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Transitional Facies and Sequence Stratigraphic Complexity of Shallow-
Marine Star Point Formation to Coastal-Plain Blackhawk Formation
Along Depositional-Strike, Wasatch Plateau, Utah

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
In partial fulfillment of the
Requirements for the degree of

Master of Science
In
Earth and Environmental Sciences
Geology

By
Andrew Ranson

B.S. University of New Orleans, 2010

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ABSTRACT

Facies and stratigraphic architecture right at the transition from marine to non-marine environments is poorly documented. In the Cretaceous outcrops of Utah, Star Point and Blackhawk Formations are well studied. The nature of spatio-temporal transition of these two Formations, in the deposition-strike orientation, remains undocumented. This study characterizes facies and stratigraphic complexity at the transition of the two Formations that crop out in depositional-strike orientation in the Wasatch Plateau. Data from outcrop including photomosaics and measured sections demonstrate this complexity at a range of scales. The Star Point constitutes a shoreface environment. The Blackhawk constitutes a coastal-fluvial environment.

In the northern part of study area, the transition from marine to continental strata is expressed by intertonguing succession. The dip-oriented outcrops show pinch-outs of two parasequences into coastal-plain deposits. This complexity decreases southward, the southern outcrops show a simple transition. At least two sequence boundaries are correlated across the outcrop belt.

Keywords: Sequence Stratigraphy, Star Point Formation, Blackhawk Formation, Wasatch Plateau, marginal marine deposits, depositional strike variability, sequence boundary, Sedimentology, Stratigraphy

INTRODUCTION

In the stratigraphic record, transition of shallow-marine to coastal plain depositional environment is generally thought of as a smooth transition without much complexity. Usually it is described as a gradual upward transition from marine to non-marine settings with a small number of sub-environments. However, by focusing on the sub-environments in the marginal-marine strata, this study set out to document that this transition from shallow marine to coastal plain can be rather very complex stratigraphically.

In the Wasatch Plateau (Fig. 1A), Utah, upward transition of the Cretaceous shallow-marine Star Point Formation to coastal-plain Blackhawk Formation has been poorly documented, compared to the neighboring Book Cliffs. This study investigates the complex intertonguing of the coastal plain and shallow-marine environments in outcrops along the north-eastern Wasatch Plateau.

In outcrops, including the famous Book Cliffs (Fig.1A), regional sequence stratigraphic framework is normally described in dip-oriented sections (Taylor and Lovell, 1995; Van Wagoner, 1995; Howell and Flint, 2003; Yoshida et. al, 1998). This study gives a rare insight of this framework as it varies along depositional-strike. Particularly the sequence boundaries identified in this study gives a spatial, strike oriented perspective of an incised valley with its associated interfluves.

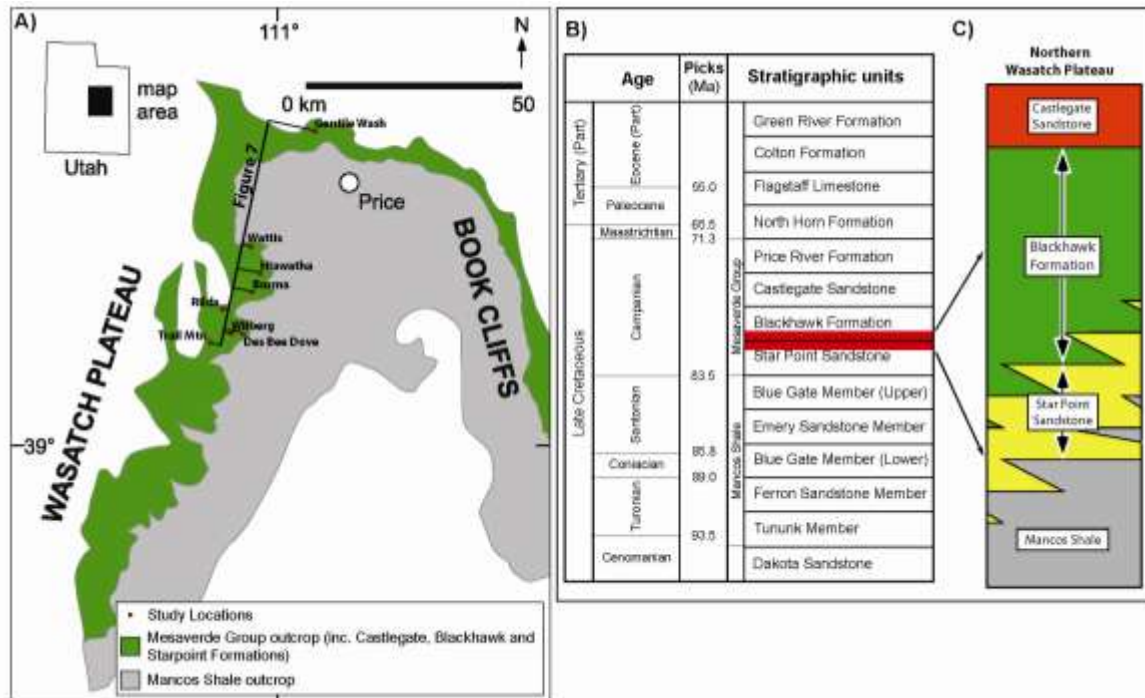


Figure 1: The present study focuses on the north-eastern Wasatch Plateau (A), contiguous with the famous Book Cliffs. Note the locations of the studied outcrop “windows”. The studied interval is the transition of the Star Point Formation into the Blackhawk Formation (red box in B). This interval is described by the intertonguing of the marine Star Point Sandstones with the non-marine Blackhawk Formation (C). (modified from Hampson et al., 2011)

Fluvial incision eroding top of marine sandbody may not always be the result of a sea level fall. In one particular outcrop, a fluvial incision into a upper marine sandstone is likely the result of a backwater effect (Chow, 1959; Parker, 2008). The backwater effect is a hydrodynamic event that is seen in modern environments, such as the Mississippi River (Nittrouer et. al, 2011). The backwater effect can create multiple incisions, and give a false sense of a drop in sea level in the rock record. However, there has been no documented backwater effect in the rock record to date. The example presented here could be the first recorded event in the outcrop.

The objectives of this paper are: (1) to identify and investigate the depositional environments at the transition interval between the Star Point and Blackhawk Formations, in documenting complex

land-ocean interactions in the Cretaceous Interior Seaway, (2) characterize sequence stratigraphic framework in a depositional strike orientation, and (3) give a new approach into interpreting fluvial incision, one not based on sea level fall, but an autogenic backwater effect.

Regional Geology and Study Area

During the late Cretaceous, central North America was covered by a north-south trending, epicontinental sea known as the Western Interior Seaway (Kauffman and Caldwell, 1993). The modern Wasatch Plateau, of eastern Utah was located parallel to the western coastline of the Interior Seaway during the Campanian Age (Fig. 2), thus preserving the sedimentary strata along depositional strike. The eight study sites (outcrop “windows”), are located in the north-eastern half of the Wasatch Plateau (Fig. 1A).



Figure 2: Cretaceous paleogeography of the Western Interior Seaway during the Campanian Age (~80 Ma ago). During this time the Star Point and Blackhawk Formations were deposited in a retro-arc foreland basin. Deltas and barrier islands were forming along the western shoreline and were sourced from the Sevier Orogenic belt in the west. (modified from Ron Blakely)

The studied late Cretaceous succession focuses on the transition of the upper Star Point and lower Blackhawk Formations, both of which belongs to the Mesaverde Group (Young, 1955; Cole et al., 1997). The Mesaverde Group was deposited in the seaway, as its shoreline repeatedly advanced and retreated resulting in a complex intertonguing of marine and non-marine strata (Henry and Finn, 2009). These deposits were sourced from the uplifted Sevier Orogeny to the west (Willis, 2000; Kaufmann and Caldwell, 1993). Rocks within the Wasatch Plateau normally have a dip of about two degrees to the northwest (Lamarre and Burns, 1997). Canyons were carved into the Wasatch Plateau as a result of erosion, exposing the Mesaverde Group and providing excellent windows outcrop options within the strata of our research.

The Star Point sandstone tongues (Fig. 1B), which have been interpreted to contain a number of parasequences (Hampson et al., 2011; Dubiel et al., 2000; Holman, 2001), overlie and intertongue the offshore deposits of the Machos Shale (Clark, 1928; Spieker, 1931). The Star Point Sandstone mostly consists of five parasequences that are predominantly linear to moderately lobate, wave dominated shorelines that define an overall concave-landward shoreline trajectory. Two of the five parasequences contain strong lobate river-dominated delta-front deposits that locally occur (Hampson et al., 2011). The majority of the Star Point sand bodies are overlaid by extensive coal zones of the Lower Blackhawk Formation. The coal flora indicates a climate of warm temperate to subtropical (Parker, 1976).

The Blackhawk Formation (Fig. 1B) constitutes an overall coastal-fluvial environment (Spieker, 1931), which was deposited behind the western shoreline of the seaway, landward of the Star Point deposits. The Blackhawk has been observed to contain more abundant, thicker and extensive channelized sandbodies as the Formation becomes younger (Marley et al., 1979). There are currently no

documented sequence stratigraphic boundaries in the non-marine Blackhawk Formation in the Wasatch Plateau.

Methodology and Dataset

The Mesaverde Group crops out continuously along the eastern edge of the Wasatch Plateau for a distance of 100 kilometers (Hampson, 2011). The north-eastern portion of the Wasatch Plateau's cliff face is sub parallel to the regional depositional strike of the western paleo-shoreline of the seaway (Flores et al., 1984; Dubiel et al., 2000; Hampson et al., 2011). A series of canyons cut into the outcrop belts of the Mesaverde Group in this portion of the Wasatch Plateau. Eight of these canyons served as ideal study locations to capture the complexity of the transitional zone of the Star Point and the Blackhawk Formation at a range of scales (facies, outcrop and regional). The sandstone exposures have mostly high visibility along the outcrop belt. However, the dominating mudstones tend to be covered by scree, which may be vegetated. In panoramic it is generally easy to distinguish the scree covered mudstone strata compared to the more resilient sandstone architecture.

In this study, detailed lithologies were measured at all eight outcrop "windows" through the top of the Star Point and the overlying lower Blackhawk Formations. These lithologies contain bed thicknesses, sedimentary structures, grain size variations, ichnology, bioturbation index, and paleocurrents. The bioturbation index (BI) of Taylor and Goldring (1993) is used to measure the degree of bioturbation in the sediments, and represented as BI log alongside lithologies as shown by Gani et al. (2008). All lithologies were hung from the top of the Star Point Formation, using the Axel Anderson-Cottonwood-Spring Canyon coal zone as the datum to create a regional sequence stratigraphic framework. Numerous photos were also taken to illustrate key facies stratigraphic features.

Several photomosaics of the outcrops were generated to conduct facies architectural and sequence stratigraphic analysis. The method of facies architectural analysis (Jackson, 1975; Allen, 1983) was used to show the complexity of the transitional zone at the outcrop scale. The facies architectural analysis also allowed for characterizing the intermediate-scale depositional complexities.

RESULTS

Facies Associations and Depositional Environments

Eight facies associations, each representing a particular sub-environment of deposition, were recognized at the Wasatch Plateau outcrops. The identified facies associations are offshore marine, lower shoreface, upper shoreface, fluvial channel, tidal channel, swamp, coastal/flood plain, and bay that are summarized in Table 1. In combination, these associations are interpreted to represent two major depositional settings, marginal-marine and terrestrial coastal plain. By studying various sub-environments of the marginal-marine strata in the Wasatch Plateau, this study reveals that the transition from shallow marine to coastal plain can be rather very complex. Importantly, this intertonguing transition contains incised channels, sequence boundaries, and abrupt, up-dip pinch outs of shallow-marine sandbodies (i.e. parasequences) into coastal plain mudstones, something that can serve as an analog for a lesser-known type of stratigraphic hydrocarbon trap.

Offshore Marine Facies Association (Fig. 3-A): These deposits consist mainly of mudstones with interbeds of very fine- to fine-grained, hummocky cross-stratified sandstones. The sandstone bed thickness ranges from 10 cm to 50 cm. A lower unit with *Cruziana* ichnofacies and a BI ranging from 3 to 5 was identified. The ichnogenera includes *Siphonichnus*, *Terebellina*, and *Helminthopsis*. An upper unit of mixed *Cruziana* and *Skolithos* ichnofacies with a BI ranging from 3 to 5 was identified. The ichnogenera includes *Terebellina*, *Helminthopsis*, *Palaephycus tubularis*, *Ophiomorpha*, and *Gyrochorte*.

