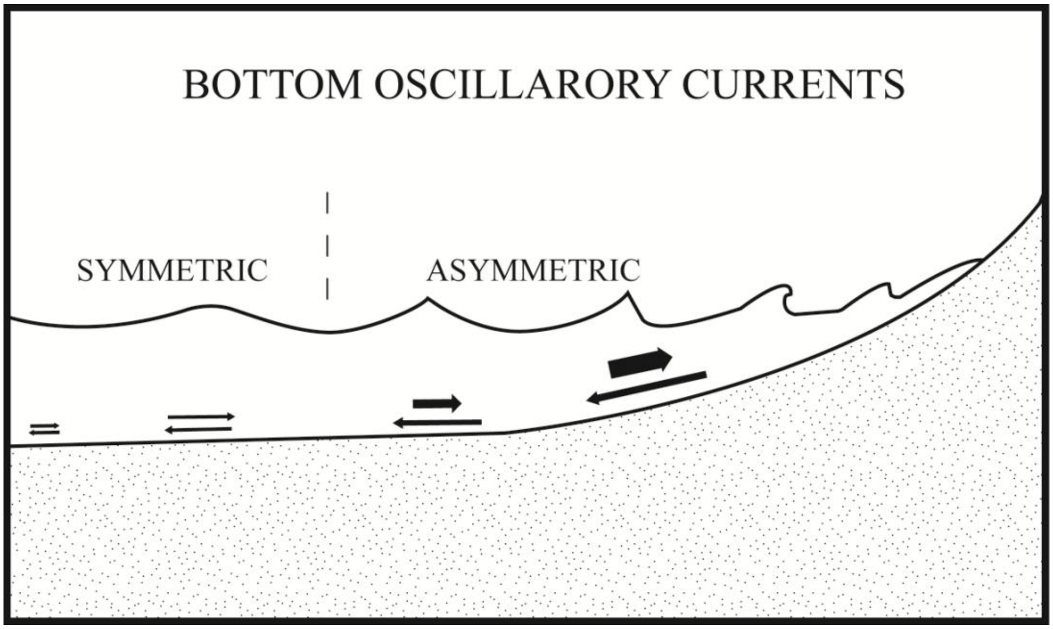


Figure 11. Schematic representation of the shoreface profile showing the time velocity asymmetry of the orbital motion of shoaling waves. Arrows represent the velocity of the orbital motion at the bed. The thickness of arrows represents the magnitude of the velocity and the length of the arrows represents the time that the current is acting on the bed. The time velocity asymmetry of the orbital motion is what drives sediment in a landward direction and produces landward directed cross-bedding in the upper shoreface (Modified from Clifton, 2006).

