2014-06-05

Facies Analysis, Sequence Stratigraphy and Paleogeography of the Middle Jurassic (Callovian) Entrada Sandstone: Traps, Tectonics, and Analog

George R. Jennings III
Brigham Young University - Provo

Facies Analysis, Sequence Stratigraphy, and Paleogeography of the

Middle Jurassic (Callovian) Entrada Sandstone:

Traps, Tectonics, and Analog

George R. Jennings III

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Thomas H. Morris, Chair
Scott M. Ritter
Jani Radebaugh

Department of Geological Sciences

Brigham Young University

June 2014

ABSTRACT

Facies Analysis, Sequence Stratigraphy, and Paleogeography of the
Middle Jurassic (Callovian) Entrada Sandstone:
Traps, Tectonics, and Analog

George R. Jennings III
Department of Geological Sciences, BYU
Master of Science

The late Middle Jurassic (Callovian) Entrada Sandstone has been divided into two general facies associations consisting primarily of eolian sandstones in eastern Utah and "muddy" redbeds in central Utah. Sedimentary structures within the redbed portion are explained by the interfingering of inland sabkha, alluvial, and eolian depositional systems. A complete succession from the most basinward facies to the most terrestrial facies in the Entrada Sandstone consists of inland sabkha facies overlain by either alluvial or eolian facies. Where both alluvial and eolian facies interfinger, alluvial facies overlain by eolian facies is considered a normal succession. Sequence boundaries, often identified by more basinward facies overlying more landward facies, are observed in the Entrada Sandstone and are extrapolated for the first time across much of Utah, including both the eolian-dominated and redbed-dominated areas. Using these sequence boundaries as well as recent tephrochronologic studies, three time correlative surfaces have been identified in the Entrada. Based on the facies interpretations at each surface, five paleogeographic reconstructions and five isopach maps have been created, illustrating two major intervals of erg expansion and the location of the Jurassic retroarc foreland basin's potential forebulge. Eolian (erg-margin) sandstones pinch-out into muddy redbeds creating combination traps, as evidenced by dead oil (tar) and bleached eolian sandstone bodies within the Entrada. The Entrada Sandstone is a world-class analog for similar systems, such as the Gulf of Mexico's Norphlet Sandstone, where eolian facies grade into muddy redbed facies.

Keywords: Entrada Sandstone, late Middle Jurassic, Callovian, facies analysis, paleogeographic reconstruction, isopach map, hydrocarbon trap, stratigraphic trap, eolian, alluvial, sabkha, redbed, erg-margin, Norphlet Formation, sequence stratigraphy, Utah, terrestrial sequence stratigraphy

ACKNOWLEDGMENTS

Funding for this project was obtained from AAPG in the form of the Raymond D. Woods Memorial Grant. Additional funding was received from Brigham Young University. Thank you.

I am especially grateful to my thesis advisor Dr. Thomas H. Morris for his guidance, support, and generosity in dealing with a stubborn, argumentative graduate student who refused to take anything for granted. Thank you for patiently listening to all of my crazy ideas and having the intellect and discretion to separate the good ideas from the bad ones. You have been one of my greatest teachers and examples.

Thank you to everyone else who helped with this project. I especially appreciate all the hard work and encouragement of Toby Dossett. Without you I never would have started fieldwork in time to finish when I planned to.

A special thanks also goes to two of the greatest teachers I have had the privilege of learning from, Mr. David Thurston (my high school biology and geology teacher), and Dr. Timothy Lawton (my undergraduate advisor at NMSU). Thank you Mr. Thurston for introducing me to the wonder of geology and inspiring me to reach my academic potential. Thank you Dr. Timothy Lawton for taking an ignorant freshman under your wing and giving me the opportunity to flourish through careful tutelage.

Thank you to my parents for raising me to think for myself and supporting me in my pursuit of a higher education. Above all however, I want to thank my wife, Kara, for her love and support. She is the most patient, lovely, and wonderful person on earth.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Many dramatic landscapes, including those at Arches National Park and Goblin Valley State Park, are sculpted from the Entrada Sandstone. The Entrada Sandstone, deposited in the Jurassic Cordilleran retroarc foreland basin, has been informally divided into two general facies associations consisting of eolian sandstones in eastern Utah and "earthy" or "muddy" redbeds in central Utah. While the eolian sandstones have been well studied (e.g. Kocurek, 1980; Kocurek & Dott, 1983; Marino, 1992; Carr-Crabaugh & Kocurek, 1998; Monn, 2006; Makechnie, 2010; Hicks, 2011), the "muddy" portion of the Entrada has been largely overlooked. Hicks (2011) recently proposed that the redbeds in the Entrada primarily represent intertidal and supratidal (sabkha) deposits.

This study has a threefold purpose: (1) to establish better evidence for facies interpretations in the "muddy" portion of the Entrada Sandstone, (2) to utilize terrestrial sequence stratigraphic methods in an effort to demonstrate the evolution of Entrada facies relationships through time, and (3) to illustrate the orientation of the retroarc's foredeep and the evolution of a potential forebulge through time. Specifically, "sequences" from the alluvial and inland sabkha redbeds of central Utah are correlated to the eolian beds of eastern Utah using terrestrial sequence stratigraphic concepts. Based on these correlations, five paleogeographic reconstructions have been created to demonstrate two major intervals of erg expansion during Entrada deposition. Pinch-outs of erg-margin sandstone beds created combination traps as demonstrated by the presence of dead oil (tar) and bleached eolian sandstone bodies. As an outcrop analog, this study should provide insights into similar subsurface systems such as the petroliferous Norphlet Sandstone located in the northeastern Gulf of Mexico. Finally, the reconstructions illustrate that the edge of the retroarc foredeep is oriented from NNE to SSW and that a potential undulatory forebulge evolved eastward of the foredeep edge.

GEOLOGIC SETTING/STUDY AREA

Deposited in the Jurassic retroarc foreland basin in the western United States (Kocurek & Dott, 1983), the Entrada Sandstone overlies the Carmel Formation and its lateral equivalents and underlies the regionally extensive J-3 unconformity which typically defines the base of the Curtis Formation (Pipiringos & O'Sullivan 1978; Wilcox & Currie, 2008). Laterally the Entrada correlates to the Preuss Sandstone and the Twist Gulch Formation, all of which are characterized by lithologically similar redbeds (Imlay, 1952; Perkes & Morris, 2011) and are all referred to as "Entrada" in this paper (Figure 1). The Entrada was primarily deposited during the late Middle Jurassic Callovian age (Imlay 1952) from ~168 to ~161 Ma (Dossett, 2014). During this time, Utah was located between 20° and 30° north latitude (Peterson, 1988a) allowing trade winds to create an arid environment conducive to the formation of alluvial, sabkha, and eolian systems (Kocurek & Dott, 1983). Throughout the Jurassic Period, sea-level fluctuated dramatically in Utah, but during Entrada deposition, normal marine waters were restricted primarily to Wyoming with a small tongue crossing the Colorado border (Kocurek, 1981; Kocurek & Dott, 1983). This study focuses on examining the Entrada in Utah wherein arid terrestrial systems dominated the landscape.

METHODS

One section near Cannonville Utah, three sections around the San Rafael Swell, and one section near Vernal Utah, were measured along a ~400 km transect from south-central Utah to north-eastern Utah (Figure 2). Standard field techniques were used to identify the facies present in the redbeds of the Entrada Sandstone. Each facies was assigned the simplest interpretation that explained all observations. The detailed sections were generalized to illustrate the broad trends present in the facies successions. An exhaustive literature search was conducted to identify measured sections of the Entrada. These sections were modified so that vertical scale and formatting are the same as the sections measured in this study.

Sequence boundaries are identified in this study using fluvial and eolian sequence stratigraphic concepts (Figure 3). This study assumes that changes in these systems are primarily driven by eustatic sea-level and sediment supply as opposed to tectonics or climate. This assumption follows the precedent set by Carr-Crabaugh and Kocurek (1998) who maintain that the climate remains arid or semi-arid throughout the deposition of the Entrada Sandstone. While the Entrada was deposited in a tectonically active area, the Jurassic Cordillera is thought to consist mostly of relatively low relief mountains or hills at this time (DeCelles, 2004) and subsidence is assumed to be relatively uniform on a regional scale (Carr-Crabaugh & Kocurek, 1998). Finally, the Entrada is thought to have been deposited in a topographically flat environment as is evidenced by the extremely flat, laterally extensive beds present in the Entrada. As a result, the Sundance Seaway to the north would have exerted a strong influence on the water table.

Because eustatic sea-level is assumed to be the dominant factor in the formation of sequence boundaries in both the alluvial and eolian systems present in the Entrada Sandstone, these two systems can be linked in a common stratigraphic framework (Carr-Crabaugh & Kocurek, 1998). In both cases the sequence boundary is identified by a vertical change in facies resulting from base-level rise and fall. In the alluvial system, stream gradient is controlled by the position of sea-level (Figure 3). The relative position of base-level therefore determines whether erosion or deposition occurs in an alluvial system. In the eolian system, the water table, which in this case is assumed to be controlled by eustatic sea-level, also dictates the accumulation or erosion of sediments.

In sections dominated primarily by alluvial facies, sequence boundaries are placed at the base of intervals of stacked channels. Stacked channels were deposited during the lowstand systems tract when sea-level was rising slowly and accommodation was limited. As such they overlie the unconformity created during the falling stage, marking the sequence boundary. Stacked channels may also form during the highstand systems tract, but are rarely preserved because of the erosional unconformity created by subsequent sea-level fall (Catuneanu, 2006).

In eolian systems, dunes are accumulated and preserved when the water table is rising, and sediment supply exceeds the rate of water table rise. When sediment supply is roughly the same as water table rise, sabkha environments form. If water table rise is greater than sedimentation, then a subaqueous environment is created. A super surface forms during times of bypass or erosion. This results from a static or falling water table. If eustatic sea-level is the primary force controlling water table position, then dunes are deposited during the lowstand and highstand systems, sabkhas and subaqueous environments are deposited during the transgressive systems, and super surfaces form during the falling stage systems (Figure 3; Kocurek & Havholm, 1993).

After observing regionally extensive surfaces exhibiting polygonal mud cracks, and other evidence for prolonged exposure (a super surface), Carr-Crabaugh and Kocurek (1998) placed sequence boundaries at the transition from eolian sandstones, deposited as the highstand systems tract (see discussion section), to sabkha mudstones, deposited as the transgressive systems tract (Figure 3). In order to for this to occur they suggest that during the onset of water table rise (lowstand systems tract), the sediment supply matches the rate of base-level rise, allowing for sabkha to develop. As base-level continues to rise, sediment supply also increases, allowing for the continued deposition of sabkha sediments, until as sea-level rise begins to slow down, sediment supply finally out-paces water table rise, and dunes are accumulated during highstand. Then, during sea-level fall, a super surface is formed and sediment supply once again decreases allowing the cycle to begin again. This study follows this model, and places sequence boundaries in eolian sections where eolian facies are overlain by sabkha facies.

Two major sequence boundaries were identified in this study and eventually correlated eastward into the eolian-dominated part of the Entrada (Carr-Crabaugh & Kocurek 1998). Using a combination of eolian and fluvial sequence stratigraphic concepts and absolute ages obtained from volcanic air fall ash beds (Dossett, 2014), three time correlative surfaces in the Entrada are extrapolated across Utah. Based on these three surfaces, five paleogeographic reconstructions and five isopach maps were created, illustrating the evolution of depositional facies and depocenters through time. Paleogeographic reconstructions were created in ArcGIS. Isopach maps were purposely hand drawn in Adobe Illustrator so as to honor not only the data points, but also to honor geologic principals, context, and reality.

FACIES

Descriptions and Interpretations

Facies were differentiated in outcrop based on differences in sedimentary characteristics such as primary and secondary sedimentary structures, trace fossils, and grain size. Three broad facies are observed in the measured sections (Figure 4) and belong to eolian, alluvial, and sabkha depositional systems. These facies interpretations were applied to sections reported and described in the literature. Sandstone beds described as having medium- to large-scale, high-angle trough cross-stratification are interpreted as eolian. Redbeds described as being brecciated, “wispy,” disturbed, or flat to wavy bedded are interpreted as a sabkha facies, as are any units described as having evaporite nodules or molds. Redbeds containing thin, laterally continuous, rippled siltstone beds, channel forms (either sand- or mud-filled), mud rip-up clasts, or conglomerates are interpreted as alluvial plain. Facies described in the literature as "redbeds" are interpreted to mean "not eolian," and therefore may represent either alluvial or sabkha environments.

Facies Discussion

In a typical near-coast desert environment, an idealized vertical regressive facies succession should be as follows: marine, beach, intertidal, and sabkha (Figure 5). The sabkha sediments may be overlain by either alluvial or eolian materials that may interfinger (Glennie, 1970). Although alluvial and eolian deposits may interfinger, this study assumes that eolian sediments advance over alluvial deposits. This relationship can be observed in satellite photographs of the erg/alluvial fan intersection near the Al Hajar Mountains in the Arabian Peninsula and in satellite photographs of the Sossusvlei wadis being cut off by eolian dunes in the Namib desert.