Facies Association	Description	Ichnology
Offshore Marine	Mudstones with thin interbedding of very fine- to fine-grained hummocky cross-stratified sandstones; sandstone bed thicknesses range from 10 cm to 50 cm.	BI: 3 to 5; Cruziana ichnofacies; ichnogenera include Siphonichnus, Terebellina, Helminthopsis, Skolithos, Palaeophycus tubularis, Ophiomorpha and Gyrochorte.
Lower Shoreface	Fine-grained sandstones; bed thickness ranges from few cm up to 1 m; upward transition from hummocky cross-stratified sandstones to swaley to planar-laminated sandstones; symmetrical wave-ripples are preserved at bed tops; bioturbated, wavy mudstone beds.	BI: 3 to 5; mixed Cruziana and Skolithos ichnofacies; ichnogenera include Palaeophycus heberti, Skolithos, Ophiomorpha, Paleophycus tubularis, Chondrites, Terebellina, Asterosoma, and Thalassinoides.
Upper Shoreface	Fine- to coarse-grained sandstones; bed thickness ranges from 5 cm to 3 m; trough cross-stratification, mostly unidirectional but some bipolar.	BI: 0 to 3; Skolithos ichnofacies; ichnogenera include Ophiomorpha and Skolithos.
Swamp	Carbonaceous mudstones and coals; four separate coal beds ranging in thicknesses from 20 cm to 1.5 m; coal is bright and shiny, and fractures easily; leaf impressions and root traces.	BI: 0 to 1; Teredolites, and rare unidentified trace fossils.
Tidal Channel	Inclined heterolithic strata of mudstones and very fine-grained sandstones; sandstones contain current ripples and rare dune-scale stratification.	BI: 0 to 2; ichnogenera include Skolithos, Teredolites, Planolites and Thalassinoides.
Bay	Mudstones interbedded with thin, very fine-grained sandstones; sandstone thicknesses range from few cm to 50 cm; symmetrical wave-ripples in sandstones.	BI: 0 to 4; mixed Cruziana and Skolithos ichnofacies; ichnogenera include Terebellina, Palaeophycus heberti, and Thalassinoides.
Fluvial Channel	Very fine- to medium-grained sandstones; erosional channel bases with scattered mud clasts; sharp upper contacts with current ripple cross stratification; low-angle accretion surfaces; trough cross-stratification; convolute structures; bed thicknesses range from 10 cm to 2 m.	BI: 0, rarely 3; unidentified terrestrial trace fossils.
Coastal Plain/Flood Plain	Laminated to massive mudstone bedding encasing fluvial sandstones; no identifiable sedimentary structures; thick paleosols located in interfluves; local root traces.	BI: 0 to 1; unidentifiable rare terrestrial trace fossils.

Table 1: Facies association along with their descriptions and ichnology of the study interval that comprises the transitional zone between the Star Point and the Blackhawk Formations.

This facies association is interpreted to indicate an offshore marine environment, with a shallowing-upward trend. The majority of the deposits being mudstones with *Cruziana* ichnofacies indicate relatively low-energy conditions that are consistent with offshore marine environments below fair-weather wave base (Dott and Bourgeois, 1982). The hummocky cross-stratified sandstone beds indicate occasional storm events (Dott and Bourgeois, 1982). Storm beds are common in the offshore marine environments because strong storms have the ability to carry some of the shoreface sands to offshore and deposit them (Hamblin and Walker, 1979).

Lower Shoreface Facies Association (Fig. 3-B): These strata consist almost entirely of fine-grained sandstone beds with thickness ranging from a few cm up to 1 m. There is an upward-transition from hummocky cross-stratified sandstones to swaley to planar-laminated sandstones. Wave-ripples are preserved at some bed tops. Bioturbated, wavy mudstone beds were observed locally. A mixed *Cruziana* and *Skolithos* ichnofacies with a BI ranging from 3 to 4 were identified. The ichnogenera include *Palaeophycus heberti*, *Skolithos*, *Ophiomorpha*, *Paleophycus tubularis*, *Chondrites*, *Terebellina*, *Asterosoma*, and *Thalassinoides*.

Based on sedimentary structures and trace fossil assemblages, this facies association is interpreted as a lower shoreface deposit. The majority of the deposits being sandstones indicate a high-energy environment with persistent wave interaction. The upward-transition from hummocky to swaley to planar-laminated sandstones indicates the lower shoreface environment becoming more proximal stratigraphically upward, as the storm- and fair-weather waves having stronger interaction with the sea floor with decreasing water depth (Wright et al., 1979). The wave-ripples at the top of the beds indicate

marine environment above fair-weather wave base. The mixed *Cruziana* and *Skolithos* ichnofacies also indicate a lower shoreface environment (Pemberton et al., 1992).

Upper Shoreface Facies Association (Fig. 3-C): This facies association consists mostly of fine- to lower coarse-grained sandstone beds, ranging in thicknesses from 5 cm to 3 m. Dominant sedimentary structure is trough cross-stratification, mostly unidirectional but some are bipolar. Primary paleocurrent directions of these dunes range from 72 to 93 degrees. A *Skolithos* ichnofacies with a BI ranging from 0 to 3 is identified. The ichnogenera includes *Ophiomorpha* and *Skolithos*.

Based on sedimentary structures and trace fossil assemblage, this environment is interpreted as an upper shoreface. Paleocurrents of the dunes probably indicate that, locally, dominant longshore current was towards the northeast. The coarser grain size of the sandstones and the lack of mudstones indicate a very high energy environment seaward and closer to the beach (Harms et al., 1975). The *Skolithos* ichnofacies and the low BI also indicate a very high energy environment such as an upper shoreface (Gani et al., 2008).

Tidal Channel Facies Association (Fig. 3-D): This facies association consists of inclined heterolithic strata of mudstones and very fine-grained sandstones. The sandstones strata contain current ripples and rare dune-scale cross stratification. Some double mud drapes are also present. The BI ranges from 0 to 2. The ichnogenera includes *Skolithos*, *Teredolites*, *Planolites*, and *Thalassinoides*.

This succession is interpreted as tidal channel deposits. The inclined heterolithic strata indicate a migrating tidal channel (Thomas et al., 1987), where mudstones were deposited during times of no tidal change (i.e. slackwater periods) and the sandstones were deposited when the tides were moving in and out. Double mud drapes also suggest a tidal influence in the environment. Moreover, presence of marine trace fossils indicates that the channel was influenced by marine processes.

Bay Facies Association (Fig. 3-E): These deposits consist of mostly mudstones interbedded with thin, very fine-grained sandstone beds with erosional bases. Symmetrical wave-ripples are present in the sandstone beds, which range in thickness from a few cm to 30 cm. A mixed *Cruziana* and *Skolithos* ichnofacies with a BI ranging from 0 to 4 was observed. The ichnogenera includes *Terebellina*, *Palaeophycus heberti*, and *Thalassinoides*.

Restricted trace-fossil suite with non-uniform trend of BI log (Gani et al., 2008), and the presence of wave ripples but the lack of hummocky cross-stratification indicate a relatively shallow and protected marine environment such as a bay environment (Coleman, 1966; Dalrymple et al., 1992). Predominance of mudstones suggests a relatively low energy environment. However, the presence of thin, erosional sandstone beds with wave ripples indicates occasional stronger wave conditions affecting the bay floor.

Swamp Facies Association (Fig. 3-F): The succession consists of highly carbonaceous mudstones and coals. Multiple coal beds are present with thicknesses ranging from 20 cm to 3 m. The

coals are bright and shiny, and easily fractured. Some leaf impressions and root traces are present. The BI ranges from 0-1. Some *Teredolites* and rare vertebrate burrows are present locally in the coal beds.

This facies association is interpreted to deposit in swamps. Carbonaceous mudstones and coals are indicator of massive amounts of vegetation growth, which are commonly present in swampy environments near the coasts (Cobb and Cecil, 1993).

Coastal Plain / Flood Plain Facies Association (Fig. 3-G & 3-H): This facies association consists primarily of mudstone and siltstone deposits with subordinate, thinly bedded sandstones. Locally, the mudstone and siltstone deposits can contain carbonaceous material and palaeosols.. The deposits are rarely bioturbated with unidentifiable organism. Paleosols were identified at the Rilda Canyon outcrop with a thickness of up to 5.9 m. The massive appearing palaeosol deposit lacks any facies structures and reacted with hydrochloric acid.

This succession indicates a coastal/flood plain deposits, based on the fact that paleosols and encase fluvial channel sandstones. The carbonaceous material is interpreted as vegetation growth on the floodplain. The mature calcareous palaeosols represent a major hiatus in deposition (Sheldon and Tabor, 2009).

Fluvial Channel Facies Association (Fig. 3-I): These deposits consist of channelized, very fine- to medium-grained sandstones, which show erosional U-shaped bases overlain by scattered mud clasts, and sharp upper contacts underlain by current ripple cross-lamination. Trough cross-stratification and convolute structures are also present. Internally, the sandstones show low-angle accretion surfaces,

dipping roughly 90 degrees away from the dips of the dune-scale cross-bedding. There are no identifiable burrows in this facies association, therefore, the overall BI is 0.

This facies association is interpreted to indicate a fluvial channel deposits. Erosional U-shaped bases indicate fluvial channel cutting into underlying substrates (Miall, 1983). Low-angle accretion surface indicates lateral migration of meandering channels (Bernard et al., 1970), whereas dune-scale cross-stratification and current ripples indicate unidirectional current flow typical of a fluvial channel. Convolute structures indicate rapid deposition, and dewatering after deposition of overlying bed.