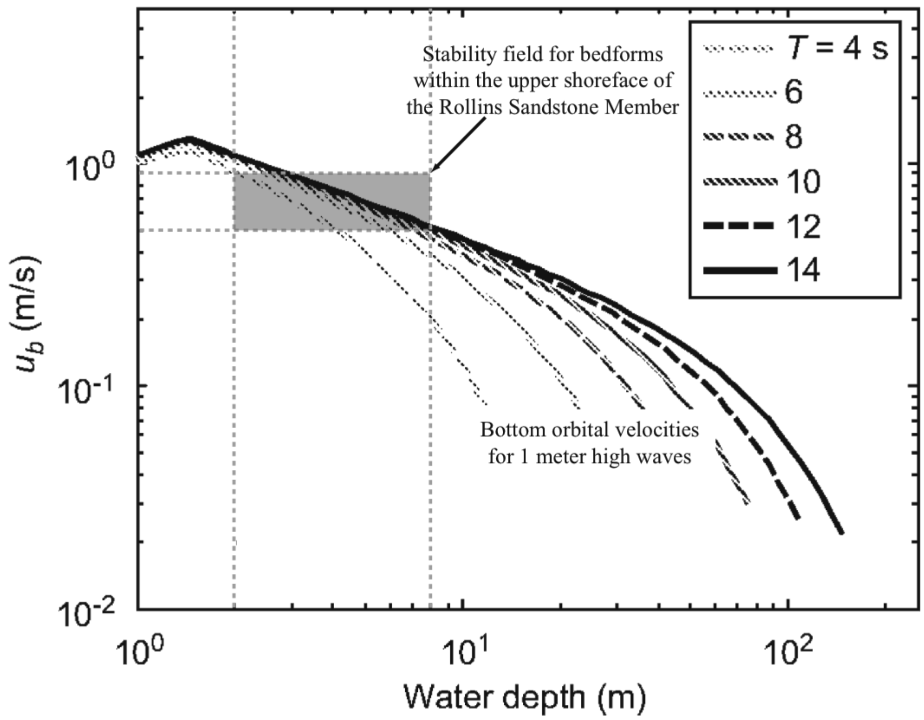
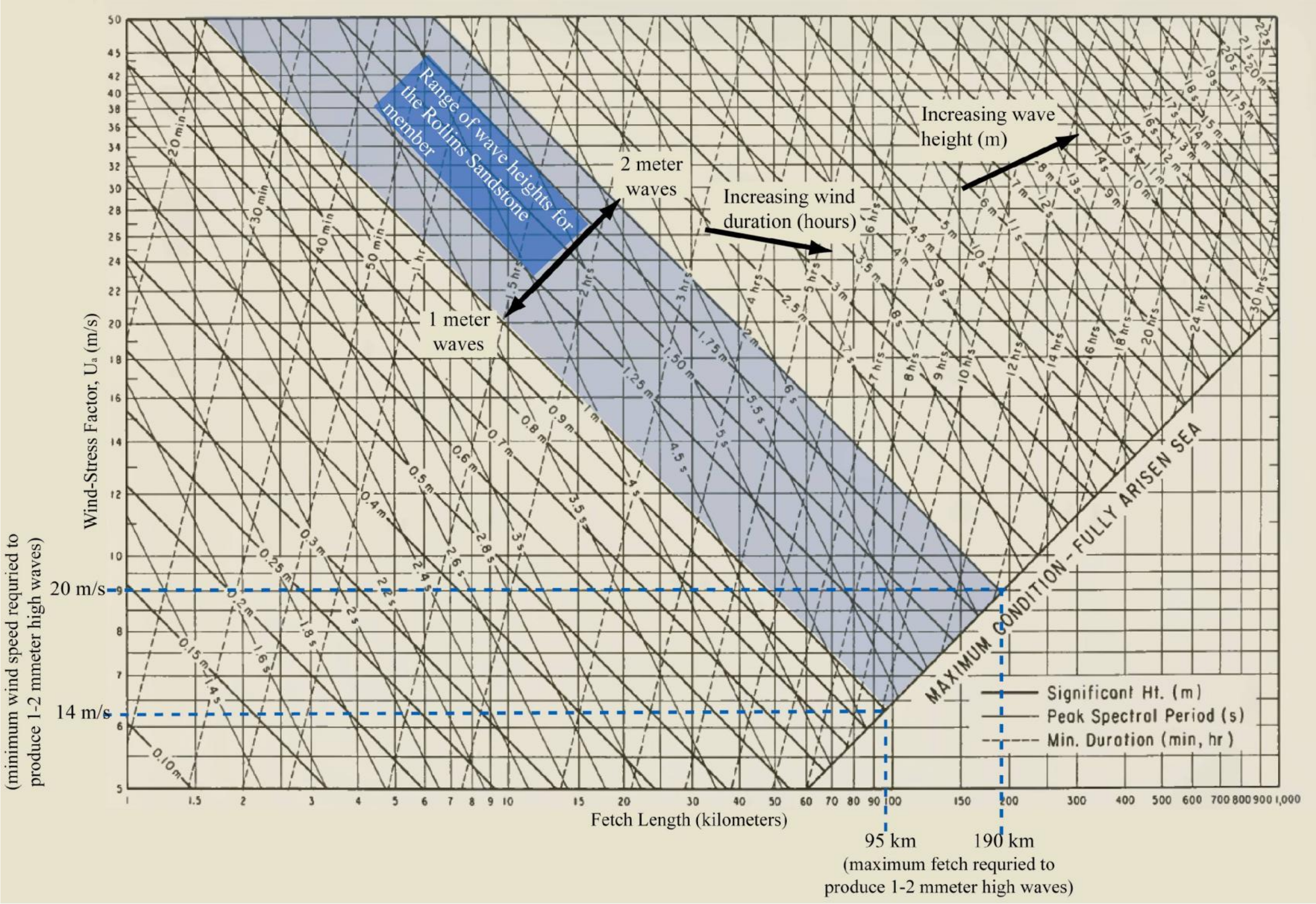