Eolian

The presence of eolian deposition in the Entrada Sandstone is well documented (e.g. Kocurek, 1980; Kocurek & Dott, 1983; Marino, 1992; Carr-Crabaugh & Kocurek, 1998; Monn, 2006; Makechnie, 2010; Hicks, 2011). An idealized Waltherian succession of eolian strata in the Entrada begins with loess deposits overlain by sand sheets, capped by interbedded eolian dunes and interdunes. Loess is defined as any terrestrial clastic sediment composed predominantly of silt-sized grains deposited by wind processes. Deposits of loess may transition laterally into a sand sheet facies (Pye, 1996). Loess is often locally reworked through various processes, including bioturbation and syn-depositional weathering (Pye, 1995). Sand sheets often form near erg margins and are characterized by prevalent horizontal and low angle laminae, although they may also contain ripple-produced strata and massive mottled sandstone up to a meter thick (Brookfield & Silvestro, 2010; Fryberger et al., 1983). Eolian dunes are characterized by high angle trough cross-stratified sandstone. Interdune deposits are characterized by algal laminated sandstone (Dayrymple & Morris, 2007), and may contain subaqueous, eolian, and evaporitic sedimentary structures. While often exhibiting similar sedimentary structures to both sabkha and sand sheets, interdune deposits are typically thinner and less continuous (Fryberger et al., 1983). Carbonate grains are often deposited with siliciclastic grains by eolian processes. The presence of ooids or other carbonate grains in a sandstone does not indicate that the sandstone was deposited subaqueously or even near the shoreline. Subaqueous and near shore deposition is generally characterized by a lack of siliciclastics. Windblown carbonate grains have been detected at least 170 km inland and deposition of coastal sediments through eolian processes has also been observed up to 850 m above sea-level (Glennie, 1970).

In the Entrada Sandstone, eolian dune deposits are characterized by fine sandstone with high angle trough cross-stratification (facies 1a, Figure 4), while interdune deposits typically have horizontally laminated to algal matted, wavy to lumpy sedimentary structures (facies 1b, Figure 4) (Dalrymple & Morris, 2007). The sand sheet consists of laterally continuous, fine sandstone with planar to low angle laminations with some soft sediment deformation (facies 1c, Figure 4). Dune, interdune, and sand sheet facies often have some fine sand-sized carbonate grains. Loess deposits are characterized by massive to faintly laminated, loosely consolidated, yellow gray siltstone that is always closely associated with other eolian facies (facies 1d, Figure 4).

Alluvial

Desert alluvial depositional environments consist of both alluvial plain and alluvial channels. Alluvial plain sediments consist of flood deposits as well as overbank mud deposits. Modern flood deposits may consist of sands with steep foresets, planar laminae, and sets of climbing ripples (Glennie, 1970). They may also have faintly laminated to massive sands. Generally however, flood deposits are planar laminated (McKee et al., 1967). Massive siltstone/mudstone deposits with dessication cracks are also indicative of overbank deposits (Miall, 2010). Because alluvial channels rarely reach the ocean in desert environments, channels fill with their own sediment which may range in size from clay to boulders. Due to intermittent flow, braided patterns may be created. Sedimentary structures can indicate anything from upper to lower flow regimes (Southard & Boguchwal, 1990). Clay is often deposited as the last of the water seeps into the ground. Dessication cracks often form in the clay and may be ripped up during the next flood (Glennie, 1970). Massive siltstone/mudstone may be deposited in abandoned channels (Miall, 2010).

In the Entrada Sandstone, alluvial plain deposits typically consist of massive red mudstone interbedded with laterally continuous rippled gray siltstone beds usually ranging from 5-10 cm thick (facies 2b, Figure 4). The alluvial system is present in the west-central portion of Utah (Perkes & Morris, 2011). The alluvial channel facies (facies 2a, Figure 4) may be vertically separated by massive red mudstone beds interbedded with gray rippled siltstone beds, or the channels may be stacked with very thin clay breaks separating the channels. The alluvial channel facies often weather to hoodoos. Generally the Entrada lacks conglomeratic units typically characteristic of desert alluvial systems. Despite not having conglomerates, the Entrada does contain channels filled with fine-grained floodplain sediments with mud rip-ups at the base. The lack of larger grains in the Entrada does not reflect a lack of sufficient energy to carry them, as is evidenced by the presence of pebble-sized clay rip-ups; rather it reflects the lack of a source for large grains.

Sabkha

Two types of sabkhas exist in the modern; coastal sabkhas and inland sabkhas. Coastal sabkhas are characterized by sedimentary structures created by algal mats as well as nodular to bedded anhydrite, gypsum, halite, and dolomite. Sediments are dominated by the adjacent lagoonal and intertidal areas (commonly carbonate) (Glennie, 1970; Kinsman 1969). Today, along the Trucial Coast, coastal sabkhas range up to 8-10 km in width (Kinsman, 1969). In the extreme case of the Rann of Kutch, India, the Arabian Sea annually floods inland 150 km from the open sea and covers an area of about 30,000 km^2. Deposition in this sabkha consists mostly of siliciclastic and evaporitic sediments rather than carbonate because siliciclastic sediment from the Indus River Delta directly to the north prohibits most carbonate deposition in the area (Glennie, 1970). Although in the Jurassic foreland of Utah, this type of flat terrestrial embayment may have existed, most of the sabkha observed in the study area is further than 150 km from known time-equivalent open marine deposits (Kocurek, 1981; Kocurek & Dott 1983). In contrast, inland sabkhas (playas) typically do not have recognizable algal mats, despite algae existing in this environment. Instead, wavy to disturbed laminations are the most common sedimentary structures. Sediment is supplied to inland sabkhas through alluvial systems and wind adhesion (Glennie, 1970) and typically consists of non-carbonate sediments (Kinsman, 1969). While both coastal and inland sabkhas are common in the Holocene, inland sabkhas cover a vastly greater area than coastal sabkhas (Glennie, 1970).

Because of the lack of carbonate sediments in the sabkha, as well as the distance from the open marine waters present in Wyoming and Idaho, sabkha environments in the Entrada of Utah are generally interpreted as inland sabkhas. It should be noted however, that Kocurek (1980) describes well-developed algal mat structures, floating gypsum crystal and nodule molds or replacements, and “chicken-wire” structure thought to have originated from evaporites, in section 29 Hanna (Figure 2, Figure 6). This section straddles the line between inland and coastal sabkha. It has many features associated with coastal sabkhas, but does not have any carbonates. It also has sedimentary structures consistent with what has been interpreted as alluvial channels elsewhere in this study. This environment is probably most analogous to the modern example of the Rann of Kutch, which consists of very flat topography, heavy siliciclastic influence, and seasonal flooding of marine water.

In the Entrada Sandstone, inland sabkha deposits are identified primarily by the presence of “chippy,” “wispy,” or disturbed bedding in pinkish siltstone or very fine sandstone. The disturbed nature of the bedding is thought to result from haloturbation (Glennie, 1970; Hicks, 2011). Dessication cracks and replaced evaporite nodules are also diagnostic of inland sabkha deposits in the Entrada.

Intertidal and Beach

Because the dominant marine deposition is often carbonate in a desert environment, adjacent beach and intertidal areas are typically composed of reworked carbonate sediments. In the Persian Gulf today, carbonate sand grains, ooids, and skeletal sediments are often reworked into low beach ridges (Purser & Evans, 1973). The lower intertidal zone may be characterized by any of the following: rippled carbonate sand, pelletal sediment, skeletal sediment, muddy carbonate sand, and ooids. Tidal deltas consisting primarily of ooids may also form in the lower intertidal zone (Purser & Evans, 1973). The upper intertidal zone is typified by algal mats divided into cinder, polygonal, crinkle, and flat zones (Bathurst, 1975; Purser & Evans, 1973). Few rocks with these characteristics or other clastic tidal indicators such as herringbone cross-stratification, double drape laminae, and upward fining successions, have been observed or reported in the area of interest. Additionally the lack of nearby marine deposits indicates that the redbeds of the Entrada were not primarily deposited in a tidal setting.

Shallow Marine

In an arid environment, marine deposits are often characterized by carbonate deposition. This results from high evaporation rates concentrating carbonate in marine water as well as a lack of siliciclastic influx into the system. Siliciclastic material is limited because alluvial systems do not typically reach the ocean in low relief desert environments. Instead these losing, ephemeral streams often dry out before reaching the ocean, depositing sediment in terrestrial environments (Glennie, 1970). While it is possible for eolian systems to supply enough siliciclastic sediment to drown out carbonate production (Shinn, 1973), in the case of the Entrada Sandstone, the predominant wind direction (south) transported eolian sand away from the marine environment. The lack of a siliciclastic source, coupled with warm temperatures, creates an ideal setting for carbonate deposition (Glennie, 1970). No carbonate rocks with these characteristics in Utah's Entrada Sandstone have been observed or reported in the area of interest. Therefore, none of the rocks in the Entrada Sandstone in Utah are interpreted to be of marine origin. However, carbonate rocks have been reported north of the area of interest in the stratigraphically equivalent Preuss Sandstone in Idaho (Imlay, 1952) and Wyoming (Kocurek & Dott, 1983).

CORRELATIONS

Chronostratigraphic Devisions

The Entrada Sandstone in eastern Utah is interpreted to be a wet eolian system, in which preservation of sediments results from a relatively rising water table (Carr-Crabaugh & Kocurek, 1998). As discussed previously, relative water table rise may be forced by climatic, tectonic, or eustatic changes. This study assumes that eustatic sea-level is the dominant control of water table rise and fall in the Entrada for several reasons. The Entrada was deposited in an arid to semi-arid environment with little evidence for major climatic changes (Carr-Crabaugh & Kocurek, 1998). While the Entrada was deposited in a relatively active tectonic regime with localized variations influenced by tectonism, there is little data demonstrating large changes in regional subsidence. Finally, the presence of the Sundance Seaway to the north of Utah and the extremely low topographic relief of the region during this time suggest that eustatic sea-level determined how groundwater fluctuated in this area.

Long term accumulation of sediment in an eolian system can occur only with a relative rise in the water table. A static, or falling water table results in periods of bypass or erosion, forming a super surface (Figure 3) (Kocurek & Havholm, 1993). A super surface is equivalent to a traditional eustatic sequence boundary if, as is the case in this study, sea-level is the controlling factor in water table position. This boundary marks the onset of sea-level fall. In the Entrada, this surface is often marked by a shift from a more terrestrial facies to a more basinward facies (e.g. from eolian deposits to inland sabkha or alluvial deposits).

A fluvial sequence boundary is also created by the onset of sea-level fall (Figure 3). As base-level drops, the stream gradient steepens, and the fluvial system downcuts to reach equilibrium. This erosive event is overlain by stacked channels as the stream fills in limited accommodation. As sea-level rises during rapid transgression, accommodation increases and the channels spread further apart. As sea-level rise slows down during the late highstand systems tract and accommodation becomes more limited, stacked channels begin forming again. The preservation potential of the highstand stacked channels is low, however, because the subsequent falling stage systems tract typically destroys them through erosion. As a result, the sequence boundary of a fluvial system is typically identified as the base of the stacked channels (Catuneanu, 2006).

Fluvial sequence stratigraphy can be related to the sequence stratigraphy of a wet eolian system if base-level is the controlling factor in both stream gradient and water table position. This assumption needs to be carefully considered. Marine influence of river systems is generally limited to tens of kilometers (Catuneanu, 2006), with some low gradient landscapes (such as the Pleistocene fluvial systems of the Java continental shelf) recording marine influences up to 200 km (Posamentier, 2001). Many of the alluvial systems in the sections measured in this study are on the verge of, or even further than, 200 km from the open ocean. The fluvial architecture of these systems may or may not be more influenced by climatic and tectonic processes. Sea-level is assumed to control the alluvial processes in this study because of the extremely flat topography in Utah at this time and the lack of data regarding climatic and tectonic influences. Additionally the sequences created this way correlate well with the eolian sequences, creating relatively uniform sequence packages.

Sequence boundaries are placed in each section either where more basinward facies overlie more terrestrial facies (i.e. where sabkha or alluvial mudstones overlie eolian sandstone) or as fluvial architectural changes occur (Figure 3 & Figures 6-9). In some sections sequence boundaries were not observable because of the presence of only a single facies in the section. In these instances lithostratigraphy and the thickness of nearby sequences were used to guide correlations. Usually the placement of the sequence boundary in such situations does not affect the outcome of the paleogeographic reconstruction because the facies is the same throughout the section. The two sequence boundaries observed in this study are correlated eastward and match Carr-Crabaugh and Kocurek's (1998) surfaces four and six.

At several sections volcanic air fall ash beds were sampled and analyzed by Dossett (2014). Located on the south-west side of the San Rafael Swell, the tephra at Moore Road yielded an age of ~165 Ma and is located between the base of the Entrada Sandstone and sequence boundary 1 (Figures 6-9). Because the exact location of this ash bed is known only around the southern part of the San Rafael Swell with an areal extent of ~750 km^2, the stratigraphic position of this time line is extrapolated to other measured sections by subjectively placing it between the base of the Entrada and sequence boundary 1 (Figures 6-9).

Isopach Maps

Between Dossett's (2014) tephrochronology and the sequence boundaries described in this paper, three chronostratigraphic surfaces have been extrapolated across Utah. Based on these three devisions in the Entrada Sandstone, a series of five isopach maps have been generated (Figure 10, Figure 11). These isopach maps demonstrate the active evolution of the Jurassic foreland trough throughout the deposition of the Entrada Sandstone. When an isopach map of the entire Entrada Sandstone is examined (Figure 10), the Entrada Sandstone thickens to the west with only slight evidence of a forebulge present in the southeast part of Utah. The isopach maps illustrating the stratigraphic thicknesses between the various chronostratigraphic devisions, however, do indicate the presence of ephemeral, segmented, paleotopographic highs that may represent the tectonic forebulge trending roughly north-south in eastern Utah. Phillips & Morris (2013) noted a similarly oriented forebulge to the west of the topographic highs in the Navajo Sandstone. This early bulge (~170 Ma) separated the White Throne Member of the Temple Cap Formation and Harris Wash Member of the Page Sandstone. Thus, these isopach maps may highlight the continued eastward movement of the Jurassic hinterland and associated forebulge through time.