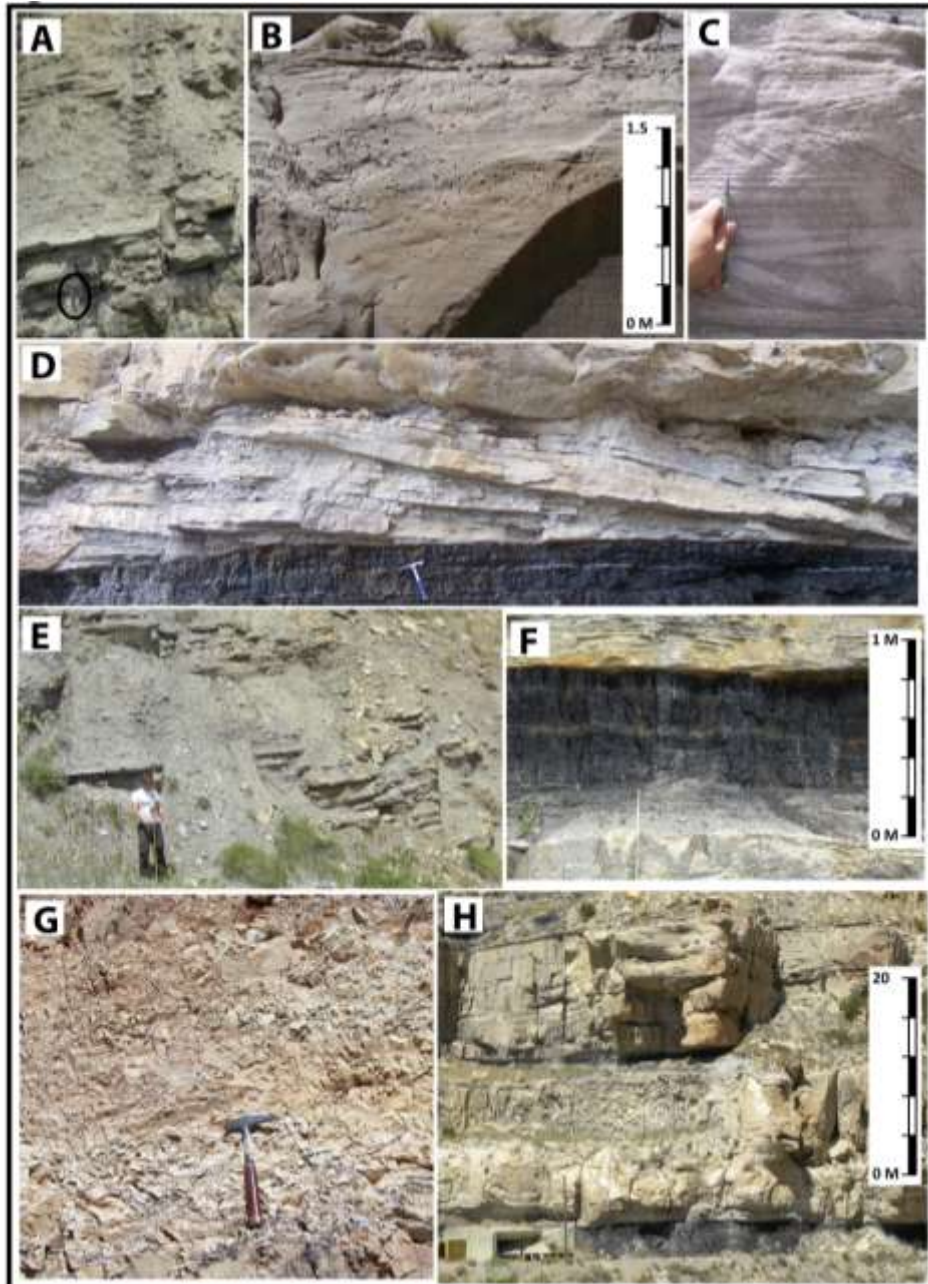


Figure 3: Representative facies photos of the Star Point and Blackhawk Formations in the north-eastern Wasatch Plateau. A) Offshore mudstones with thin bedded hummocky cross strata of the Star Point Formation (hammer is circled for scale). B) Lower shoreface deposits with hummocky and swaley cross strata. Note the intense Ophiomorpha burrowing. C) Dune cross-stratification of the upper shoreface deposits. Note the lack of trace fossils locally. D) Inclined heterolithic strata interpreted as a tidal channel deposit that are sandwiched between a coal seam (lower) and a erosionally-based (interpreted as incised valley) fluvial channel deposit (upper). E) Alternating layers of carbonaceous mudstones and sandstones with wave ripples that are interpreted to deposit in bay environments. A coal seam caps this bay succession. F) Coal seams and carbonaceous mudstones, representing a swamp environment. G) Paleosol developed within flood plain mudstones. H) A pair of fluvial channel deposits encased in coastal plain mudstones in the Blackhawk Formation.

Overall Depositional Pattern

In the study area, eight different depositional environments appear and reappear both temporally and spatially. Coarsening-upward offshore and shoreface strata indicate a typical regressive shoreline. These shallow-marine deposits are then overlain by strata of coastal plain environments, such as swamps, tidal and fluvial channels, and bays. The southern part of the study area (e.g., Trail Mountain Mine) represents a rather smooth upward transition from marine to non-marine strata (Figs. 4A, 5). However, the northern section of the study area, Wattis Road outcrop (Figs. 4B, 6), appears more complex with many depositional sub-environments, barrier island complex, fluvial incision into marine sandstone, and up-dip pinchouts of marine sandbodies. The rise of relative sea-level brings back marine environments that overlie coastal plain environments. At the Wattis Road study area, final regression of the sea is accompanied by the development of a fluvial channel with multiple incisions, eroding into upper shoreface deposits, with associated fluvial channels and coastal plain strata. Notably, abrupt, up-dip pinch outs of the two uppermost marine sandbodies within coastal plain mudstones are distinctly developed in the Wattis Road section (Fig. 6).

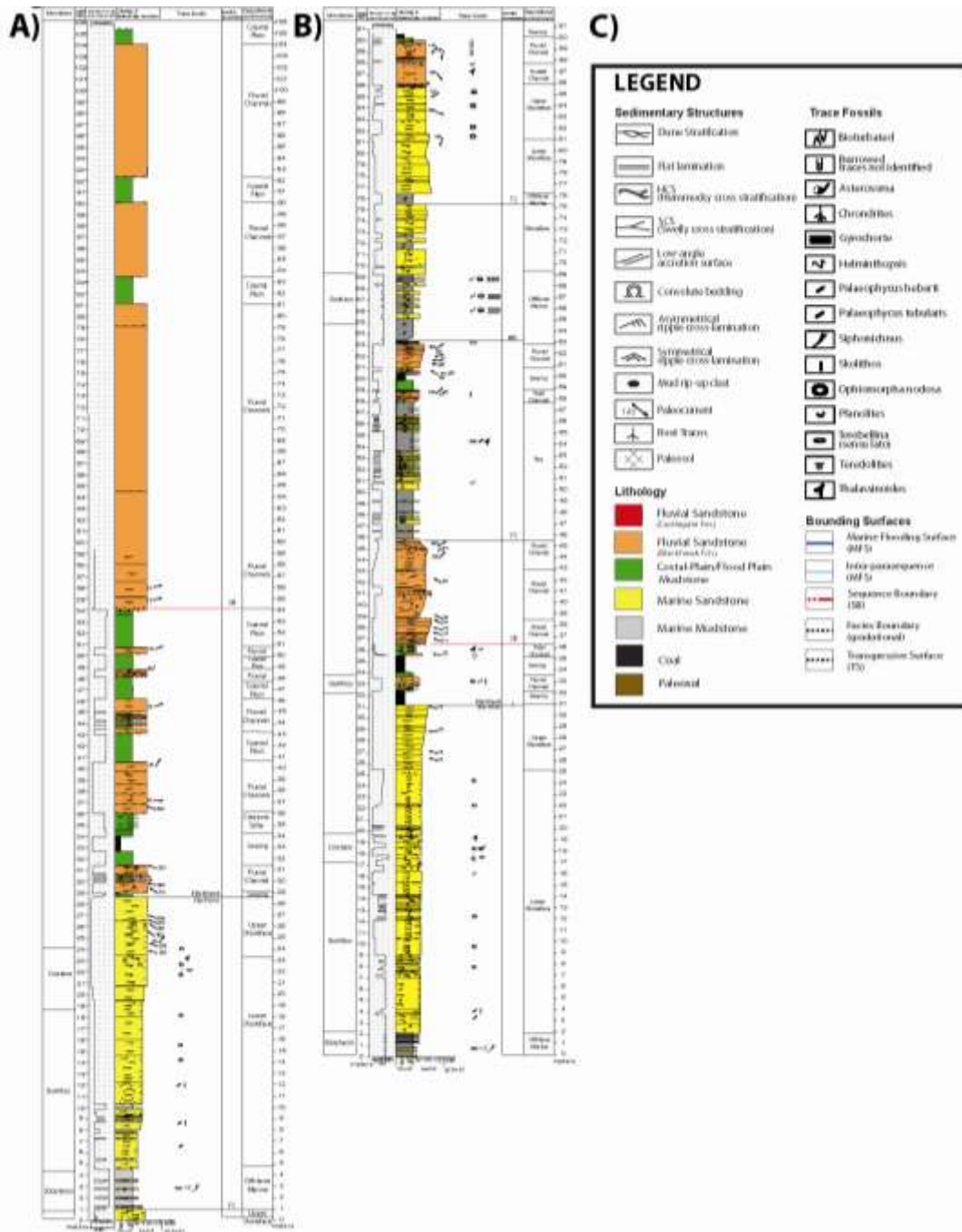


Figure 4: A) The Trail Mountain Mine litholog illustrating a smooth and gradual upward transition from marine to non-marine strata. B) The Wattis Road Litholog documenting a rather complex upward transition from marine to non-marine strata. C) General legend for litholog, facies architecture, correlation panel, and diagrams for this paper.

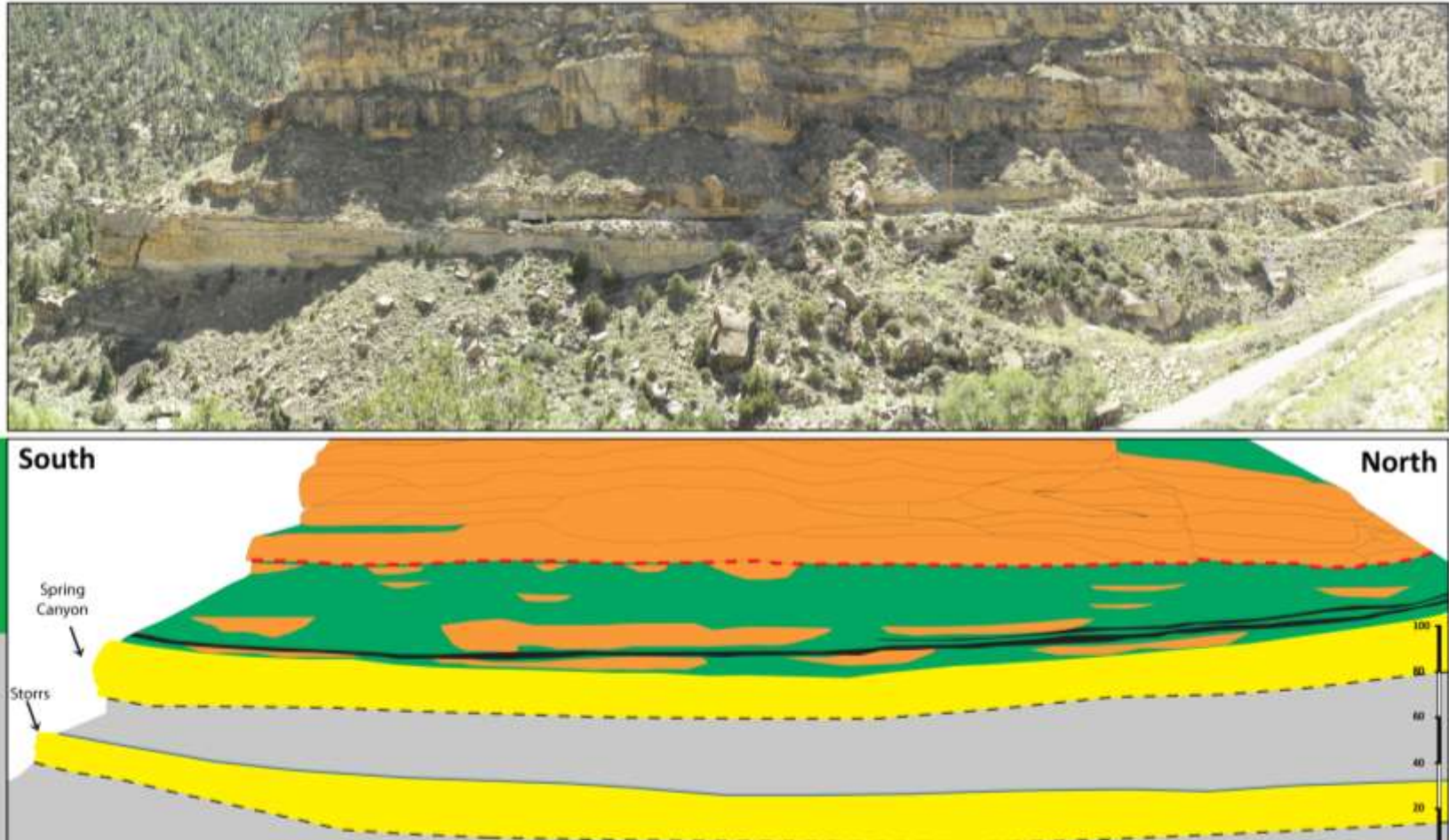


Figure 5: Trail Mountain Mine outcrop photomosaic (upper) and its corresponding facies and stratigraphic architecture (below). This location shows a simple upward transition from marine to non-marine strata. However, the fluvial channel architecture is more complex in this southern outcrop compared to its northern counterparts (Fig. 6). For legend, see Fig. 4C.