Figure 12. Bottom orbital velocity (Ub) for 1 meter high shallow water waves with periods of 4-14 seconds plotted as a function of water depth. Grey region represents the stability field for bedforms in the upper shoreface of the Rollins Sandstone Member. For wave heights other than 1 meter, the orbital velocity (Ub) is multiplied by wave height (H). Orbital velocities for waves ranging from 0.5-2.5 m in height are plotted in Table 1. T = wave period in seconds. Modified from Wilberg and Sherwood, 2006.


Range of wave heights for the Rollins Sandstone member
2 meter waves
1 meter waves
Increasing wind duration (hours)
Increasing wave height (m)
MAXIMUM CONDITION - FULLY ARISEN SEA
Significant Ht. (m)
Peak Spectral Period (s)
Min. Duration (min, hr)
Wind-Stress Factor, Ua (m/s)
(minimum wind speed requried to produce 1-2 mmeter high waves)
20 m/s
14 m/s
Fetch Length (kilometers)
95 km
190 km
(maximum fetch requried to produce 1-2 mmeter high waves)
50
45
42
40
38
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20 hrs
24 hrs
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0.15 m
0.2 m
0.25 m
0.3 m
0.4 m
0.5 m
0.6 m
0.7 m
0.8 m
0.9 m
1 m
1.25 m
1.50 m
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14 m
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17.5 m
20 m
1.4 s
1.6 s
1.8 s
2 s
2.2 s
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22 s

Figure 13. This is a diagram for predicting wave heights based on wave fetch, wind-stress factor (a function of wind speed), and wind duration. The region highlighted in blue represents the interpreted wave conditions for the Rollins Sandstone Member (1-2 meter waves). In order to produce 1-2 meter waves a minimum wind speed of 7-11 m/s is needed (y axis). 95-190 km of fetch (x axis) is required to produce 1-2 meter waves under these wind conditions. Wind stress factor is converted back to wind speed using the equation $U = 0.71U_a^{1.23}$ where U = wind speed and Ua = wind stress factor (Appendix B) (equation from Shoreface Protection Manual, 1984). Modified from Shoreface Protection Manual (1984).