DISCUSSION

Paleogeographic Maps

A series of five paleogeographic maps have been created based on the tephra at Moore Road (Dossett, 2014) and the two sequence boundaries identified in this study. Data points for these maps are located in the eastern two thirds of Utah, with no data for the western third. Artistic license has been used to fill in the western third of Utah by extending the alluvial plain westward towards the Jurassic Cordilleran. The Elko Fold Belt, located in northwestern Utah in Figures 12-16, is also added and shown to advance through artistic license. While it is thought to be present in Utah by Bjerrum & Dorsey (1995), Thorman, (2011), and by Kowallis et al. (2001), DeCelles (2004) suggests that there is little evidence for regional scale thrusting in Utah prior to the Late Jurassic.

All of the paleogeographic maps illustrate the same broad facies belts. To the west, alluvial plain dominates. The central facies belt consists of inland sabkha. Eastern Utah is comprised of a wet eolian system. Each of these facies belts expand and contract through time.

Located in the lower portion of the Entrada Sandstone, the paleogeographic map of the facies at the tephra of Moore Road (Figure 12) illustrates the erg in the eastern part of Utah, with a large tongue protruding into the south-central portion of the state. Just to the south of the tip of the tongue, a large loess deposit marks the erg margin. To the west of the eolian facies lies a large expanse of sabkha deposits. The west-central portion of the state is dominated by alluvial floodplain and channels, which are interpreted to continue to the west.

In the paleogeographic map of the facies below sequence boundary 1 (Figure 13) both the erg and the alluvial systems have advanced dramatically when compared to Figure 12. The sab kha in the central part of the state has all but disappeared. This map represents the facies present at the end of the highstand systems tract.

The paleogeographic map of the facies above sequence boundary 1 (Figure 14) represents the locations of the facies belts at the beginning of sea-level rise. The eolian facies has retracted significantly from that shown in Figure 13 as base-level rise is matched by sediment supply in central Utah allowing for the formation of sabkha deposits (Kocurek & Havholm, 1993). The alluvial system has also retracted as the stream gradient has decreased as a result of rising base-level.

In the paleogeographic reconstruction of the facies below sequence boundary 2 (Figure 15) both the eolian and alluvial systems have expanded dramatically from their previous extents. This map shows the facies belts at the end of the highstand systems tract. The two protrusions of eolian sediments to the west in the central portion of Utah represent the Bitter Seep Wash Sandstone, and its lateral equivalents (Hicks, 2011; Morris, personal communication).

The paleogeographic map of the facies above sequence boundary 2 (Figure 16) illustrates the locations of the facies belts at the beginning of sea-level rise. The eolian sediments have retracted from their previous extent and the sabkha environment has expanded as a result of the rising water table. At this time, the alluvial sediments have not retracted as they did previously. In contrast, stacked channels are found further eastward in Utah than at any other time during Entrada Sandstone deposition. This lack of retraction may result from tectonic uplift counteracting the rising base-level.

Hydrocarbon Potential

The eolian facies of the Entrada Sandstone contain potential reservoir quality rocks, with an average porosity of approximately 15% and permeability ranging from 10 to 1000 millidarcies (md) (Hicks, 2011). The erg grades westward into muddy redbeds containing porosities up to 10% and permeability up to 1 md (Hicks, 2011). Because the relatively impermeable redbeds surround the erg margin, a potential stratigraphic trap is created for hydrocarbons, assuming that the other necessary attributes of a petroleum system are present.

In the North Hill Creek/Flat Rock (NHC/FR) field located in the southern Uinta Basin, Utah (Eckels et al., 2005), the Entrada Sandstone contains all the requisite attributes of a petroleum system. At least eleven wells in the NHC/FR field have penetrated the gas-charged Entrada Sandstone (Monn, 2006). Ancient eolian deposits often consist of well sorted, well rounded, mature sediments and are excellent potential hydrocarbon reservoirs. Erg margin deposits are widely recognized as potential stratigraphic and combination traps, particularly when they are laterally associated with muddy facies (Vincelette & Chittum, 1981; Fryberger et al., 1983; Fryberger, 1986; Chan, 1989; Marino & Morris, 1996; Hicks, 2011). Hydrocarbon plays with a similar source, migration, structural setting, and timing to the one present in the NHC/FR field, as well as other plays, may exist along the erg pinch-out, where it exists in the subsurface.

Paleogeographic reconstructions illustrate the migration of facies belts through time (Figures 12-16). These reconstructions highlight two major intervals of erg expansion (Figure 13, Figure 15). In both cases, the edge of the erg terminates into muddy sabkha and alluvial facies, creating potential stratigraphic traps.

Section 23. SE-SRS is located on the east side of the San Rafael Swell, a large Laramide structure, (Figure 2) in an ideal location for a classic combination trap. Both intervals of maximum erg expansion are also present, and the pinch-out can be directly observed terminating against the San Rafael Swell. Tar sands are present in both erg pinch-outs in this section

(Figure 17), proving that the stratigraphic pinch out of the eolian facies of the Entrada was once an effective hydrocarbon trap.

In addition to the stratigraphic trap potential of the erg margin pinch-out, isolated sandstone bodies surrounded by muddy redbeds may also be potential reservoir targets. To the south of section 22. Moore Road (Figure 2), a single tabular set of high-angle trough cross-stratified sandstone with a maximum thickness of 6.4 m and excellent porosity and permeability is preserved, surrounded above and below by muddy redbeds. Hicks (2011) named this unit the Bitter Seep Wash Sandstone (BSWS). The BSWS disappears into the subsurface to the west. To the east, the unit has been eroded due to the uplift of the San Rafael Swell. The area in which the BSWS is currently exposed is approximately 32 km^2 (Herbst & Morris, 2011), but the sandstone probably occupies a much larger area in the subsurface. Another sandstone body occupying the same stratigraphic location as the BSWS is also observed to the north of section 22. Moore Road (Figure 2).

Two viable explanations for the depositional setting of these two sandstones exist. Hicks (2011) interpreted the BSWS to represent the migration of a single dune set into a sabkha pond, thus implying that the unit is surrounded on all sides by muddy redbeds. Mancini et al. (1985) also suggests that isolated eolian dunes may blow across playas and other muddy redbeds. If water is present in a playa lake, then preservation potential of a dune being blown into it is high. A second possibility is that these sandstones are connected to the main erg, and represent the westward pinch-out of the eolian system. Figure 15 illustrates two small westward protrusions along the western edge of the erg-margin in east-central Utah demonstrating what the second hypothesis may have looked like. When exploring for hydrocarbon traps near the erg-margin, both models should be considered because both systems can produce excellent traps.

While the Entrada Sandstone has considerable stratigraphic intervals of mudstone, the terrestrial nature of deposition of these facies make them unlikely hydrocarbon sources. Hydrocarbons likely matured in source rocks present in other formations and migrated into the Entrada Sandstone via faults (Wallace & Jacobs, 2013; Eckels et al., 2005). A more detailed understanding of possible sources, migration pathways, and the relative timing of each of these attributes is key to further unlocking the economic potential of the Entrada Sandstone.

In addition to being a potential reservoir target, the Entrada Sandstone is also a world class outcrop analog to other eolian systems such as the Norphlet Formation (Figure 18). The Upper Jurassic Norphlet Formation located in the eastern Gulf of Mexico area has excellent reservoir quality eolian rocks with average porosities of about 10% and permeabilities ranging from 0.5 to over 100 md (Tew et al., 1991). The Norphlet Formation was deposited in arid conditions adjacent to the Appalachian Mountains. The paleogeography of the region was dominated by a broad desert plain, rimmed to the north and east by the Appalachians and to the south by a developing shallow sea. Depositional environments followed the typical progradational pattern found in most desert environments (Figure 5, Figure 18) with eolian sediments being sourced from the adjacent redbeds. The Norphlet Formation is overlain by a marine transgression that reworked the upper portion of the formation (Mancini et al., 1985). The facies described in the Norphlet Formation (Mancini et al., 1985) are virtually identical to the facies described in this study (Figure 4, Figure 18).

While the Norphlet Formation is a prolific hydrocarbon producer, petroleum systems in the formation have been limited to structural traps usually involving salt structures (Mancini et al., 1985; Marzano, et al., 1988; Tew et al., 1991). The edge of the Norphlet erg system may have expanded and contracted similarly to the eolian sediments deposited in the Entrada Sandstone.

As a result, the possibility of erg pinch-outs into muddy redbeds is quite high. The stratigraphic trap potential of the Norphlet Formation, and other similar formations around the world, have not been explored to their full potential. Further study of erg-margin pinch-outs may yield additional petroleum accumulations that have been previously overlooked in the Norphlet and other formations.

CONCLUSIONS

The late Middle Jurassic Entrada Sandstone has been reconstructed in greater detail than ever before based on improved facies analysis, radiometric ash ages, and terrestrial sequence stratigraphic concepts . This study interprets the "muddy" portion of the Entrada as being a mixture of alluvial and inland sabkha systems, and illustrates three broad facies belts within Utah. In the west-central part of Utah, the Entrada is characterized primarily by alluvial channels and alluvial plain deposits. The central facies belt in the study area consists primarily of disturbed, "wispy" laminae and is interpreted as an inland sabkha. The eastern part of Utah is characterized predominantly by eolian depositional processes. Because of the lack of carbonate rocks in Utah's Entrada Sandstone, depositional environments are typically assigned to terrestrial facies rather than marginal marine or marine facies. Using a combination of eolian and fluvial sequence stratigraphic concepts, two major sequence boundaries have been extrapolated across Utah. Based on isopach maps drawn from stratigraphic thicknesses of various time correlative intervals within the Entrada, the evolution of the retroarc foredeep and its associated forebulge are observed. Ephemeral paleotopographic highs appear and disappear throughout the deposition of the Entrada. Paleogeographic reconstructions based on three time significant surfaces show two major erg expansions during Entrada deposition, resulting in combination traps for hydrocarbons. In addition to being a hydrocarbon reservoir in its own right, both past and present, the Entrada

Sandstone is also a world class outcrop analog for other eolian systems such as the Norphlet Formation of the Gulf of Mexico. A greater understanding, gleaned from observations of the Entrada Sandstone, of the complex relationships between eolian sandstones, sabkha mudstones, and alluvial mudstones will enable better predictions to be made regarding the presence and location of potential hydrocarbon traps in rocks deposited in similar depositional systems worldwide.

REFERENCES

Baker, A. A., 1947, Stratigraphy of the Wasatch Mountains in the vicinity of Provo, Utah, Oil and Gas Investigations Chart OC-30, scale 1:316,800.

Bathurst, R. G. C., 1975, Carbonate Sediments and Their Diagenesis, Amsterdam, Oxford, New York, Elsevier, 658 p.

Bjerrum, C., J. and R. Dorsey, 1995, Tectonic controls on deposition of Middle Jurassic strata in a retroarc foreland basin, Utah-Idaho trough, western interior, United States, Tectonics, vol. 14, no. 4, p. 962-978.

Brookfield, M. E. and S. Silvestro, 2010, Eolian Systems, in James, N. P. and R. W. Dalrymple, eds., Facies Models 4, Geological Association of Canada, p. 139-166.

Carr-Crabaugh, M. and G. Kocurek, 1998, Continental sequence stratigraphy of a wet eolian system: a key to relative sea-level change, SEPM Special Publication No. 59, p. 213.

Catuneanu, O., 2006, Principles of sequence stratigraphy, Oxford, UK, Elsevier, 375 p.

Chan, M. A., 1989, Erg margin of the Permian white rim sandstone, SE Utah, Sedimentology, vol. 36, no. 2, p. 235-251.

Dalrymple, A. and T. H. Morris, 2007, Facies analysis and reservoir characterization of outcrop analogs to the Navajo Sandstone in the central Utah thrust belt exploration play, in Willis, G. C., M. D. Hylland, D. L. Clark, and T. C. Chidsey, eds., Central Utah: Diverse Geology of a Dynamic Landscape, Utah Geological Association, vol. 36, p. 311-322.

Dossett, T., 2014, The first 40Ar/39Ar ages and tephrochronologic framework for the Jurassic Entrada Sandstone in central Utah, M.S. thesis, Brigham Young University, Provo, Utah, 126 p.

Eckels, M. T., D. H. Suek, and P. J. Harrison, 2005, New, old plays in southern Uinta basin get fresh look with 3D seismic technology, Oil & gas journal, vol. 103, no. 11, p. 32-40.

Fryberger, S. G., 1986, Stratigraphic traps for petroleum in wind-laid rocks, AAPG Bulletin, vol. 70, no. 12, p. 1765-1776.

Fryberger, S. G., A. M. Al-Sari, and T. J. Clisham, 1983, Eolian dune, interdune, sand sheet, and siliciclastic sabkha sediments of an offshore prograding sand sea, Dhahran area, Saudi Arabia, AAPG Bulletin, vol. 67, no. 2, p. 280-312.

Glennie, K. W., 1970, Desert sedimentary environments, Amsterdam, London, New York, Elsevier, 222 p.

Herbst, S. R. and T. H. Morris, 2011, Unexpected Reservoir Quality Sandstone Within the Mudstone-Rich Portion of the Middle Jurassic Entrada Sandstone, San Rafael Swell, Utah, GSA Annual Meeting - Minneapolis, MN, Abstracts with Programs, vol. 43, no. 5, p. 610.

Hicks, T. C., 2011, Facies Analysis and Reservoir Characterization of Subtidal, Intertidal, and Supratidal Zones of the Mudstone-rich Entrada Sandstone, South-Central Utah, M.S. thesis, Brigham Young University, Provo, UT, 142 p.