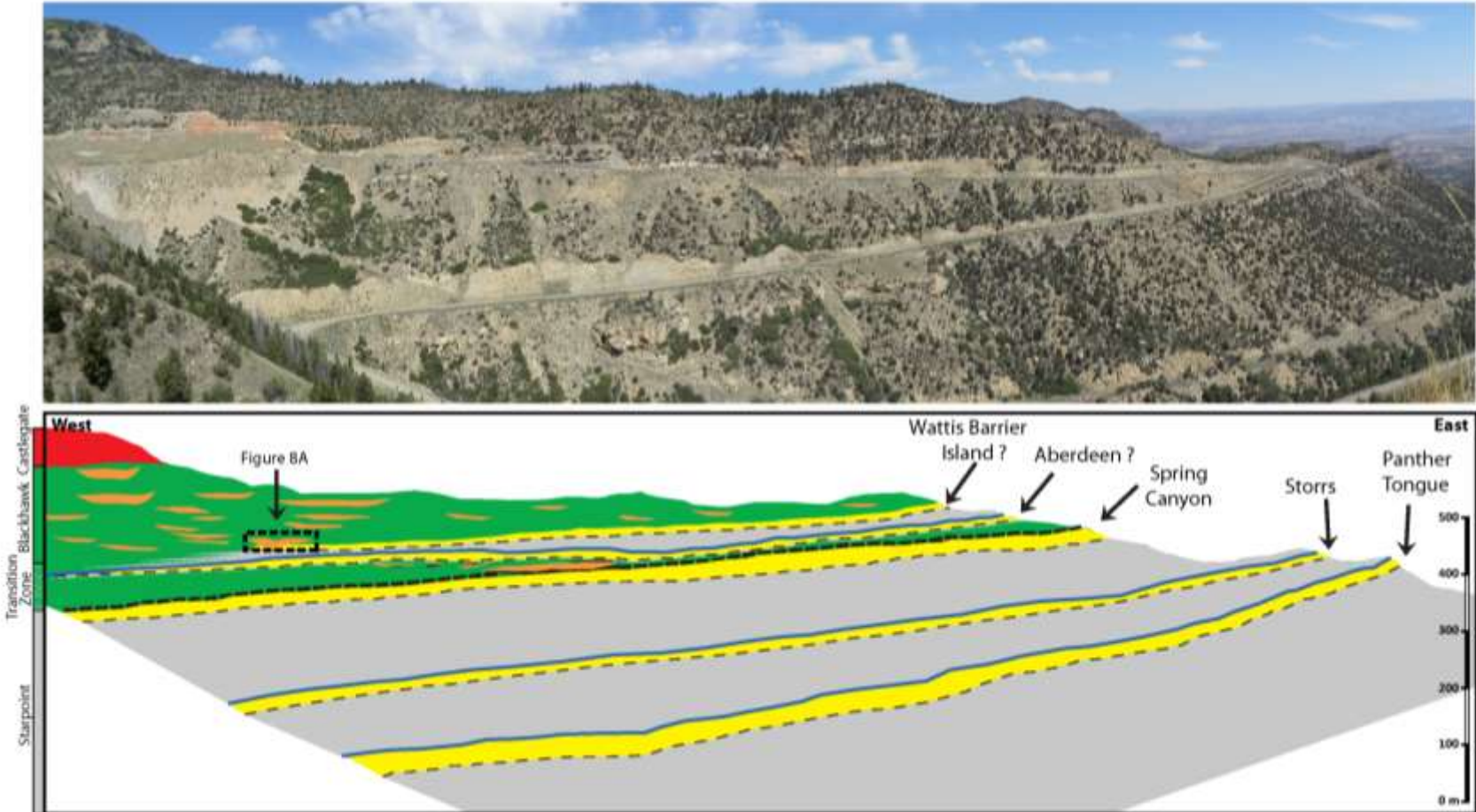


Figure 6: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic framework of the outcrop at Wattis Road section, showing a complex lateral and upward transition from marine to non-marine strata. Note the up-dip pinchouts of the two uppermost marine sandbodies into the coastal plain mudstones. For legend, see Fig. 4C.

The transitional complexity decreases toward the south from the Wattis Road outcrop, but the fluvial complexity increases. The southern part of the study area contains more complex fluvial architecture: multi-story channels and channel belt complexes. At the Burma, Des Bee Dove Mine, Wilberg, and Trail Mountain Mine, fluvial channels appear to be incising into the surrounding coastal plain strata and depositing a multi-story incised valley fill (Fig. 7).

Sequence Stratigraphic Framework

The sequence stratigraphic framework of the Star Point and Blackhawk Formations is emphasizing different bounding surfaces (Fig. 7). For the Star Point Formation that is dominated with marine facies, marine flooding surfaces were used to identify sequence stratigraphic units like parasequences. Inside parasequences, a lower order surface known as intra-parasequence minor flooding surface (Hampson, 2000), can be identified (Fig. 7). These surfaces were picked based upon the subtle yet abrupt fining of marine sandstones across these surfaces within an overall coarsening upward trend.

The Blackhawk Formation, being terrestrial in nature, is relatively challenging for establishing a sequence stratigraphic framework. Here particular attention was paid to distinguish incised-valley fills from regular channel deposits, identify paleosols, and correlate coal layers. Incisal bases of the thick and complex multi-storey sandbodies are interpreted as incised valley floors at several stratigraphic positions. At the Rilda section, a mature calcareous paleosol is present at the interfluvial area. At the Trail Mountain Mine outcrop, the youngest incised valley fill appears to be the thickest. The Wasatch Plateau also gives a unique view into the variation of the sequence boundary along a strike orientation.

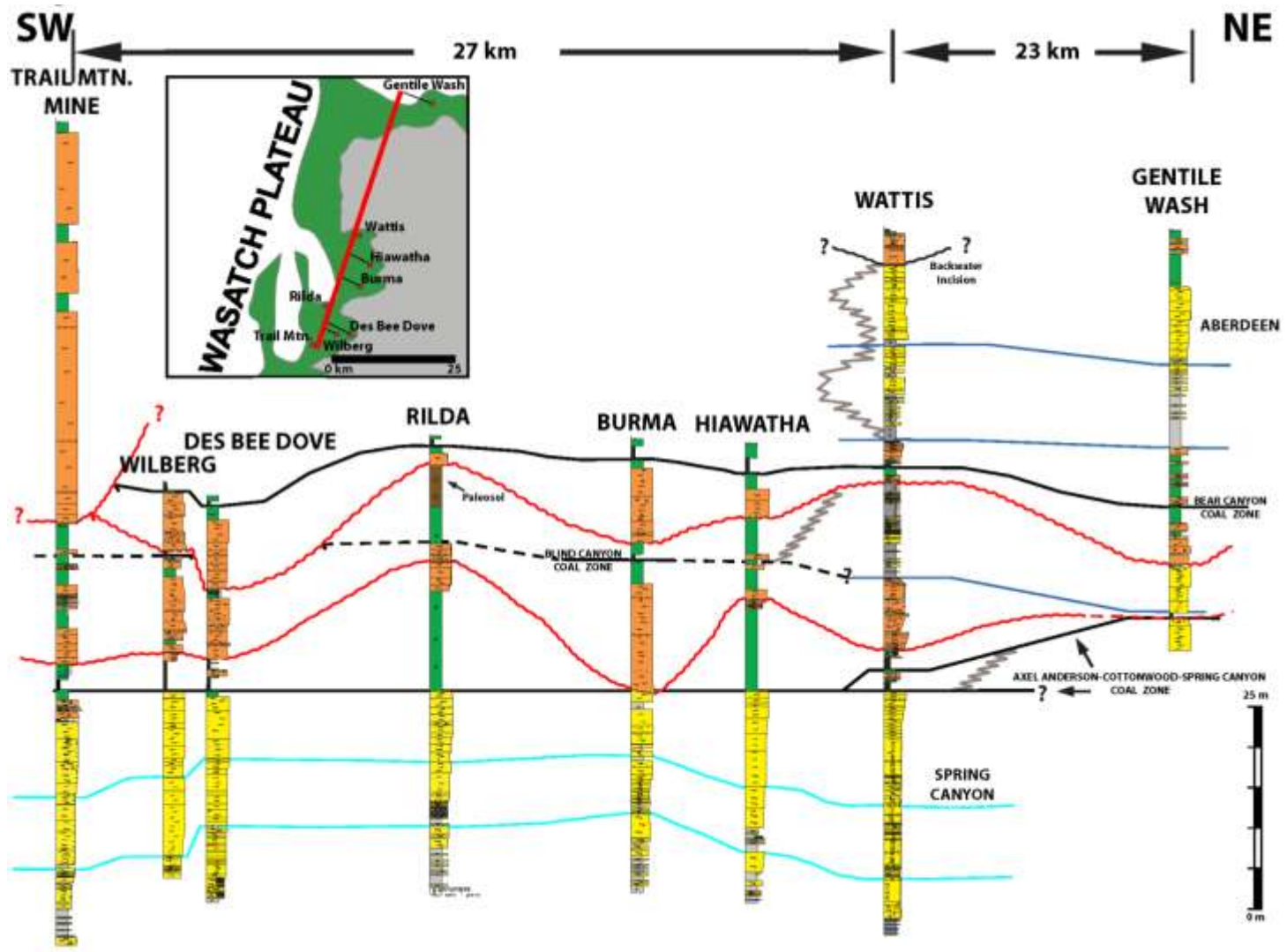


Figure 7: Along depositional-strike sequence stratigraphic correlation panel of the study area. The upper sequence boundary cuts through the Blind Canyon Coal zone, whereas the lower sequence boundary erodes into the marine sandstone of the Star Point Formation. For legend see Fig. 4C.

Incised valley fills have been interpreted in the lower Blackhawk Formation based on the criteria of Zaitlin et al. (1994). Four important features have been identified in this regard: (1) there are deep and widespread incisions at the base of these channelized deposits; (2) the multi-storey channel fill thickens laterally upward, indicating an upward increase in accommodation space; (3) the multi-storey channelized sandbodies are far larger than neighboring channelized sandbodies outside of the valley; (4) the interfluvies contain well-developed mature paleosols. The floors of these incised valleys, along with their correlative interfluvial surfaces, represent sequence boundaries generated due to relative sea-level fall.

Backwater Effect

Not all prominent fluvial incision can be interpreted as a fall in base level and therefore a sequence boundary. At the Wattis Road outcrop, a fluvial channel was identified eroding down into the marine sandstone (Fig. 8A). Evidence associated with this fluvial channel points to a different mechanism for incision, rather than a sea-level fall. Interesting clues such as the multiple erosional surfaces (Fig. 8B), marine influences when wave propagates upstream, and likely downstream continuation of this channel where it is filled with mudstones (Fig. 8C) were observed. This evidence suggests that the incision seen at the base of this channel is likely linked to a backwater effect at the river mouth (Parker et al., 2008; Petter, 2010).

The back water effect is created when waves propagate upstream of a river, causing a deposition of sand size sediments (Fig. 8D). When the waves subside, a rush of water erodes into the substrate causing a prominent erosional scar. This happens in a repeated fashion and can be caused by non-base level controls such as tides and storms. The backwater effect also initiates a restriction in bed load transportation, resulting in finer sands and muds being the only sediments transported