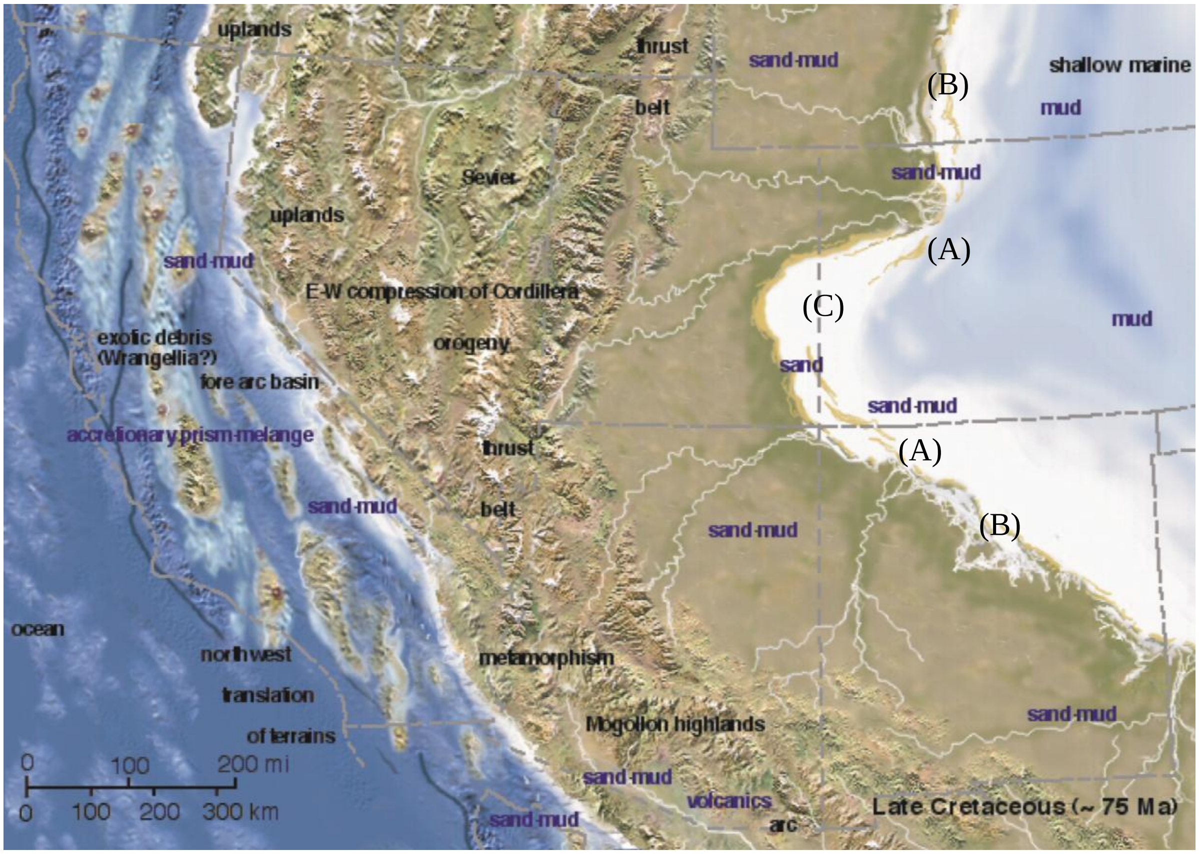

Figure 14. Paleogeographic reconstruction of the western United States around 75 Ma. The west coast of the KWIS is irregular, shown here with large deltas (A), barrier islands (B), and embayments (C). Map modified from Blakey, 2011.

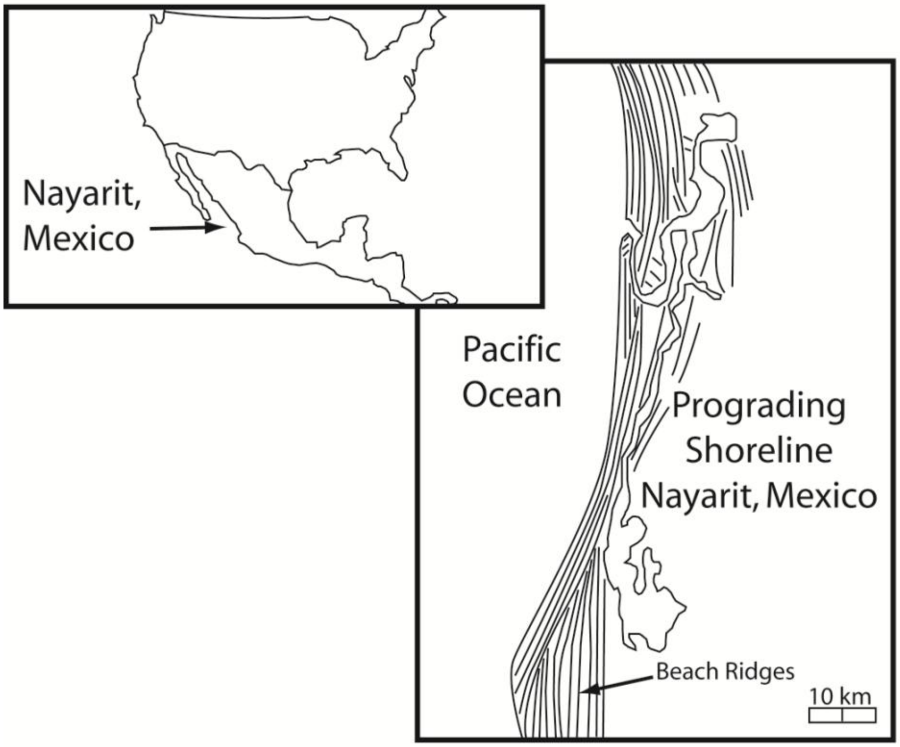

Figure 15. Illustration of the progradational wave-dominated coast at Nayarit, Mexico. The straight shoreline is indicative of a wave-dominated coastlines and the remnant beach ridges indicate at least 10-15 km of progradation. Modified from Clifton, 2006.