Imlay, R. W., 1952, Marine origin of Preuss sandstone of Idaho, Wyoming, and Utah, AAPG Bulletin, vol. 36, no. 9, p. 1735-1753.

Kinsman, D. J., 1969, Modes of formation, sedimentary associations, and diagnostic features of shallow-water and supratidal evaporites, AAPG Bulletin, vol. 53, no. 4, p. 830-840.

Kocurek, G., 1980, Significance of Bounding Surfaces, Interdune Deposits, and Dune Stratification Types in Ancient Erg Reconstruction, Ph.D. thesis, University of Wisconsin-Madison, Madison, WI, 369 p.

Kocurek, G., 1981, Erg reconstruction: the Entrada sandstone (Jurassic) of northern Utah and Colorado, Paleogeography, Paleoclimatology, Paleoecology, vol. 36, no. 1, p. 125-153.

Kocurek, G. and R. Dott, 1983, Jurassic Paleogeography and Paleoclimate of the central and Southern Rocky Mountains Region, in Reynolds, M. W. and E. D. Dolly, eds., Mesozoic Paleogeography of the West-Central United States: Rocky Mountain Symposium 2, Denver, Colorado, Society for Sedimentary Geology: Rocky Mountain Section, p. 101-116.

Kocurek, G. and K. G. Havholm, 1993, Eolian sequence stratigraphy - a conceptual framework, in Weimar, P. and H. W. Posamentier, eds., Siliciclastic sequence stratigraphy: Recent developments and applications, Tulsa, OK, American Association of Petroleum Geologists, p. 393-409.

Kowallis, B. J., E. H. Christiansen, A. L. Deino, C. Zhang, and B. H. Everett, 2001, The record of Middle Jurassic volcanism in the Carmel and Temple Cap Formations of southwestern Utah, GSA Bulletin, vol. 113, no. 3, p. 373-387.

Makechnie, G. K., 2010, Sequence stratigraphic analysis of marginal marine sabkha facies: Entrada Sandstone, Four Corners region, M.S. thesis, University of Texas at Austin, Austin, TX, 66 p.

Mancini, E. A., R. M. Mink, B. L. Bearden, and R. P. Wilkerson, 1985, Norphlet Formation (Upper Jurassic) of southwestern and offshore Alabama: environments of deposition and petroleum geology, AAPG Bulletin, vol. 69, no. 6, p. 881-898.

Marino, J. E. and T. Morris, 1996, Erg margin and marginal marine facies analysis of the Entrada Sandstone, Utah: Implications to depositional models and hydrocarbon entrapment, in Morales, M., ed., The Continental Jurassic, Museum of Northern Arizona, Bulletin 60, p. 483-496.

Marino, J. E., 1992, Erg Margin and Marginal Marine Facies Analysis of the Entrada Sandstone, San Rafael Swell, Utah: Implications to Hydrocarbon Entrapment, M.S. thesis, Brigham Young University, Provo, UT, 142 p.

Marzano, M. S., G. M. Pense, and P. Andronaco, 1988, A comparison of the Jurassic Norphlet Formation in Mary Ann field, Mobile Bay, Alabama to onshore regional Norphlet trends, Gulf Coast Association of Geological Societies Transactions, vol. 38, p. 85-100.

McKee, E. D., E. J. Crosby, and H. L. Berryhill, 1967, Flood deposits, Bijou Creek, Colorado, June 1965, Journal of Sedimentary Research, vol. 37, no. 3, p. 829-851.

Miall, A., 2010, Alluvial Deposits, in James, N. P. and R. W. Dalrymple, eds., Facies Models 4, Geological Association of Canada, p. 105-137.

Monn, W. D., 2006, A multidisciplinary approach to reservoir characterization of the coastal Entrada erg-margin gas play, Utah, M.S. thesis, Brigham Young University, Provo, UT, 33 p.

O'Sullivan, R. B. and F. W. Pierce, 1983, Stratigraphic diagram of the Middle Jurassic San Rafael group and associated formations from the San Rafael swell to Bluff in southeastern Utah, Oil and Gas Investigations Chart OC-119, scale 1:842553.

Perkes, T. L., 2010, Integrating Facies Analysis, Terrestrial Sequence Stratigraphy, and the First Detrital Zircon (U-Pb) Ages of the Twist Gulch Formation, Utah, USA: Constraining Paleogeography and Chronostratigraphy, M.S. thesis, Brigham Young University, Provo, UT, 48 p.

Perkes, T. L. and T. H. Morris, 2011, Integrating Facies Analysis, Nonmarine Sequence Stratigraphy, and the First Detrital Zircon (U-Pb) Ages of the Twist Gulch Formation, Utah, USA: Constraining Paleogeography and Chronostratigraphy, in Sprinkel, D. A., W. A. Yonkee, and T. C. Chidsey, eds., Sevier Thrust Belt: Northern and Central Utah and Adjacent Areas, Utah Geological Association, vol. 40, p. 173-192.

Peterson, F., 1988a, Pennsylvanian to Jurassic eolian transportation systems in the western United States, Sedimentary Geology, vol. 56, no. 1, p. 207-260.

Peterson, F., 1988b, Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, Western Colorado Plateau, Utah and Arizona, US Geological Survey Bulletin 1633-B, p. 17-56.

Phillips, S. P., 2012, Discriminant Analysis of XRF Data from Sandstones of Like Facies and Appearance: A Method for Identifying a Regional Unconformity, Paleotopography, and Diagenetic Histories, M.S. thesis, Brigham Young University, Provo, UT, 121 p.

Phillips, S. P. and T. H. Morris, 2013, Identification of an Extensive Paleotopographic High of the Navajo Sandstone by Surface to Subsurface Correlation of the Temple Cap Formation and Time-equivalent Portions of the Page Sandstone, in Morris, T. H. and R. Ressetar, eds., Geology of the San Rafael Swell and Henry Mountains Basin: Geologic Centerpiece of Utah, Utah Geological Association, vol. 42, p. 261-278.

Pipiringos, G. N. and R. B. O'Sullivan, 1978, Principal unconformities in Triassic and Jurassic rocks, western interior United States: a preliminary survey, U.S. Geological Survey Professional Paper 1035-A, p. 29.

Posamentier, H. W., 2001, Lowstand alluvial bypass systems: incised vs. unincised, AAPG Bulletin, vol. 85, no. 10, p. 1771-1793.

Purser, B. H. and G. Evans, 1973, Regional Sedimentation along the Trucial Coast, SE Persian Gulf, in Purser, B. H., ed., The Persian Gulf: Holocene Carbonate Sedimentation and Diagenesis in a Shallow Epicontinental Sea, New York, Heidelberg, Berlin, Springer-Verlag, p. 211-231.

Pye, K., 1995, The nature, origin and accumulation of loess, Quaternary Science Reviews, vol. 14, no. 7–8, p. 653-667.

Shinn, E. A., 1973, Sedimentary accretion along the leeward, SE coast of Qatar Peninsula, Persian Gulf, in Purser, B. H., ed., The Persian Gulf, Holocene Carbonate Sedimentation and Diagenesis in a Shallow Epicontinental Sea, New York, Springer, p. 199-209.

Southard, J. B. and L. A. Boguchwal, 1990, Bed configurations in steady unidirectional water flows. Part 2. Synthesis of flume data, Journal of Sedimentary Petrology, vol. 60, no. 5, p. 658-679.

Tew, B. H., R. M. Mink, S. D. Mann, B. L. Bearden, and E. A. Mancini, 1991, Geologic framework of Norphlet and pre-Norphlet strata of the onshore and offshore eastern Gulf of Mexico area, Gulf Coast Association of Geological Societies Transactions, vol. 41, p. 590-600.

Thorman, C. H., 2011, The Elko orogeny — a major tectonic event in eastern Nevada - western Utah, in Sprinkel, D. A., W. A. Yonkee, and T. C. Chidsey, eds., Sevier thrust belt: northern and central Utah and adjacent areas, Salt Lake City, Utah Geological Association Publication 40, p. 117-129.

Vincelette, R. R. and W. E. Chittum, 1981, Exploration for oil accumulations in Entrada sandstone, San Juan basin, New Mexico, AAPG Bulletin, vol. 65, no. 12, p. 2546-2570.

Wallace, C. A. and D. C. Jacobs, 2013, The Temple Mountain breccia pipe, Colorado Plateau, Utah - Implications for stratabound mineralization and hydrocarbon accumulation in the Paradox Basin, in Morris, T. H. and R. Ressetar, eds., The San Rafael Swell and Henry Mountains Basin: Geologic Centerpiece of Utah, Salt Lake City, UT, Utah Geological Association Publication 42, p. 415-444.

Wilcox, W. T. and B. S. Currie, 2008, Sequence Stratigraphy of the Jurassic Curtis, Summerville, and Stump Formations, Eastern Utah and Northwest Colorado, in Longman, M. W. and C. D. Morgan, eds., Hydrocarbon Systems and Production in the Uinta Basin, Utah, Utah Geological Association, p. 9-42.

Middle Jurassic Correlation Chart

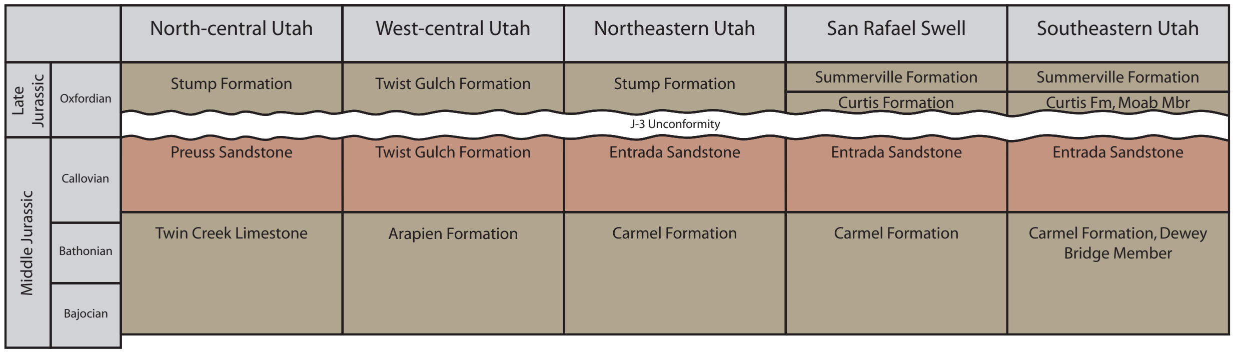


Figure 1: Middle Jurassic nomenclature around Utah. In this paper, the term "Entrada Sandstone" is used to indicate all rocks in Utah deposited at the same time as the Entrada Sandstone, including the Preuss Sandstone to the north (Imlay, 1952) and portions of the Twist Gulch Formation (Perkes and Morris, 2011).