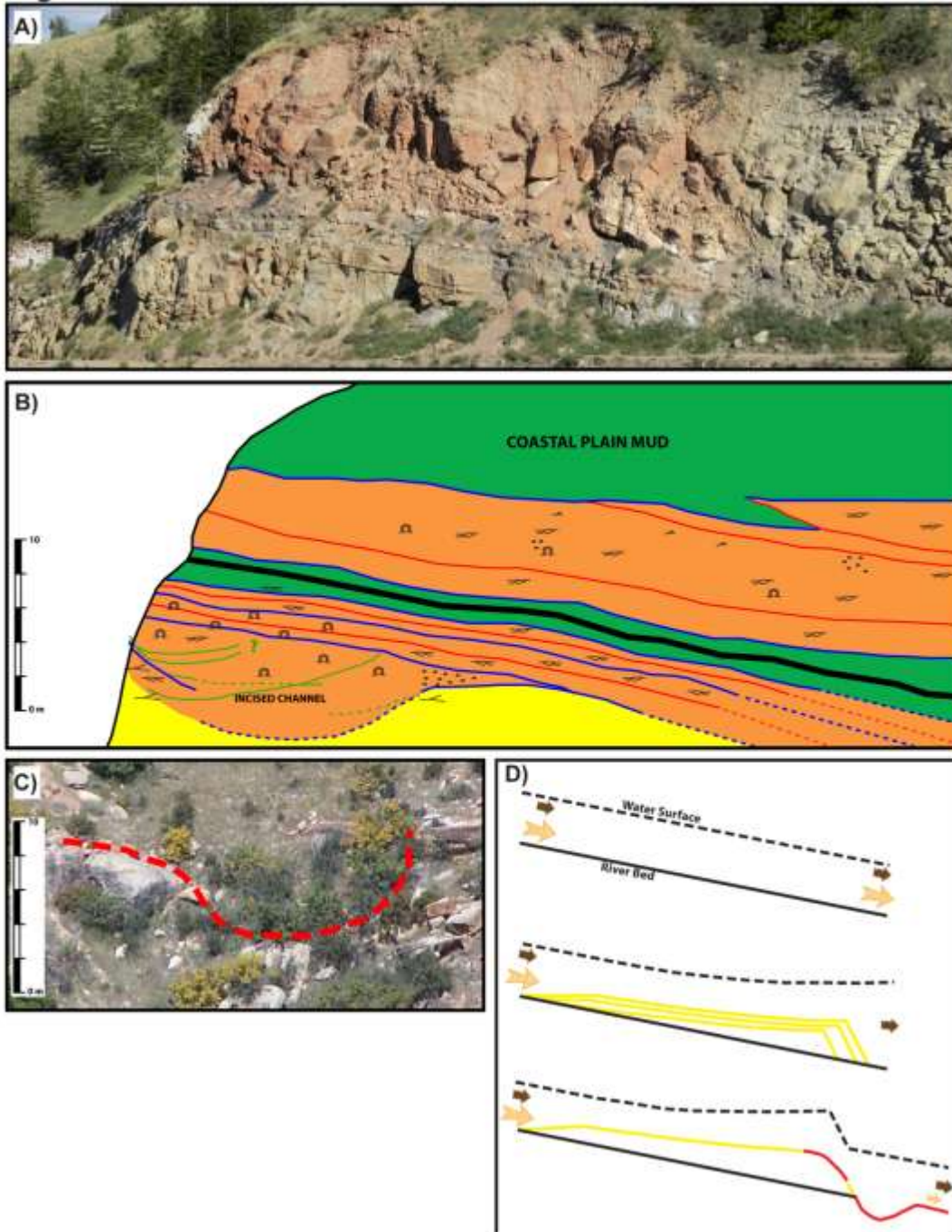


Figure 8: Prominent fluvial incision eroding the top of the uppermost marine sandstone at the Wattis Road outcrop (A) uninterpreted photo; B) interpreted facies architecture). Note the multiple erosional surfaces at the base of the channel incision. This incision is interpreted as backwater effect at the mouth of the river. For legend see Fig. 4C. C) Mud-filled fluvial channel down dip and at the same stratigraphic level of the sand-filled channel of Fig. A (outlined in red dotted line). This mud-filled channel is another indication for backwater effect. The downstream portion of the channel will be mostly mud deposition due to the sand deposition upstream. The backwater cycle (D): A normal river profile (upper); deposition of led load occurs as the wave propagates upstream (middle); when the surface wave recedes, incision will occur as a hydraulic jump is created (lower).

downstream. This type of effect has not been documented in the sedimentary rock record; nevertheless, it has been recorded in the modern environment. For example, the Mississippi River's south-west pass has the backwater effect due to a micro-tidal control (Nittrouer et. al, 2011).

The appearance of multiple erosional scars at the channel base indicates a repeated erosional event. The tidal range of the Western Interior Seaway is micro-tidal (Ericksen and Slingerland, 1990), which is enough to create a backwater effect resulting in a discontinued bedload transport.

DISCUSSION

Transitional Complexity

Although down-dip pinch-outs of marine sandbodies (parasequences) are better known, their up-dip fate is less understood. A significant stratigraphic feature of the Wattis Road outcrop is the abrupt, up-dip pinch out of marine sandbodies within coastal plain mudstones (Fig. 6). A feature like this is difficult to pin down in subsurface studies involving wireline logs and cores. Therefore, large-scale outcrop windows like the one in the Wattis Road are suitable to investigate the nature of this up-dip pinchout. These up-dip pinch outs of shallow-marine sandbodies, which have inherited basinward depositional dip, are significant because of the potential for trapping hydrocarbons at the up-dip termination of the sandbodies. Encasing coastal plain mudstones can act as seals. Hydrocarbon could migrate up the marine sandbodies and accumulate where sandbodies abruptly pinches out into the mudstones. Knowledge of this complex facies transition in the Wattis Road in a marginal-marine setting can assist in predicting this type of stratigraphic traps in the subsurface.

Strike Variability of the Sequence Stratigraphy

The Western Interior Seaway has been studied extensively in the depositional dip orientation (Taylor and Lovell, 1995; Van Wagoner, 1995; Howell and Flint, 2003; Yoshida et. al, 1998), like many other outcrops of the world that are used in sequence stratigraphic studies. However this study gives a unique perspective of sequence stratigraphic framework along depositional strike. A correlation panel has been constructed using lithologs of each outcrop window to demonstrate the strike variation of sequence stratigraphic scenario (Fig. 7). Only the uppermost marine sandbody of the Star Point Formation was focused in this study. This sandbody represents a parasequence in the Mancos Shale.

However, there are other stratigraphic boundaries that can be correlated inside this parasequence throughout the study area. There are subtle yet abrupt decrease in grain size within the overall upward coarsening trend of this parasequence that likely indicate small fluctuations of sea level. These boundaries are interpreted as intra-parasequence marine flooding surfaces.

A pair of sequence boundaries can be correlated from across the studied outcrop belt. The Wilberg, Des Bee Dove and Burma Road locations have distinct multi-storey channels that incise into the coastal plain mudstones. These channels are unlike of other simpler fluvial channel sandbodies generally described in the lower Blackhawk Formation (Marley et. al, 1979; Adam and Bhattacharya, 2005). Similar sized incised valley fills have been described in the Book Cliffs further to the east (Adams and Bhattacharya, 2005).

Several sequence boundaries have been observed in the Blackhawk Formation, providing a unique perspective of their along strike variability (Fig. 7). Regional persistent coal zones were used as useful marker beds. At the Des Bee Dove outcrop, the upper sequence boundary erodes out the underlying Blind Canyon coal zone. This indicates a pronounced incision at the base of the incised valley. At the Burma outcrop, the lower sequence boundary erodes into the marine sandstone, again indicating major incision. At the Rilda location, the correlative interfluvial of the upper sequence boundary is represented as thick, mature paleosols. At the Trail Mountain Mine outcrop, the upper sequence boundary is interpreted as being eroded out by a multi-storey fluvial channel. However, not enough data were gathered about this multi-storey fluvial complex to convincingly identify its base as another sequence boundary.

One notable observation in the lateral transition from south to north is that the Blind Canyon coal zone likely merges laterally with a marine flooding surface at the Wattis Road outcrop. This indicates, in general, that coal zones and marine flooding surfaces are likely equivalent surfaces resulting from base-level rise. Therefore in non-marine strata, coal can be used to identify flooding events.

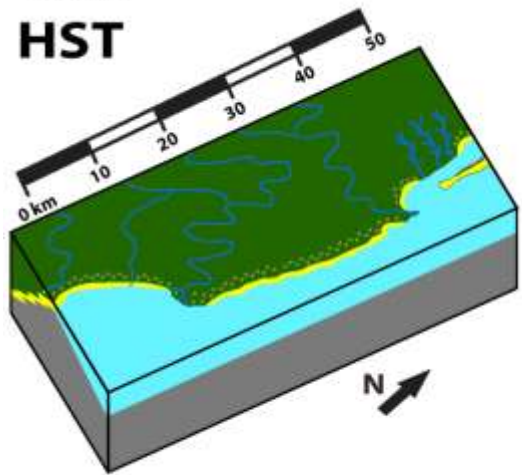
Paleogeography

Summarizing the results of this study, a paleogeographic scenario of the north-eastern Wasatch Plateau during the Comanian can be interpreted. Two paleogeographic models can be created, one during a highstand systems tract (HST) and another during a lowstand systems tract (LST) (Fig. 9).

During the HST the western shoreline of the Western Interior Seaway had a normal prograding profile. The shoreline was keeping pace with sea-level rise, due to the high sediment supply being sourced from the Sevier Orogeny (Willis, 2000; Kaufmann and Caldwell, 1993). The coals, which developed on coastal plain, is interpreted to indicate heavily vegetated swamps just landward of the shoreline. Shoreline towards the north had bay environments. Inclined heterolithic strata also indicates that tidal channels were present in the northern section, where the tidal range of the seaway is understood to be at a micro-tidal range (Ericksen and Slingerland, 1990). However, the primary fluvial channels were meandering throughout the coastal plain during the HST.

Figure 9

HST



LST

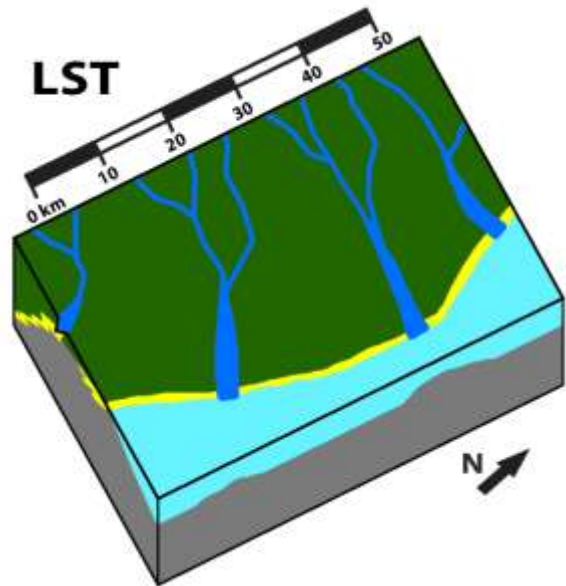


Figure 9: Paleogeography of the study area during the Campanian (~80 Ma ago). Left map is during highstand systems tract, when coastal plain is dominated by fluvial channels. The coast is featured with tidal channels, fluvial deltas, and likely barrier islands. Whereas the right map represents lowstand systems tract with the formation of incised valleys. Multiple incised valleys are developed along strike during the base level fall, separated by interfluves.

An abrupt change appears to happen at the seaway when there was a drop in sea-level. The study area begins to dry up and the LST developed pushing the shoreline basinward. Fluvial incision created incised valleys as sea-level began to drop, resulting in less meandering channel and more complex valley fills in the Blackhawk Formation. Outside of the incised valleys, the coastal became relatively stable. This allows for soils to develop on the topographic highs, such as the paleosols seen at Rilda Canyon.

Back Water vs. Sea-Level Drop

This study highlights that not every incised channels in the rock record indicate a drop in sea-level. At the mouth of a river, backwater effect can create conditions for localized channel incision. The outcrop example of backwater incision presented here will allow others to have a different perspective for interpreting channel incision. Key indicators to look for could be the multiple erosional scars at the base, along with a lack of coarse grains in the downstream deposits. Since there has been no published documentation of the backwater effect in the rock record, the Wattis Road outcrop may provide the first example of this kind.

CONCLUSION

The upward transition from marine to coastal plain strata has been commonly described as a rather smooth, gradual transition at the north-eastern Wasatch Plateau's study locations. However, the Wattis Road outcrop (northern part of the study area) has a complex spatio-temporal transition from shallow-marine environment to coastal/fluvial environment. Eight distinct depositional environments were identified as part of this stratigraphic transition between shallow-marine Star Point Formation and coastal-plain Blackhawk Formation. This study demonstrates that the marine and non-marine strata are likely more complexly intertongued in the sedimentary record than what has been depicted in general. The stratigraphy of the Wattis Road outcrops documents the high-frequency sea-level fluctuations of the Western Interior Seaway during the late Cretaceous that generated sequence stratigraphic complexity. This study also documents abrupt, landward pinch-outs of shallow-marine sandbodies within coastal plain mudstones, a least-understood aspect of shoreline sedimentology. These pinch-outs can serve as excellent stratigraphic traps of hydrocarbons.

This study also presents a unique aspect of the sequence boundaries along depositional strike. The sequence boundaries are correlated in a strike direction to incised valley floors and their associated interfluves. It demonstrates that during a base level fall, incision can occur in restricted regions around the interfluves. As the base level rises and stabilizes, flooded swamps may exist, producing coal marker beds. One of the coal layers can be laterally correlated to a marine flooding surface. The marine aspect of sequence stratigraphy of the Star Point Formation allowed for intra-parasequence surfaces (minor flooding surfaces) to be identified and correlated throughout the study

area. The sequence stratigraphic framework of the study area helps confirm the high frequency sea-level fluctuations of the WIS during the late Cretaceous that generated stratigraphic complexity.

Moreover, this study introduces the possibility of interpreting incisions due to the backwater effects and not sea-level fall. This is one of the first times this mechanism for incision has been recorded in the rock record. Although further research is essential to accurately identify the backwater effect in the rock record, it is important to evaluate the possibility of autogenic backwater effect in generating fluvial incision so not to incorrectly interpret sea-level fall for every incision .