Figure 16. Interpreted paleo-geographic map for the Rollins Sandstone Member. Interpretation shows a straight shoreline (A) with an extensive strandline (B). Remnant beach ridges along the strandline indicate the amount of progradation for the Rollins sandstone (B). Any deltas would be wave-dominated (C). Modified from Blakey, 2011.

Table 1. The range of current velocities at the bed for wave heights ranging from 1-2.5 m at periods of 4 and 14 second and water depths of 1-8 m. Current velocities are in m/s.

	Wave Height	1 meter waves		1.5 meter waves		2 meter waves		2.5 meter waves	
	Wave Period	4s	14 s	4s	14 s	4s	14 s	4s	14 s
Water Depth	1 meter	1	1	1.5	1.5	2	2	2.5	2.5
	4 meter	0.4	🟩 0.8	🟩 0.6	1.2	🟩 0.8	1.6	1	2
	8 meter	0.1	0.4	0.15	0.6	0.2	🟩 0.8	0.25	1

🟩 indicates stability field for the bedforms found in the upper shoreface of the Rollins Sandstone Member

Appendix A

Calculation of the amount of time represented by each highstand parasequence within the Rollins Sandstone Member:

The Mount Garfield Formation does not contain any high-resolution age dates. In order to estimate the amount of time represented by each parasequence in the highstand systems tracts assumptions must be made. The Mount Garfield Formation represents 3.5 Ma of time and contains 9 depositional sequences and 11 parasequences within the highstand systems tracts. By simply dividing the number of depositional sequences by the amount of time represented by the formation, each sequence represents approximately 0.4Ma. The time tied up by each sequence records a lowstand phase, a transgressive phase, and a highstand phase. Most sequences contain only one highstand parasequence. If the lowstand phase, transgressive phase, and highstand phase represent approximately the same amount of time within the sequence then each phase represents approximately 0.2 Ma. This does not account for the sequences that contain more than one highstand parasequence. If sequences with more than one highstand parasequence are taken into consideration this estimate will be even less. This is consistent with other estimates for highstand parasequences within the SFB (approximately 0.1-0.2 Ma) (Kamola, personal communication).

Calculation of the amount of subsidence recorded by each vertical succession through the shoreface:

The highstand shoreface within the Rollins Sandstone Member has prograded at least 40 km. Each parasequence within the highstand systems tract represents approximately 0.1-0.2 Ma. The shoreline within the Rollins Sandstone Member would have had progradation rates of approximately 0.4m/year. Each vertical succession through that highstand shoreface deposit only represents a small portion of the total time recorded by the parasequence. Each vertical succession through the highstand shoreface will only record as much time as it takes for the shoreface profile to prograde past a single measured section location. Modern shoreface profiles typically extend offshore for approximately 1 km (Clifton, 2006). Assuming the shoreface profile extends approximately 1 km offshore, with progradation rates of 0.4 m/year, each vertical succession represents about 2,500 years.

Subsidence rates for the distal part of foreland basins are interpreted to be 3-10 cm/1000 years (DeCelles, 2004; Fleming and Jordan, 1989; Willis, 2000). If each vertical succession records approximately 2,500 years of time, the amount of subsidence recorded by any one vertical succession is between 7.5-25 cm. 7.5-25 cm of subsidence is negligible for a 35-40 meter thick shoreface succession, and can be ignored for the purposes of the water depth estimates for each sub-unit.

Appendix B

Converting wind stress factor to wind speed:

Wind stress factor = U_a

Wind speed = U

Equation from the Shoreface Protection Manual (1984)

$U_a = 0.71U^{1.23}$

The range of Ua for the Rollins Sandstone is 6.25 – 9 m/s

For: $U_a = 6.25$ m/s

$$6.25 = U^{1.23}$$

$$U = 6.25^{1/1.23}$$

$$U = 13.81 \text{ m/s}$$

For $U_a = 9$ m/s

$$9 = U^{1.23}$$

$$U = 9^{1/1.23}$$

$$U = 19.88 \text{ m/s}$$