Location Map

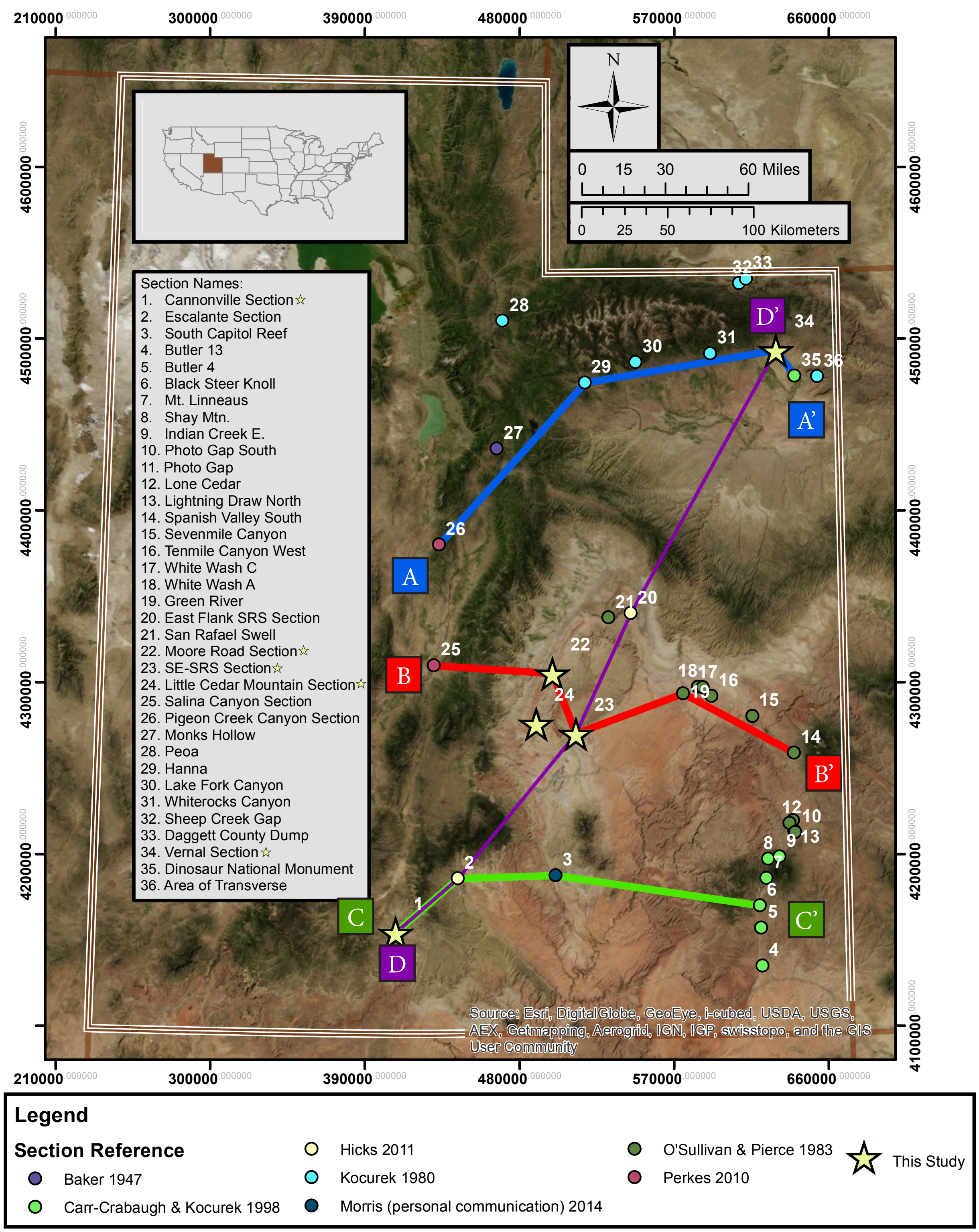
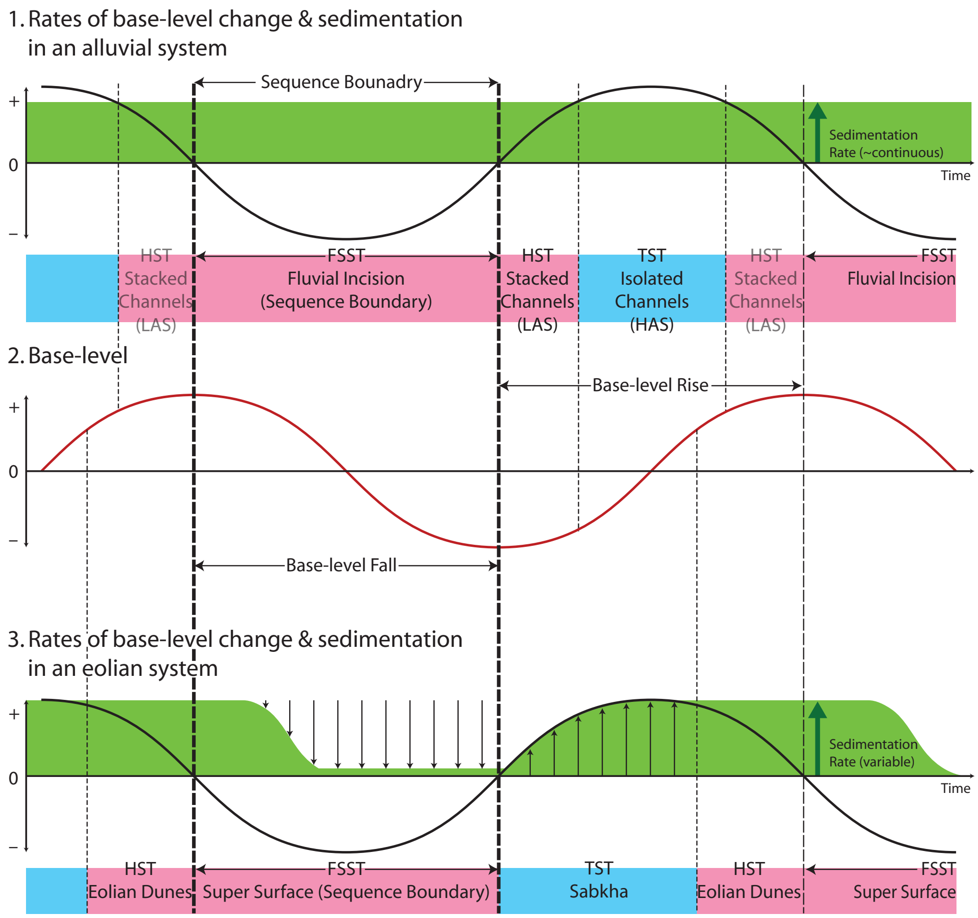


Figure 2: Map showing the locations of all the measured sections used in the study as well as cross section lines for Figures 5-8.

Sequence Stratigraphy of Eolian & Alluvial Systems



HST:	The highstand systems tract (HST) is deposited as the rate of base-level rise slows down to the point where the rate of sedimentation exceeds the rate of base-level rise.
FSST:	The falling stage systems tract (FSST) occurs during base-level fall, and represents a period of erosion or non-deposition. The FSST marks a sequence boundary (SB).
LST:	The lowstand systems tract (LST) is deposited at the onset of base-level rise when the rate of sedimentation exceeds the rate of base-level rise.
TST:	The transgressive systems tract (TST) is deposited when the rate of base-level rise equals or exceeds the rate of sedimentation.

Figure 3: Comparison of a base-level curve (2) and its relationship to alluvial (1) and eolian (3) systems (modified from Catuneanu, 2006). Sequence stratigraphic systems tracts are defined relative to the relationship between base-level and sediment supply. In an alluvial system (1), the HST is comprised of stacked channels (a low accomodation system, LAS), but is rarely preserved due to fluvial incision during the FSST. The FSST marks the sequence boundary. The LST also consists of stacked channels (LAS). The TST is typified by isolated channels (a high accomodation system, HAS). In an eolian system (3), the HST is comprised of eolian dunes. The FSST is represented by a super surface (SB). As base-level drops in the Entrada Sandstone, sediment supply also decreases (Carr-Crabaugh & Kocurek, 1998). As base-level begins to rise, sediment supply also increases at the same rate. This relationship eliminates the LST (as defined above), and allows for the TST to be deposited directly over the super surface. The TST consists of sabkha deposits. Thus, the sequence boundary is marked by the base of the LST (stacked channels) in the alluvial system, and by the base of the TST (sabkha) in the eolian system.

Facies Comparison Chart

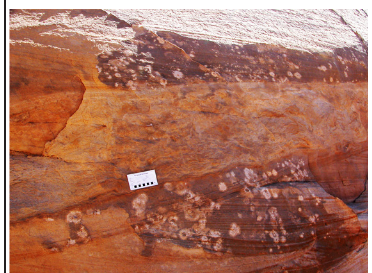
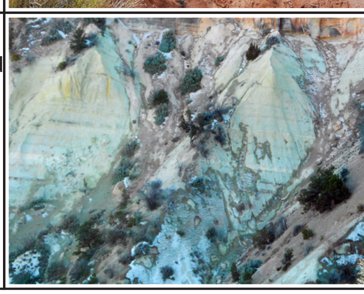
Facies	Identifying Characteristics	Picture	Features Described in the Modern	Depositional Environment
Facies 1a	Very fine to fine sandstone with high angle TCS; Occasional carbonate grains present.		High angle TCS. The influence of a coastal supply of carbonate sand carried through eolian processes have been detected at least 170 km inland. Coastal sediments have also been deposited through eolian processes up to 850 m above sea level (Glennie, 1970).	Eolian Dune
Facies 1b	Horizontally laminated/algal matted sandstone typically bounded by high angle TCS		Horizontally laminated/algal matted sandstone. Sub-aqueous, eolian, and evaporitic sedimentary structures may be present depending on the type of interdune. Sedimentary structures may be obliterated by intense bioturbation. Interdune deposits tend to be thinner and less continuous than sabkha or sand sheet deposits (Fryberger, 1983).	Interdune
Facies 1c	White, well rounded & sorted fine sandstone with local fine to medium laminae. Planar to low angle laminations dominate with some soft sediment deformation and ripple produced strata. Forms latterly continuous beds.	 	Horizontal to low angle laminae are prevalent. Sand sheet deposits transition into eolian dune and interdune deposits. Sedimentary structures may appear similar to interdune facies, but sediments are thicker, less variable, and much more laterally extensive. Other common sedimentary structures may include ripple-produced strata and massive mottled sands that are horizontally extensive and several feet thick (Brookfield & Silvestro, 2010; Fryberger 1983).	Sand sheet
Facies 1d	Massive to faintly laminated yellow-gray siltstone that is almost unconsolidated. Always closely associated with eolian deposits.		Any terrestrial clastic sediment, composed predominantly of silt-sized particles which are deposited by wind processes. It is often modified by local reworking, bioturbation, and syn-depositional weathering. Loess may transition into a sand sheet (Pye, 1996).	Loess

Figure 4: Facies comparison chart describing what the facies look like in the Entrada Sandstone and how they compare to analogous modern depositional environments. Photos illustrate what each facies in the Entrada looks like in outcrop. Facies 1a-d are associated with an erg system.

Facies Comparison Chart (Cont.)

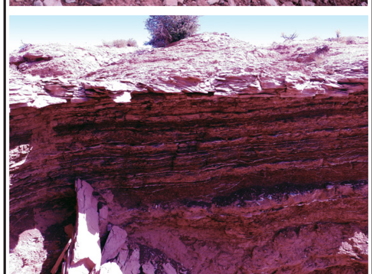
Facies	Identifying Characteristics	Picture	Features Described in the Modern	Depositional Environment
Facies 2a	"Massive" siltstone to very fine sandstone with occasional fine to medium grains with mud breaks in between layers. Mud rip ups sometimes present at the base of channels. Often weathers into hoodoos.	 	Channels fill with their own sediment and create braided patterns. Sedimentary structures range from low to high flow regimes. Clay is often deposited as the last of the water seeps into the ground. Dessication cracks often form in the clay and may be ripped up during the next flood (Glennie, 1970). Massive silt/mud may be deposited in abandoned channels (Miall, 2010).	Alluvial Channel
Facies 2b	Rippled gray siltstone (commonly 5-10cm thick) containing sigmoidal & climbing ripples with multiple current directions. Beds pinch and swell with soft sediment deformation. Gray beds are separated by massive red cover/mud occasionally with dessication cracks.	 	Flood deposits may consist of sands with steep foresets, horizontally laminated sands, and sets of climbing ripples (Glennie, 1970). They may also have faintly laminated to massive sands. However, they are generally horizontally laminated (McKee, 1967). Massive silt/mud with dessication cracks may be indicative of overbank deposits (Miall, 2010).	Alluvial Plain
Facies 3	Siltstone to very fine sandstone with "chippy" to "whispy" laminae. May contain dessication cracks and replaced evaporite nodules.		Algae are known to exist, but algal mats are typically not recognized. Wavy laminations are the most common sedimentary structure. Haloturbation may create disturbed bedding. Sedimentation occurs from wadis and wind adhesion. In the modern, inland sabkhas cover much more area than do coastal sabkhas (Glennie, 1970).	Inland Sabkha (Playa)

Figure 4 (Cont.): Facies 2a and 2b are associated with an alluvial system. Facies 3 is associated with an inland sabkha system.

Waltherian Succession

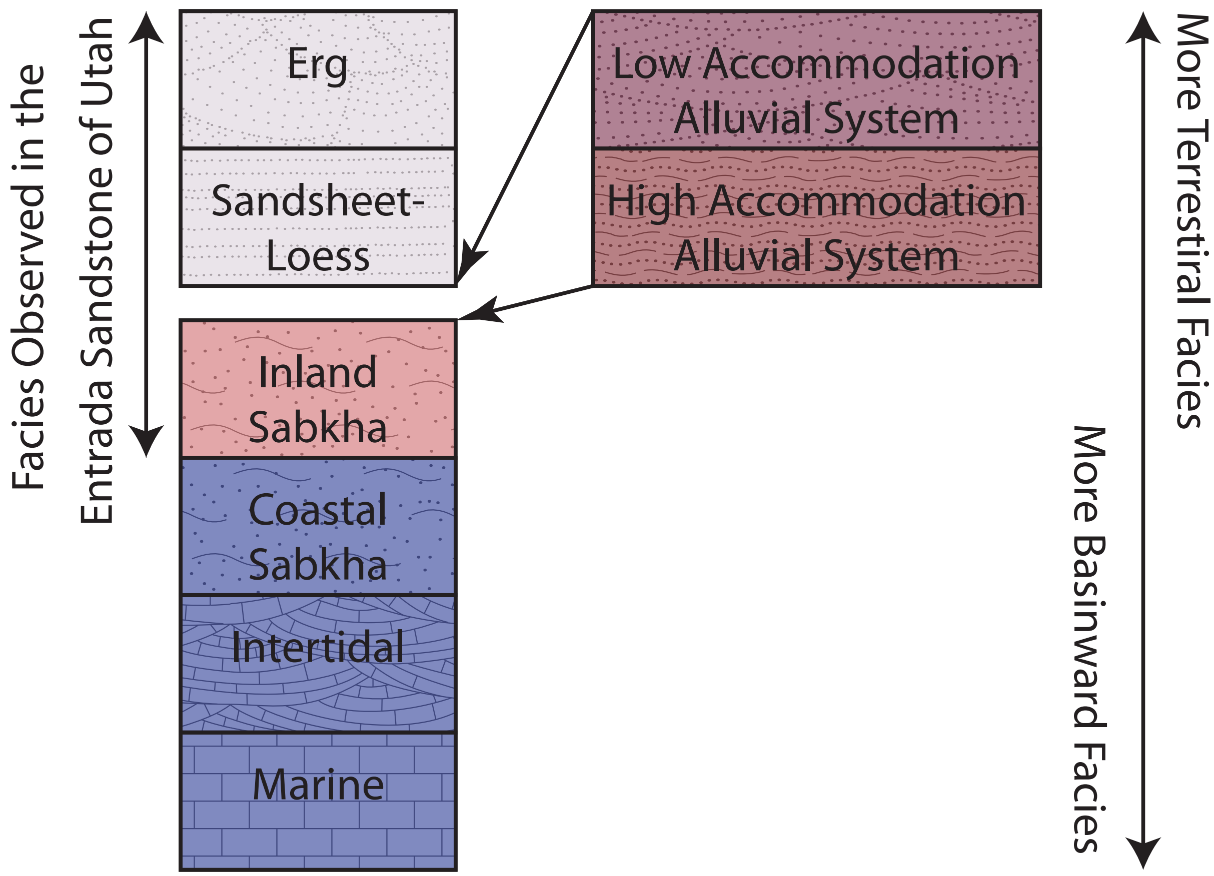


Figure 5: Idealized Waltherian succession in a typical desert environment. Sabkha facies may be overlain by either alluvial or eolian facies and still be considered a Waltherian succession. However, when alluvial and eolian facies interfinger, eolian facies are typically deposited over alluvial facies. Sequence boundaries are identified in the measured sections either where more basinward facies overlie more terrestrial facies, or by the base of low accommodation alluvial systems.