References

- Adams, M.M. and Bhattacharya, J.P., 2005: No change in fluvial style across a sequence boundary, Cretaceous Blackhawk and Castlegate Formations of central Utah, USA: *Journal of Sedimentary Research*, 75, p. 1038-1051.
- Allen, J.L., 1983: Studies in fluvial sedimentation: bars, bar complexes and sandstone sheets (low- sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders: *Sedimentary Geology*, v. 33, p. 237 – 293.
- Bernard, H.A., 1970: Recent sediments of southeast Texas: Texas Univ. Bur. Econ. Geology Guidebook Number 11.
- Clark, F. R., 1928: Economic geology of the Castlegate, Wellington, and Sunnyside quadrangles, Carbon County, Utah; *USGS Survey Bulletin*, p.165.
- Chow, V. T., 1959: *Open-Channel Hydraulics*; 680 pp., McGraw-Hill, New York.
- Cobb, J.C., and Cecil,, C.B., 1993: Modern and ancient coal-forming environments; *GSSA Special Paper 286*, p. 198.
- Coleman, J.M., 1966: Ecological changes in a massive freshwater clay sequence: *Gulf Coast Assoc. Geol. Soc. Trans.*, v. 16, p. 159-174.
- Dalrymple, R.W., Zaitlin, B.A., and Boyd, R., 1992: Estuarine facies models:conceptual basis and stratigraphic implications; *Journal of Sedimentary Petrology*; v.62, p. 1130 – 1146.
- Dott, R.H., Jr., and Bourgeois, J., 1982: Hummocky stratification: significance of its variable bedding sequences; *Geol. Soc. Am. Bull.*, v. 93, p. 663-680.

- Dubiel, R.F., Kirschbaum, M.A., Roberts, L.N.R., Mercier, T.J., and Heinrich, A., 2000: Geology and coal resources of the Blackhawk formation in the southern Wasatch Plateau, central Utah; USGS professional paper 1625-B, United States Geological Survey.
- Ericksen, M. C., and Slingerland, R., 1990: Numerical simulations of tidal and wind-driven circulation in the Cretaceous Interior Seaway of North America; Geological Society of America Bulletin, v. 102, no. 11, p. 1499-1516.
- Flores, R.M., Blanchard, L.F., Sanchez, J.D., Marley, W.E. and Muldoon, W.J., 1984: Paleogeographic controls of coal accumulation, Cretaceous Blackhawk Formation and Star Point Sandstone, Wasatch Plateau, Utah. *Geol. Soc. Am. Bull.*, 95, 540-550.
- Gani, M.R., and Bhattacharya, J.P., 2007: Basic building blocks and process variability of a Cretaceous delta: internal facies architecture reveals a more dynamic interaction of river, wave and tidal processes than is indicated by external shape. *Journal of Sedimentary Research*, v. 77, p. 284-302.
- Gani, M.R., Bhattacharya, J.P., MacEachern, J.A., 2008. Using Ichnology to Determine Relative Influence of Waves, Storms, Tides, and Rivers in Deltaic Deposits in the Cretaceous Western Interior Seaway, Wyoming-Utah, U.S.A. Short Course Notes 51, Society for Sedimentary Geology.
- Hamblin, A.P. and Walker, R.G., 1979: Storm-dominated shallow marine deposits; the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains; *Can. J. Earth Sci.*, v. 16, p. 1673-1690.
- Hampson, G.J., 2000: Discontinuity surfaces, clinofolds, and facies architecture in a wave dominated, shoreface-shelf parasequence; *Journal of Sedimentary Research*, v. 70, issue 2, p. 325 -340.

- Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G., 1975: Depositional environments as interpreted from primary sedimentary structures and stratification sequences; Soc. Econ. Paleont. Mineral Short Course 2, 161 p.
- Henry, E.H. and Finn, T.M., 2009: Petroleum assessment of the Ferron/Wasatch Plateau total petroleum system, upper Cretaceous strata, Wasatch Plateau and Castle Valley, Utah; American Association of Petroleum Geologists; Journal, p. 45
- Holman, L. S., 2011: The effect of parasequence and geometry and facies architecture on reservoir partitioning of the Star Point Sandstone, Wasatch Plateau, Utah; American Geological Institute, Brigham Young University, master thesis.
- Howell J.A. and Flint S.S., 2003: Siliciclastics case study: the Book Cliffs: The sedimentary record of sea-level change, pp. 135-208. Cambridge University Press.
- Jackson, R.G, II, 1975: Hierarchical attributes and the unifying model of bed forms composed of cohesionless material and produced by shearing flow: Geological Society of America, Bulletin, v. 86, p. 1523 – 1533.
- Kauffman, E. G. and Caldwell, W.G., 1993: The Western Interior Basin in space and time - Evolution of the Western Interior Basin; Geological Association Canada, Special Paper, 39.
- Lamarre, R.A., and Burns, T.D., 1997: Drunkard's wash unit-coalbed methane production from Ferron coals in east-central Utah, in Coalson, E.B., Osmond, J.C., and Williams, E.T., eds., Innovative applications of petroleum technology in the Rocky Mountains area: Rocky Mountain association of geologist guidebook, p. 47-59.

Marley, W.E., Flores, R.M. and Cavaroc, V.V., 1979: Coal accumulation in Upper Cretaceous marginal deltaic environments of the Blackhawk Formation and Star Point Sandstone, Emery, Utah: *Utah Geology*, 6, p. 25-40.

Miall, A.D., 1983: Basin analysis of fluvial sediments in J.D. Collinson and J. Lewin, eds., *Modern and ancient fluvial systems*; *Internat. Assoc. Sedimentologists Spec. Geol.*, v. 21, p. 85-127.

Nittrouer, J.A., Shaw, J., Lamb, M. P., Mohrig, D., 2011: Spatial and temporal trends for water-flow velocity and bed-material sediment transport in the lower Mississippi River; *Geological Society of America Bulletin*, pre-issue publication.

Parker, G., Muto, T., Akamatsu, Y., Dietrich, W.E. and Lauer, J.W., 2008: Unravelling the conundrum of river response to rising sea-level from laboratory to field. Part II. The Fly-Strickland River system, Papua New Guinea: *Sedimentology*, 55, 1657-1686.

Parker, L.R., 1976: The paleoecology of the fluvial coal-forming swamps and associated floodplain environments in the Blackhawk Formation (Upper Cretaceous) of central Utah. *Brigham Young University Geol. Studies*, 22, 99-116.

Pemberton, S. G., Frey, R. W., Ranger, M. J., and MacEachern, J. A., 1992: The conceptual framework of ichnology; *in*, *Applications of ichnology to petroleum exploration--A core workshop*, S. G. Pemberton, ed.: *Society of Economic Paleontologists and Mineralogists, Core Workshop 17*, p. 1-32.

Petter, A.L., 2010: Stratigraphic implications of the temporal variability of sediment transport in rivers, deltas, and shelf margins. Unpubl. PhD thesis, University of Texas at Austin, 205 pp.

Sheldon, N.D., and Tabor, N.J., 2009, Paleoenvironmental and paleoclimatic reconstruction using paleosols: Earth-Science Reviews, v. 95, p. 1-52.

Spieker, E.M., 1931: The Wasatch Plateau coal field, Utah. U.S. Geol. Surv. Bull., 819, 210 p.

Taylor, A.M., and Goldring, R., 1993: Description and analysis of bioturbation and ichnofabric: Geological Society of London, Journal, v. 150, p. 141-148.

Taylor, D.R. and Lovell, R.W., 1995: High-frequency sequence stratigraphy and paleogeography of the Kenilworth Member, Blackhawk Formation, Book Cliffs, Utah, USA: American Association of Petroleum Geologist Memoir, 64, 257-275.

Thomas, R.D., D.G. Smith, J.M. Wood, J. Visser, E.A. Calverly-Range and E.H. Koster. 1987: Inclined heterolithic stratification – terminology, description, interpretation and significance: Sedimentary Geology 53: 123-179.

Van Wagoner, J.C., 1995: Sequence stratigraphy and marine to non-marine facies architecture of foreland basin strata, Book Cliffs, Utah, USA: American Association of Petroleum Geologist Memoir, 64, 137-223.

Willis, Grant C., 2000: "Utah's Sevier Thrust System" Utah Geological Survey Notes. v. 32 no. 1 January 2000

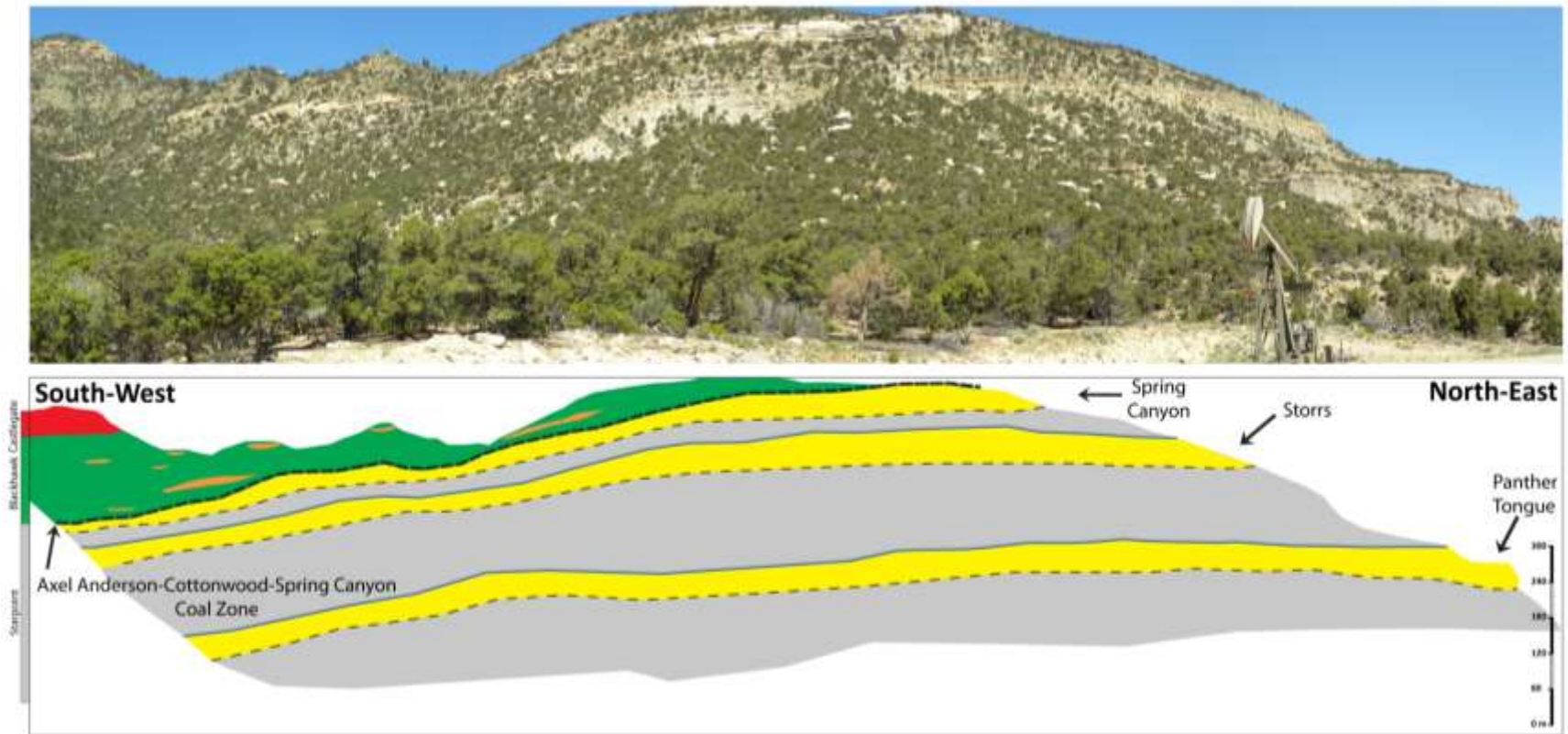
Wright, L.D., 1979: Morphodynamics of reflective and dissipative beach and inshore systems, southeastern Australia: *Marine Geology*, v. 32, p. 105-140.

Yoshida, S., Miall, A., Willis, A., 1998: Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A.; *American Association of Petroleum Geologist Bulletin*, v. 82, no. 8, p. 1596-1606.

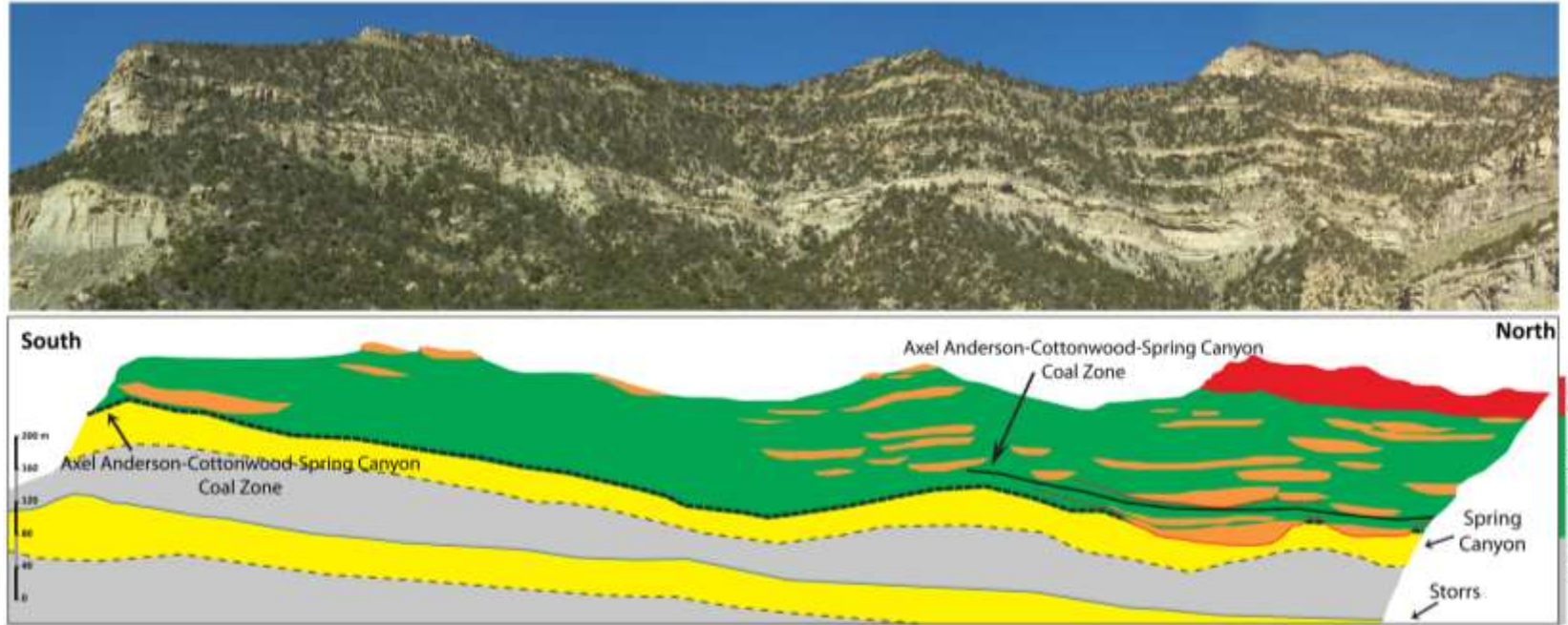
Young, R. G., 1955: Sedimentary facies and intertonguing in the upper Cretaceous of the Book Cliffs, Utah-Colorado; *Geological Society of America, Bulletin*, 66.

Zaitlin, B.A., Dalrymple, R.W. and Boyd, R., 1994: The stratigraphic organization of incised-valley systems associated with relative sea-level change. In: *Incised-valley systems; origin and sedimentary sequences* (Eds R.W. Dalrymple, R. Boyd and B.A. Zaitlin), *SEPM Sp. Publ.*, 51, 45–60.

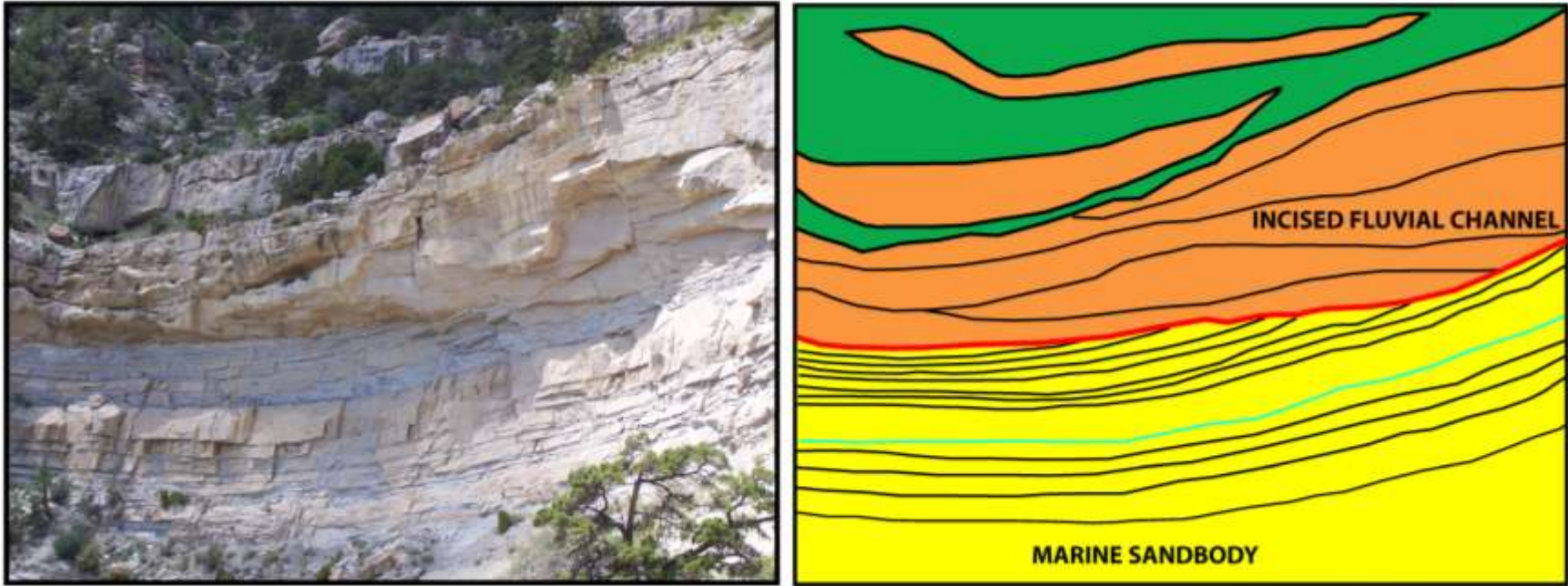
Appendix



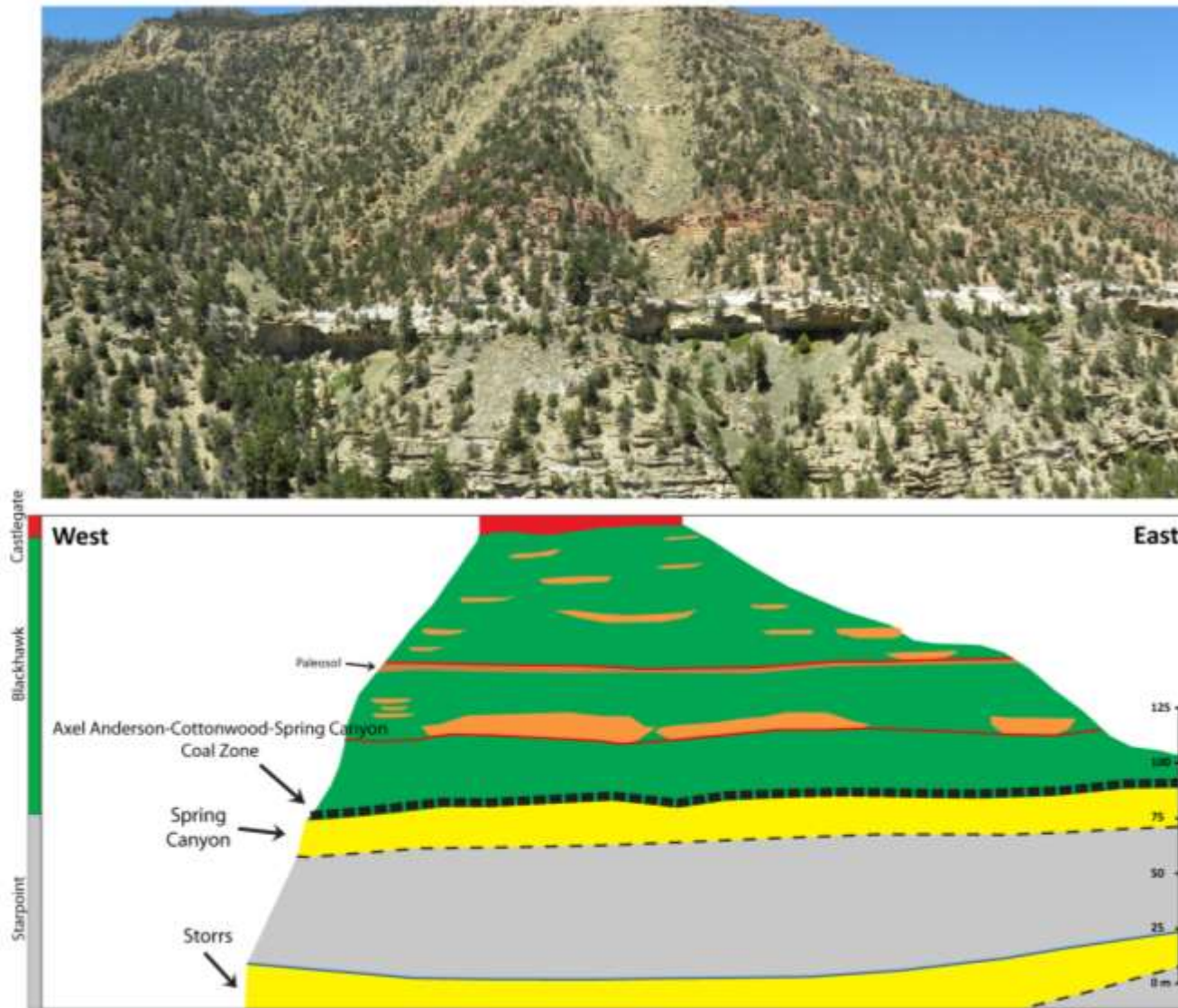
Appendix Figure 1: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic diagram of the outcrop at Hiawatha Road, showing a simple and gradual upward transition from marine to non-marine strata. This location is interpreted as one of the interfluves. For legend, see Fig. 4C.



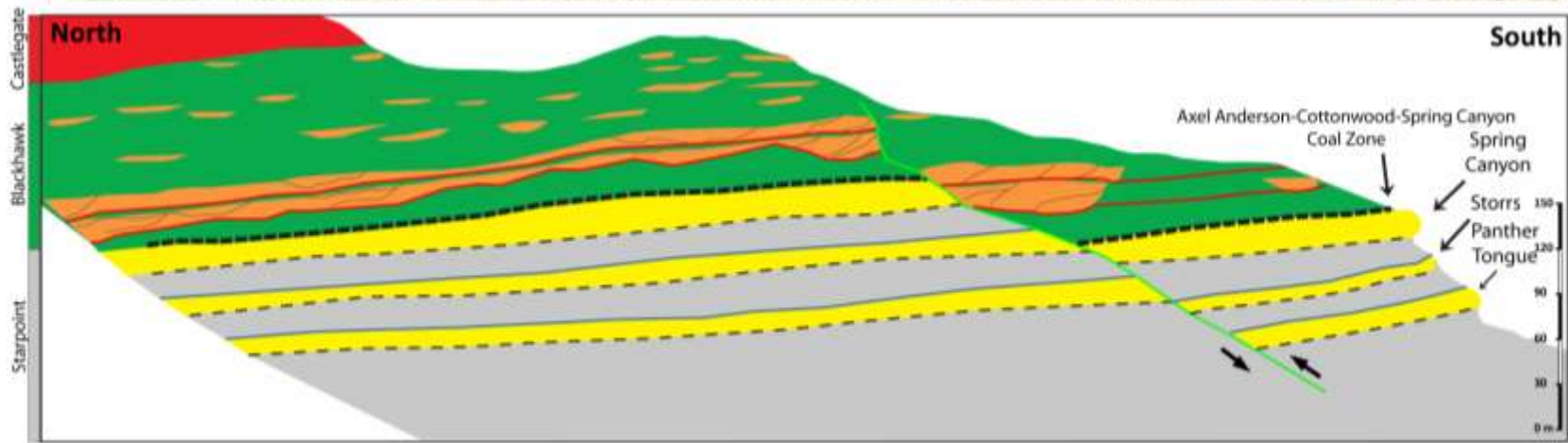
Appendix Figure 2: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic diagram of the outcrop at Burma Road section, showing a slightly complex upward transition from marine to non-marine strata. The lower sequence boundary erodes into the upper marine sandbody (Appendix Figure 3). Note that fluvial channels are clustered above the incised valley. For legend, see Fig. 4C.