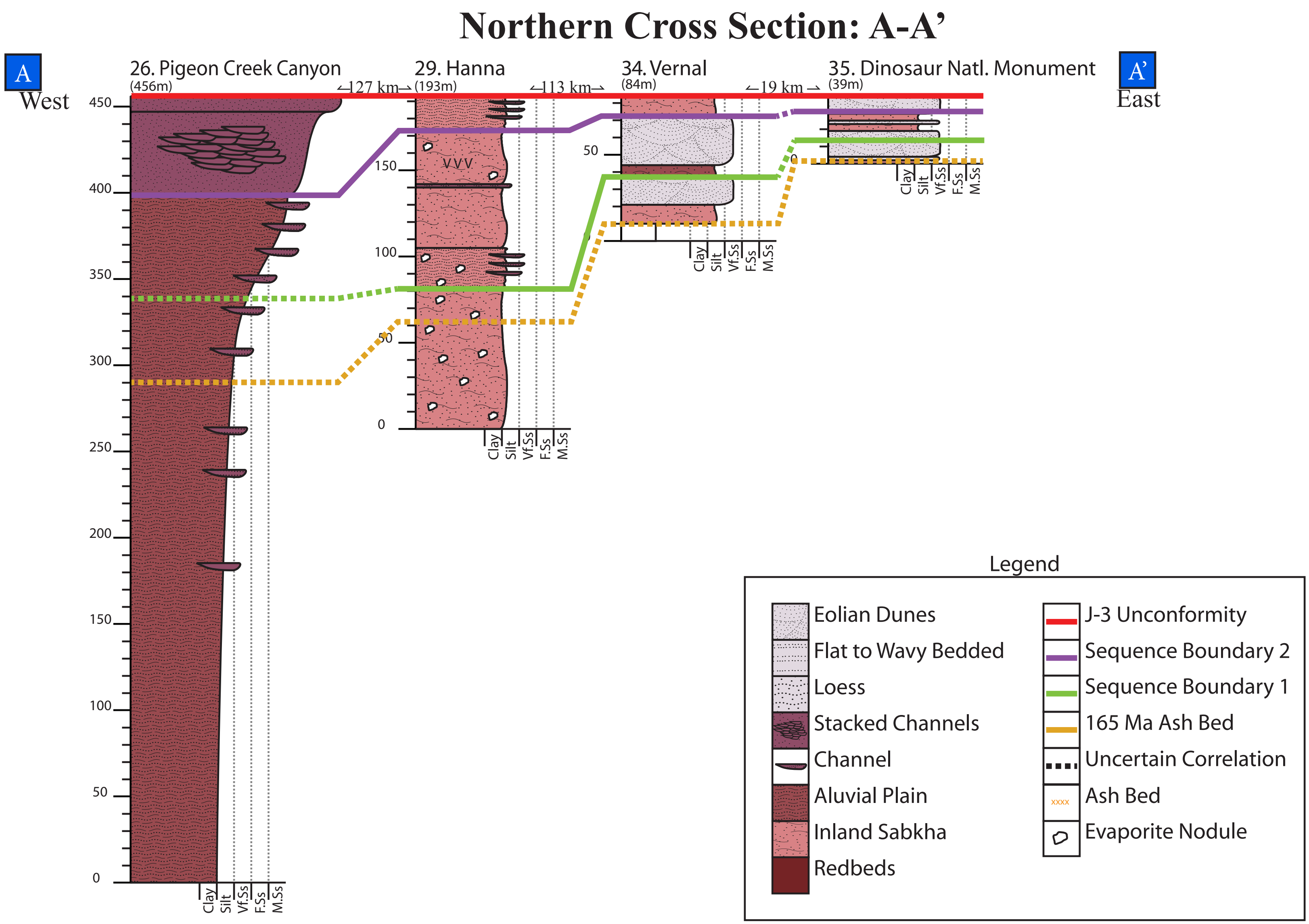


Figure 6: Northern cross section (A-A') in Figure 2. Note in figures 5 through 7 the dramatic thickening of sediments westward, towards the edge of the Jurassic foredeep.

Central Cross Section: B-B'

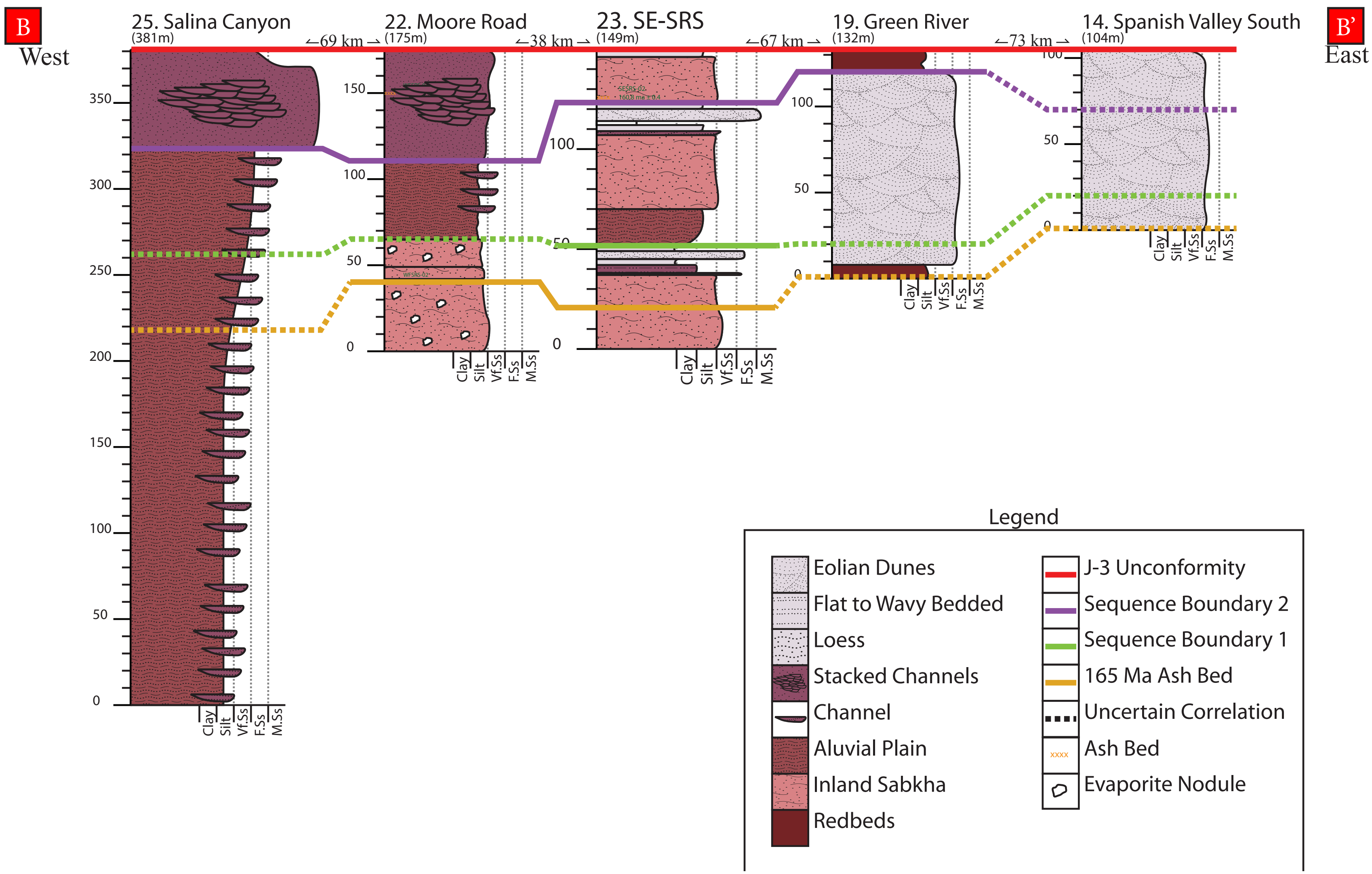


Figure 7: Central cross section (B-B') in Figure 2.

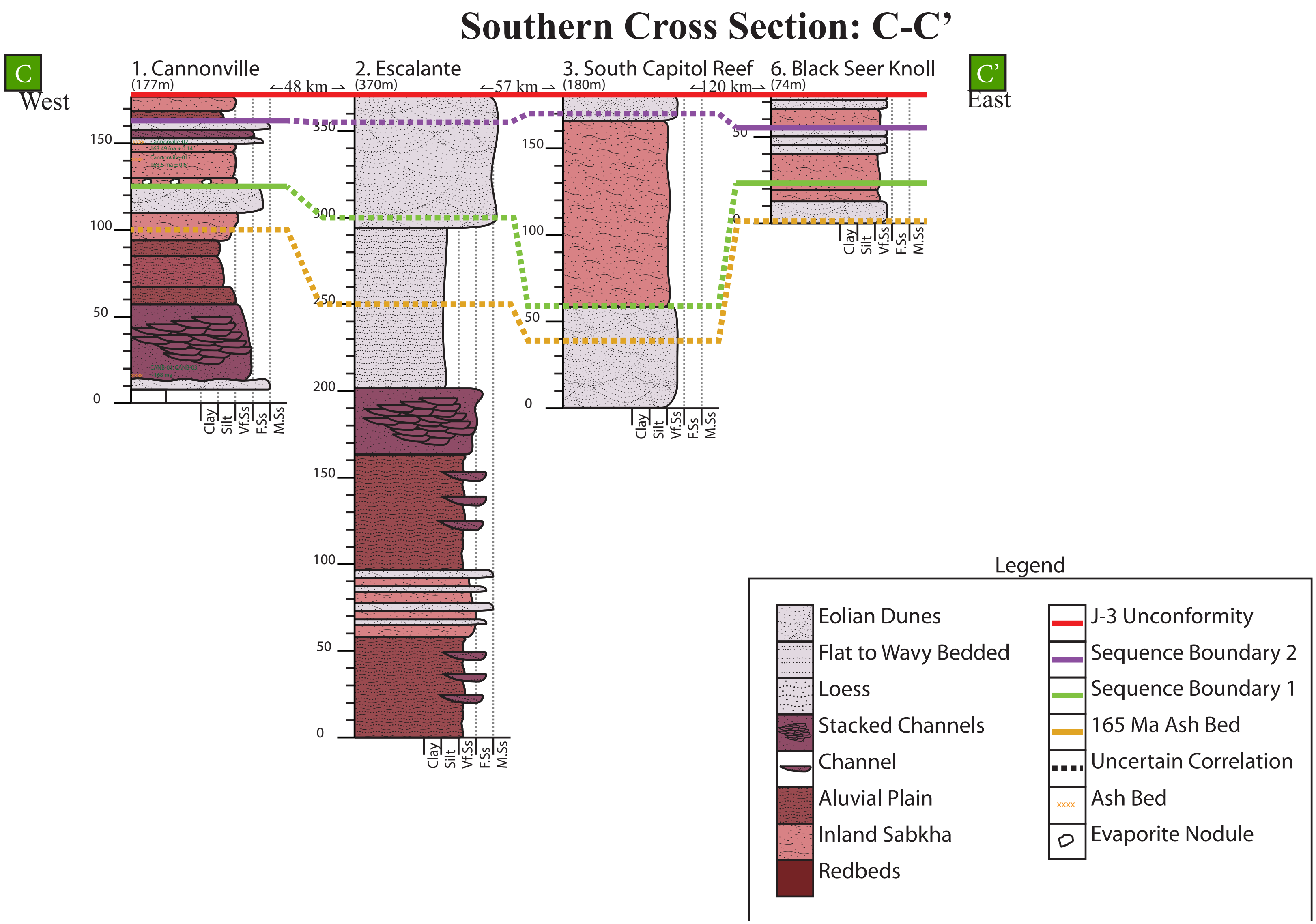


Figure 8: Southern cross section (C-C') in Figure 2. The Cannonville section is thought to be anomalously thin due to more significant erosion at this location during the J-3 Unconformity than in most other places in Utah (Peterson, 1988b).