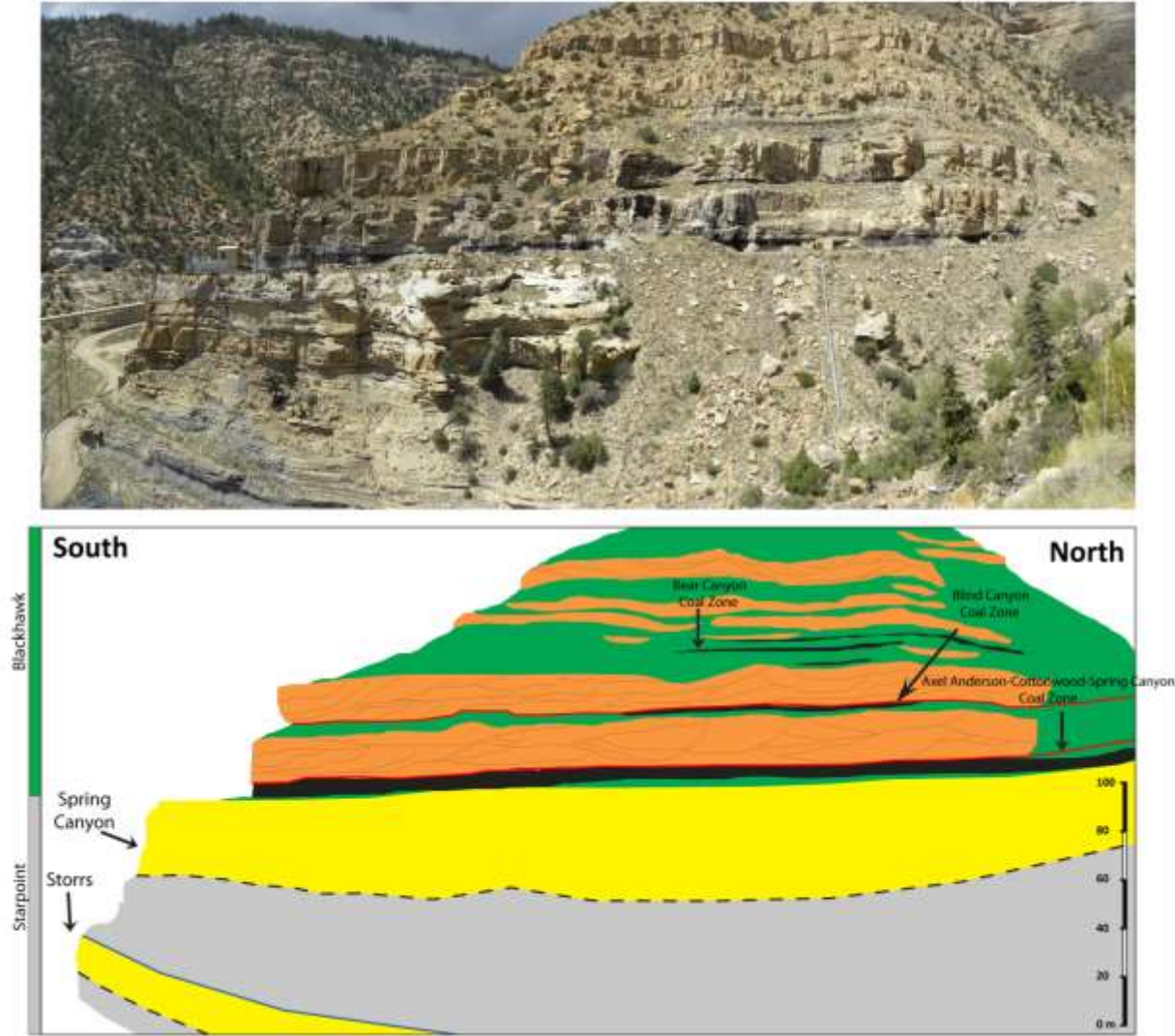
Appendix Figure 3: (left) Photo and (right) corresponding facies and sequence stratigraphic diagram of the lower incised valley fill at the Burma Road outcrop. The incised valley erodes into the Spring Canyon Member. Note the marine sandstone's bedding surfaces are truncated by the incised valley. The incised valleys that were observed in this study outcrops have an average relief of 7-9 meters whereas the average thickness of the non-incised fluvial channels is 3-5 meters.



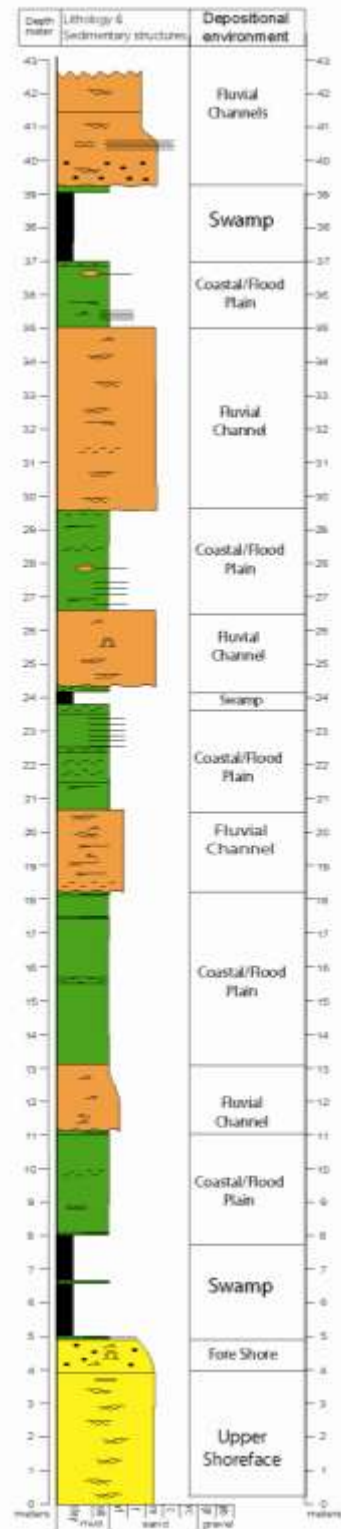
Appendix Figure 4: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic diagram of the outcrop at Rilda Canyon section. Note the presence of distinct paleosol layer that demarkets a sequence boundary. For legend, see Fig. 4C.



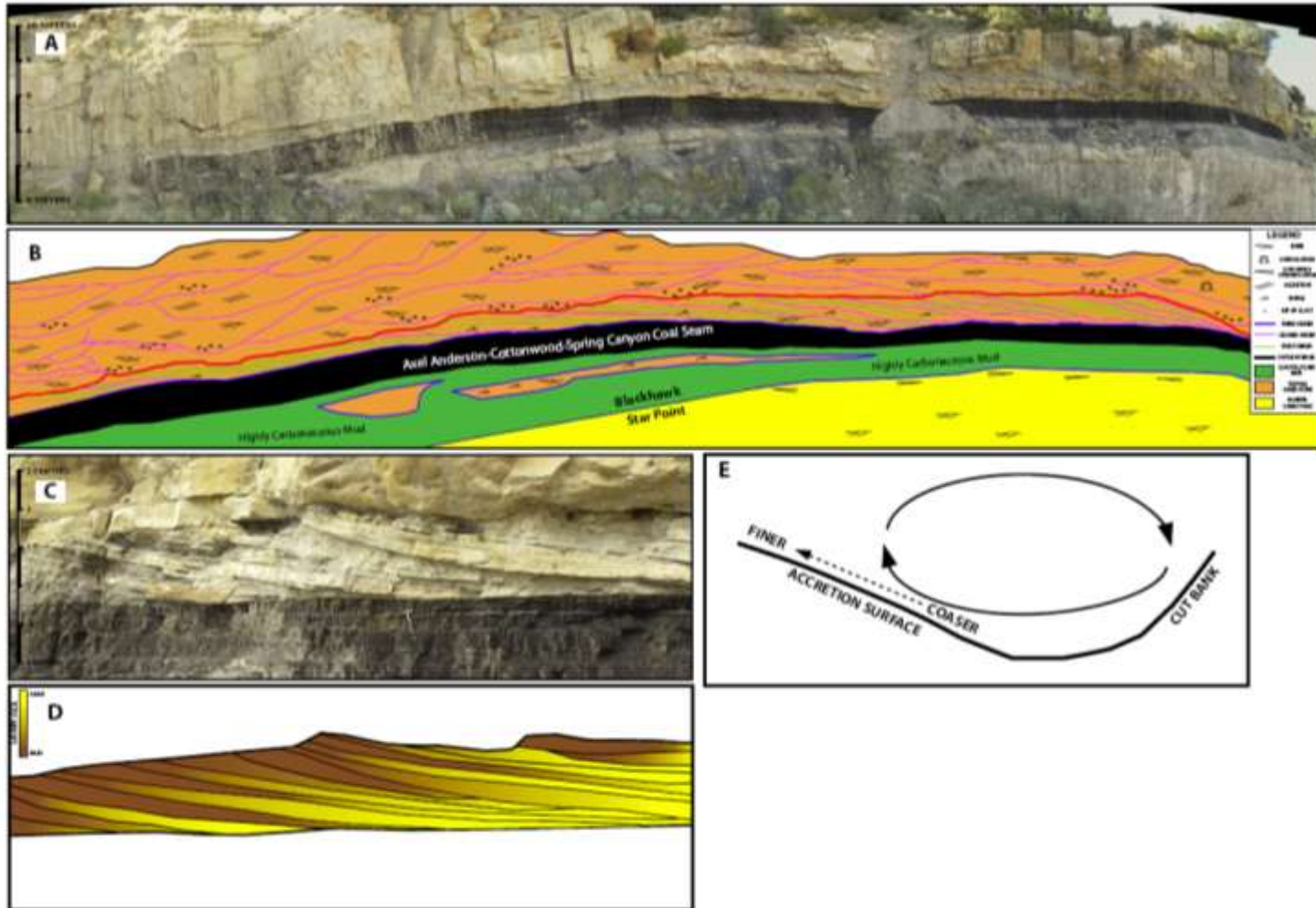
Appendix Figure 5: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic diagram of the outcrop at Des Bee Dove Mine section, showing a simple and gradual upward transition from marine to non-marine strata. However, this is the most northern outcrop where the fluvial sandbody architecture starts to become more complex southward. The green line indicates a normal fault at this location. For legend, see Fig. 4C.



Appendix Figure 6: (upper) Photomosaic and (lower) corresponding facies and sequence stratigraphic diagram of the outcrop at Wilberg Mine section, showing the gradual upward transition from marine to non-marine strata. Note the presence of two complex channel belts forming. These are interpreted as incised valley fills demarcating two sequence boundaries. For legend, see Fig. 4C.



Appendix Figure 7: A coal mining core was examined to reveal the details of the transitional zone from marine to non-marine strata. This core was taken between Trail Mountain Mine and the Wilberg Mine locations. For legend, see Fig. 4C. This litholog shows a simple upward transition from marine to non-marine strata.



Appendix Figure 8: Inclined heterolithic stratification (IHS) is used to describe the sand and mud beds that are regularly repeating and being deposited as couplets in tidal point bar environments. At the Wattis Road outcrop (A), laterally extensive IHS was visible above the Axel Anderson-Cottonwood-Spring Canyon Coal Seam. In figure B, the bedding diagram shows the complex stratal geometry of the IHS. Another IHS deposit was identified at the Wilberg Mine outcrop (C). In figure D, the grain size of this IHS variation is documented, both vertically and laterally. Note that at the down-dip side of each inclined bed, grain size is coarser that gradually becomes finer laterally upwards. The process of the meandering-river helical flow is responsible for this lateral grain size variation shown that is described in a cross section view in figure E.

Vita

Andrew Ranson was born and raised in New Orleans. He attended St. Rosalie Elementary School in Marrero, followed by Brother Martin High School in the Lakefront area. After high school Andrew attended Louisiana State University pursuing a degree in Petroleum Engineering. After having taken his first Geology class his sophomore year, Andrew decided to switch majors. He transferred to the University of New Orleans and enrolled in the Earth and Environmental Sciences department. As an undergrad, Andrew was asked to be a field assistant for Dr. Royhan Gani in the Wasatch Plateau, Utah. While working in Utah, Andrew was amazed at the quality of outcrop exposures, and started to work on a senior thesis. Andrew presented his thesis at the 2010 American Association of Petroleum Geologists annual convention in New Orleans. After the completion of Andrew's undergraduate degree he continued his studies at UNO under the guidance of Dr. Gani to expand on his senior thesis and create it into a master's thesis. While getting his master's, Andrew married Ashley Breaux from Berwick, Louisiana. After graduation, Andrew is moving to Bakersfield, California where he has accepted a job at Chevron.