Southwest to Northeast Cross Section: D-D’

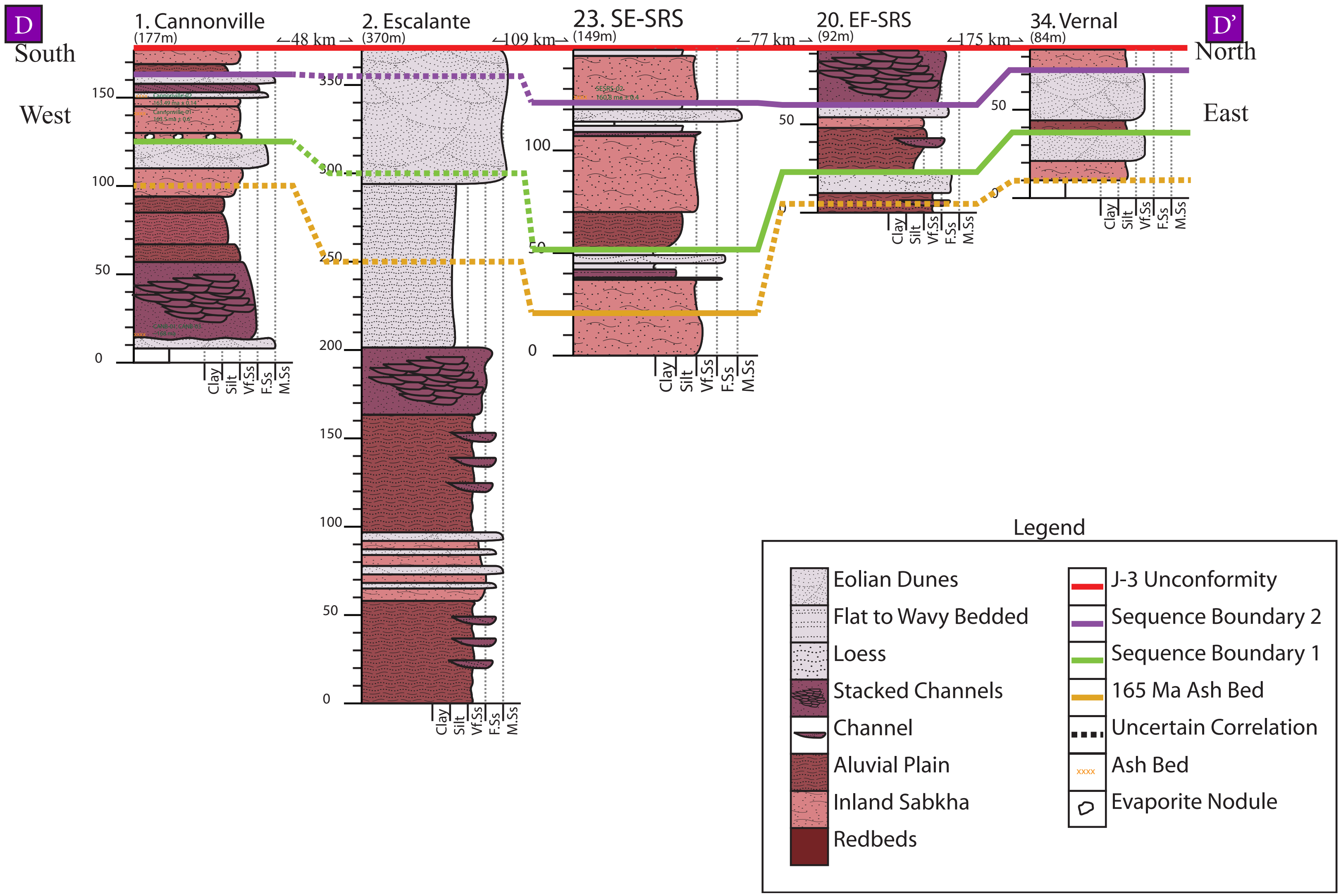


Figure 9: Southwest to northeast cross section (D-D’) in Figure 2. The Cannonville section is thought to be anomalously thin due to more significant erosion at this location during the J-3 Unconformity than in most other places in Utah (Peterson, 1988b).

Isopach Map of the Total Thickness of the Entrada

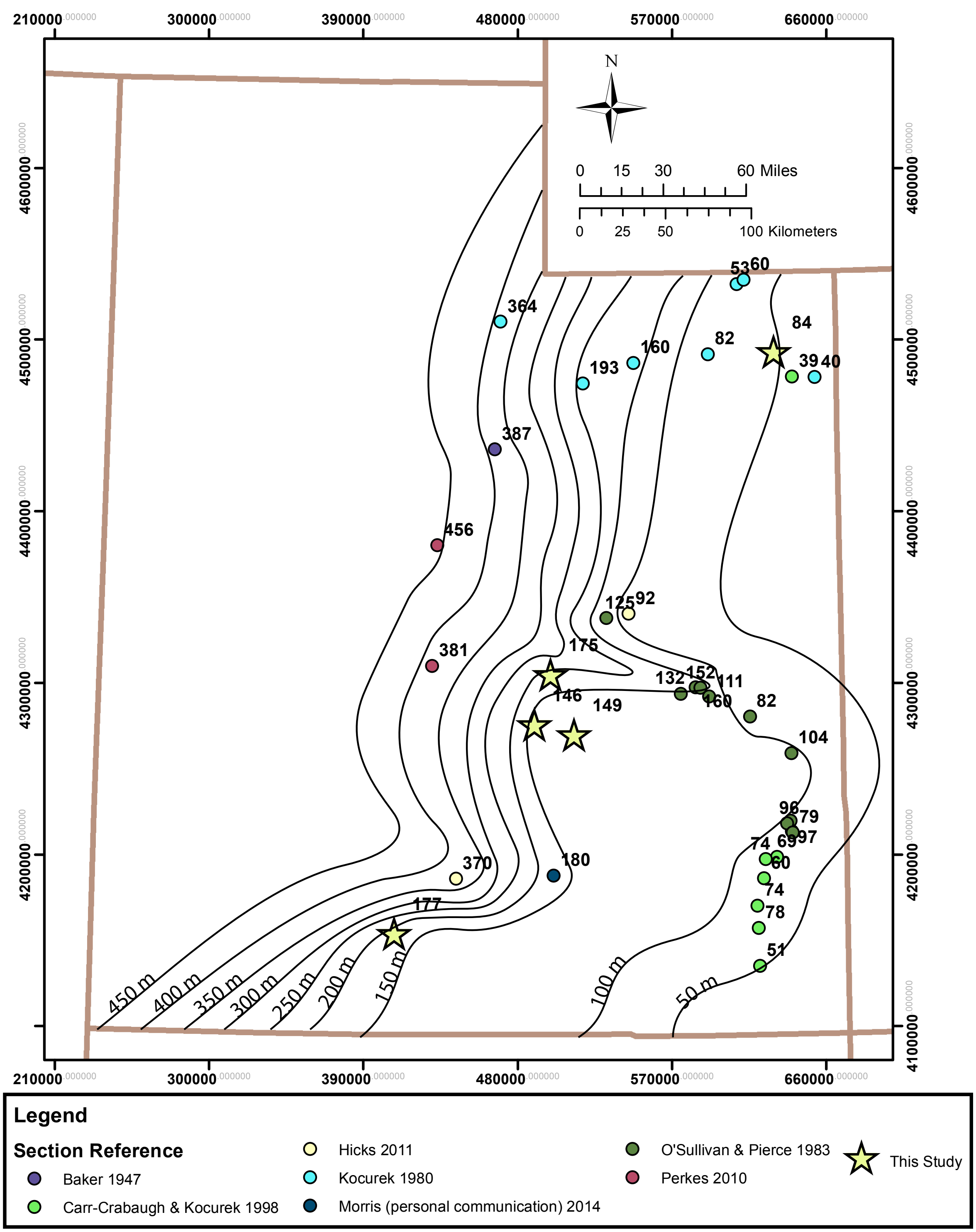


Figure 10: Isopach map of the total thickness of the Entrada Sandstone. The Entrada Sandstone thickens dramatically westward towards the Jurassic foredeep. Note the NNE to SSW orientation of the foreddep's eastern edge. Evidence of a forebulge is subtle but may be indicated by the flattening observed in the south-central to south-eastern area of Utah.

Isopach Maps of Entrada Thickness Through Time

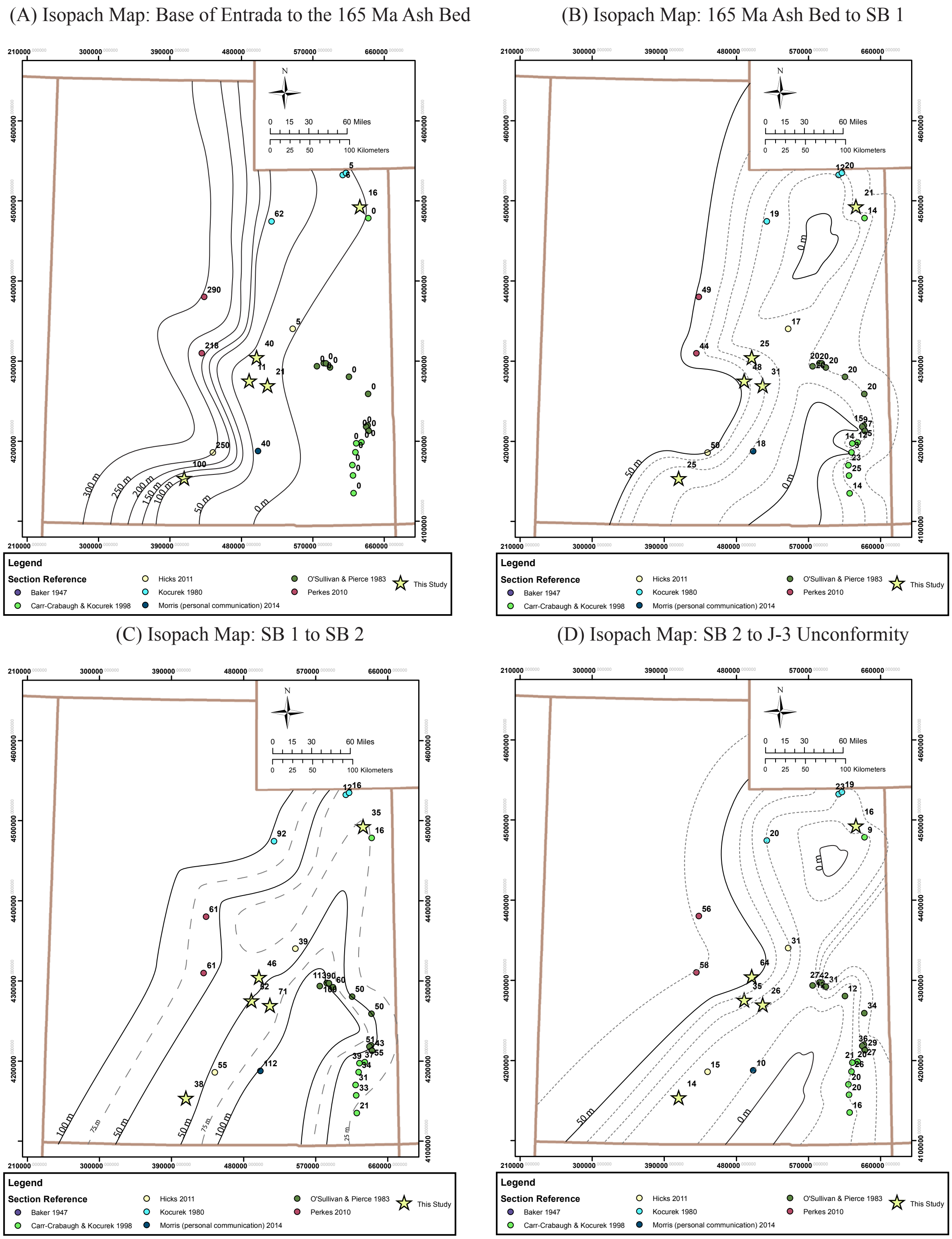


Figure 11: A series of isopach maps illustrating the active evolution of the Jurassic retroarc foreland trough through time. Note the presence of ephemeral, segmented, areas of thinning in B and D. These thin areas likely represent paleotopographic highs that may indicate the tectonic forebulge trending roughly north-south.

Facies at the Tephra of Moore Road

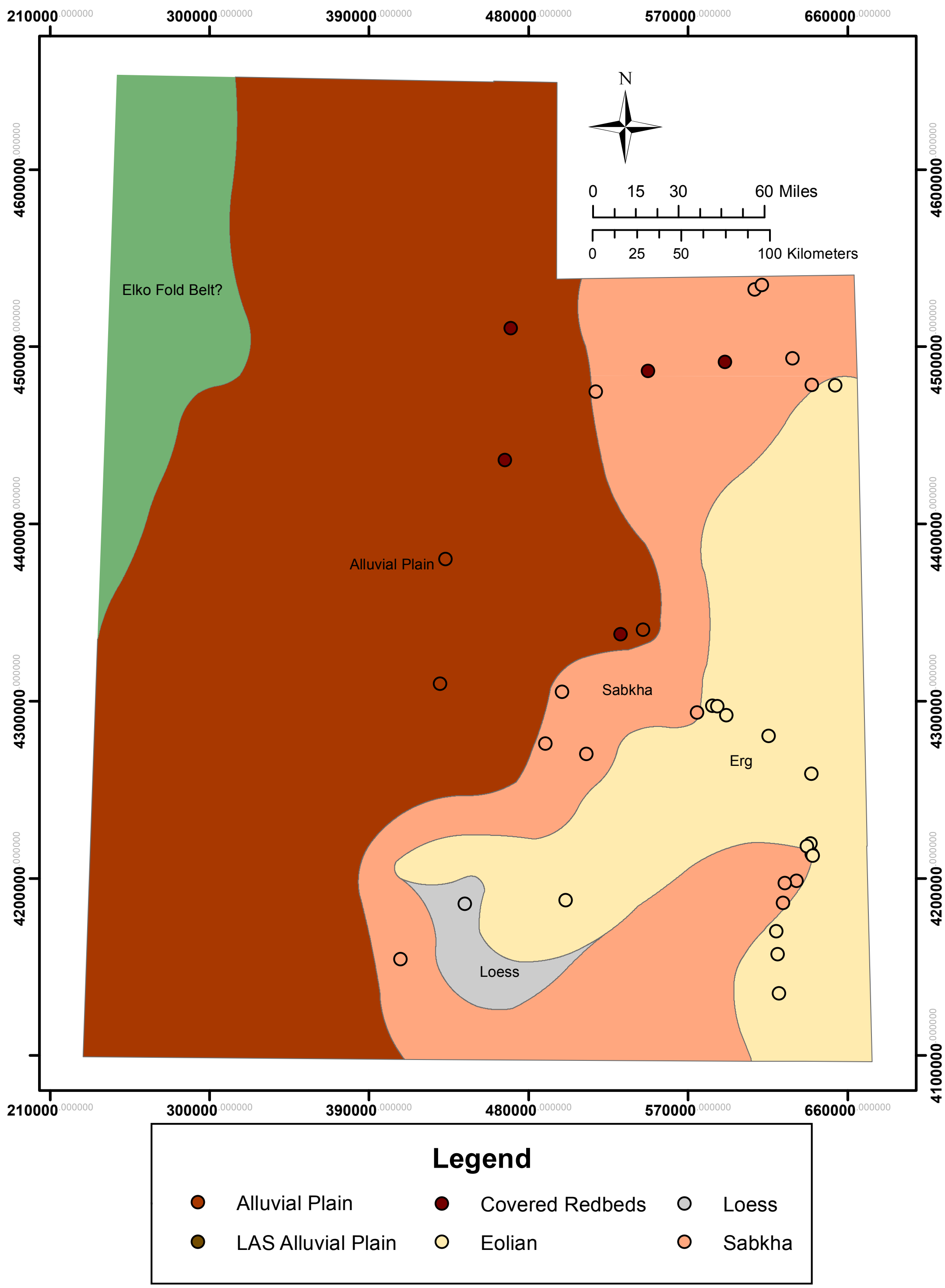


Figure 12: Paleogeographic reconstruction of the facies surrounding the tephra of Moore Road. Note the minimum extent of the erg, and the presence of a large loess deposit in south-central Utah.

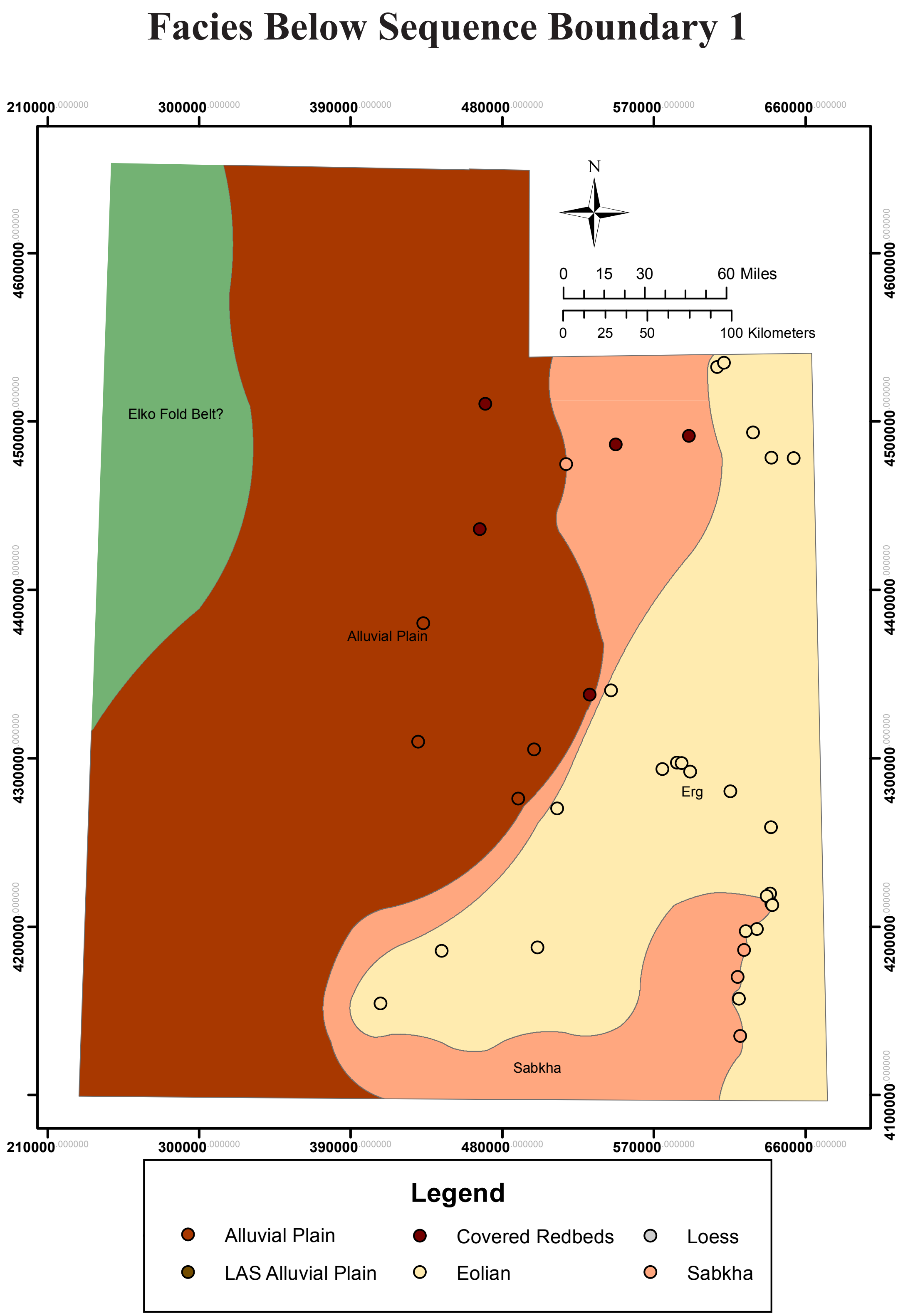


Figure 13: Paleogeographic reconstruction illustrating the facies present just below Sequence Boundary 1. Both eolian (east to west) and alluvial (west to east) systems have advanced significantly from the locations shown in Figure 12.

Facies Above Sequence Boundary 1

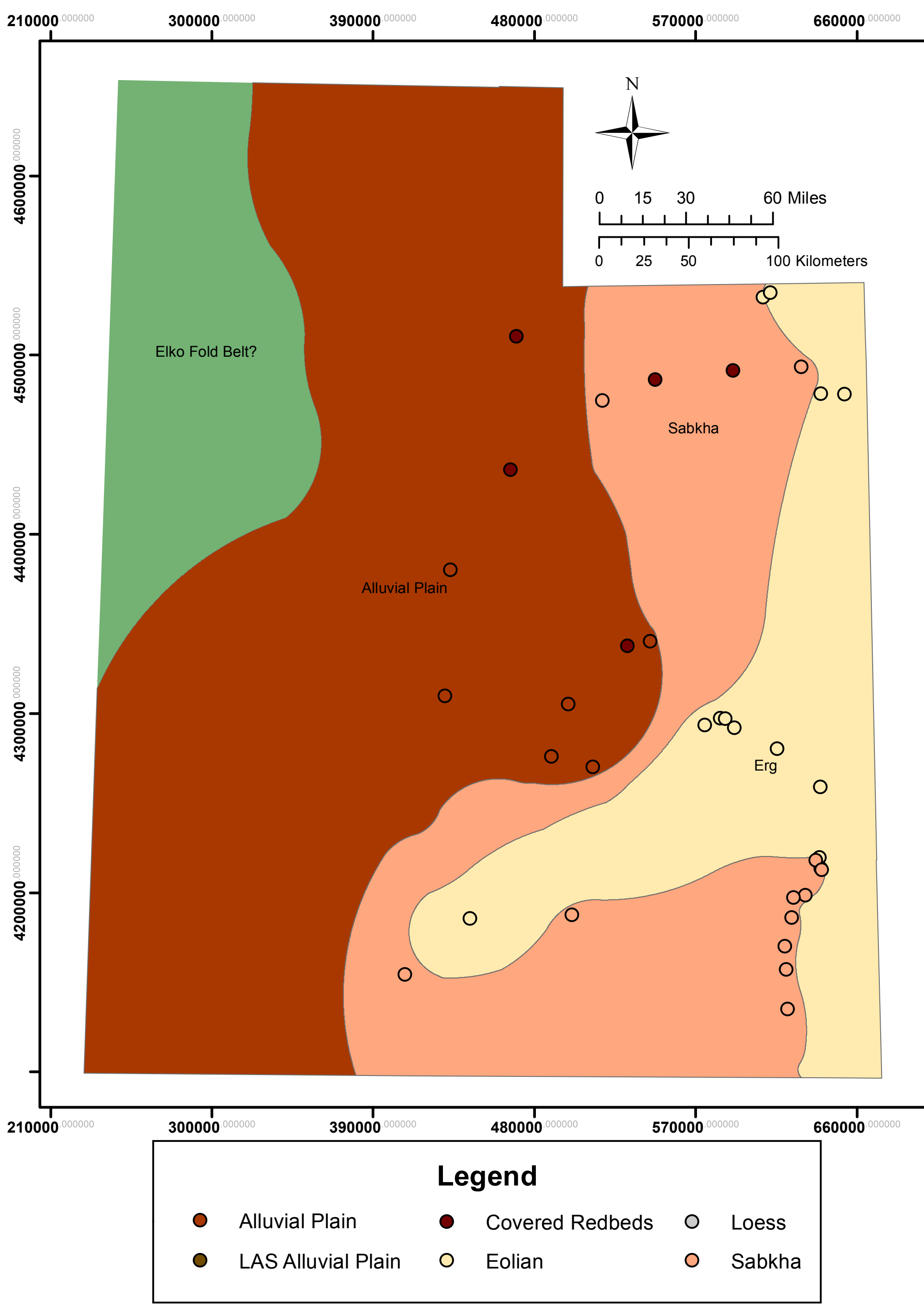


Figure 14: Paleogeographic reconstruction of the facies present in the Entrada Sandstone just above Sequence Boundary 1. Note the dramatic contraction of the eolian facies as well as the continued eastward advancement of the alluvial facies.

Facies Below Sequence Boundary 2

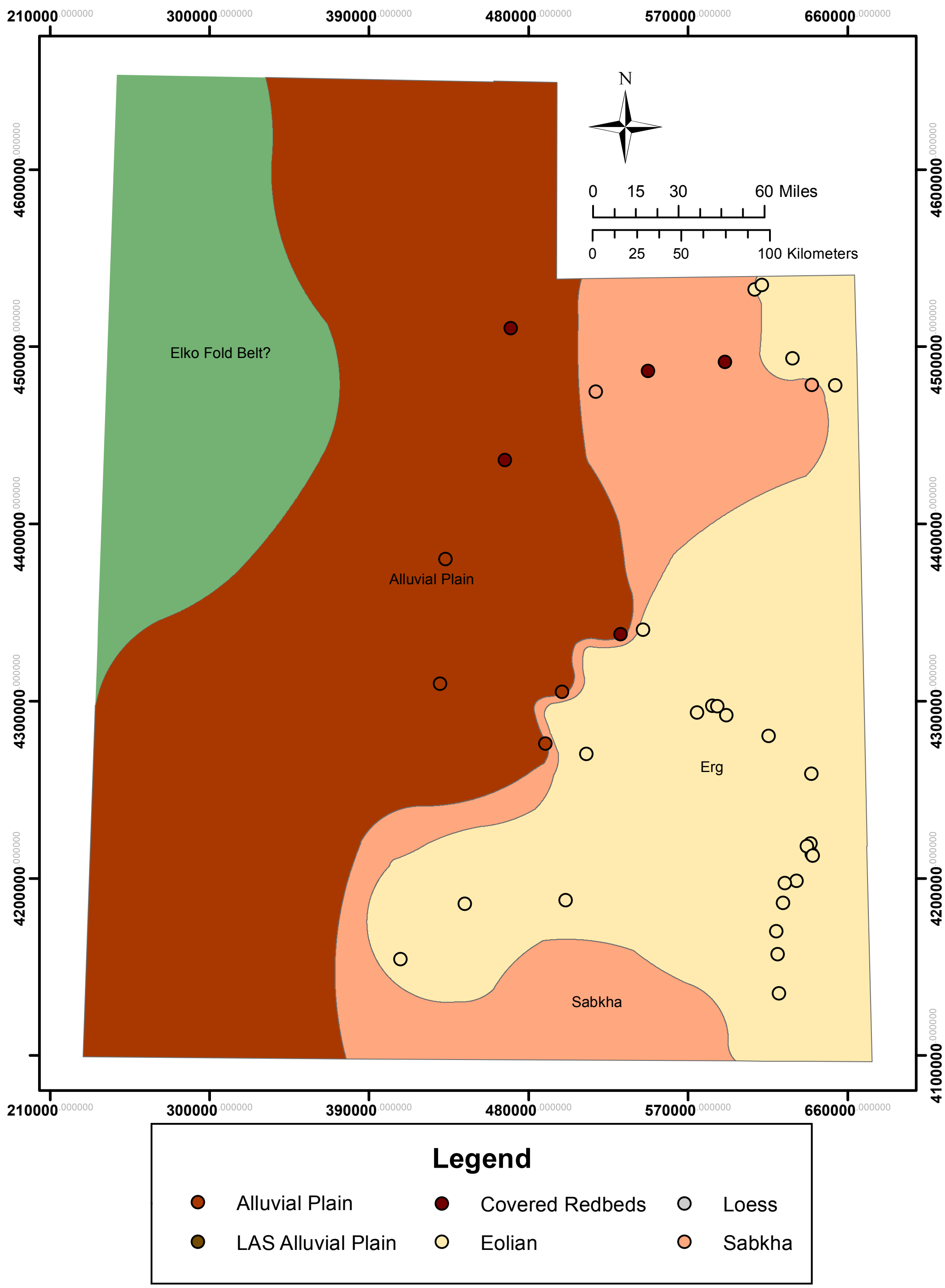


Figure 15: Paleogeographic reconstruction of the facies below Sequence Boundary 2. At this instance in time the Entrada erg is once again at a maximum extent. The alluvial system has also retreated westward.

Facies Above Sequence Boundary 2

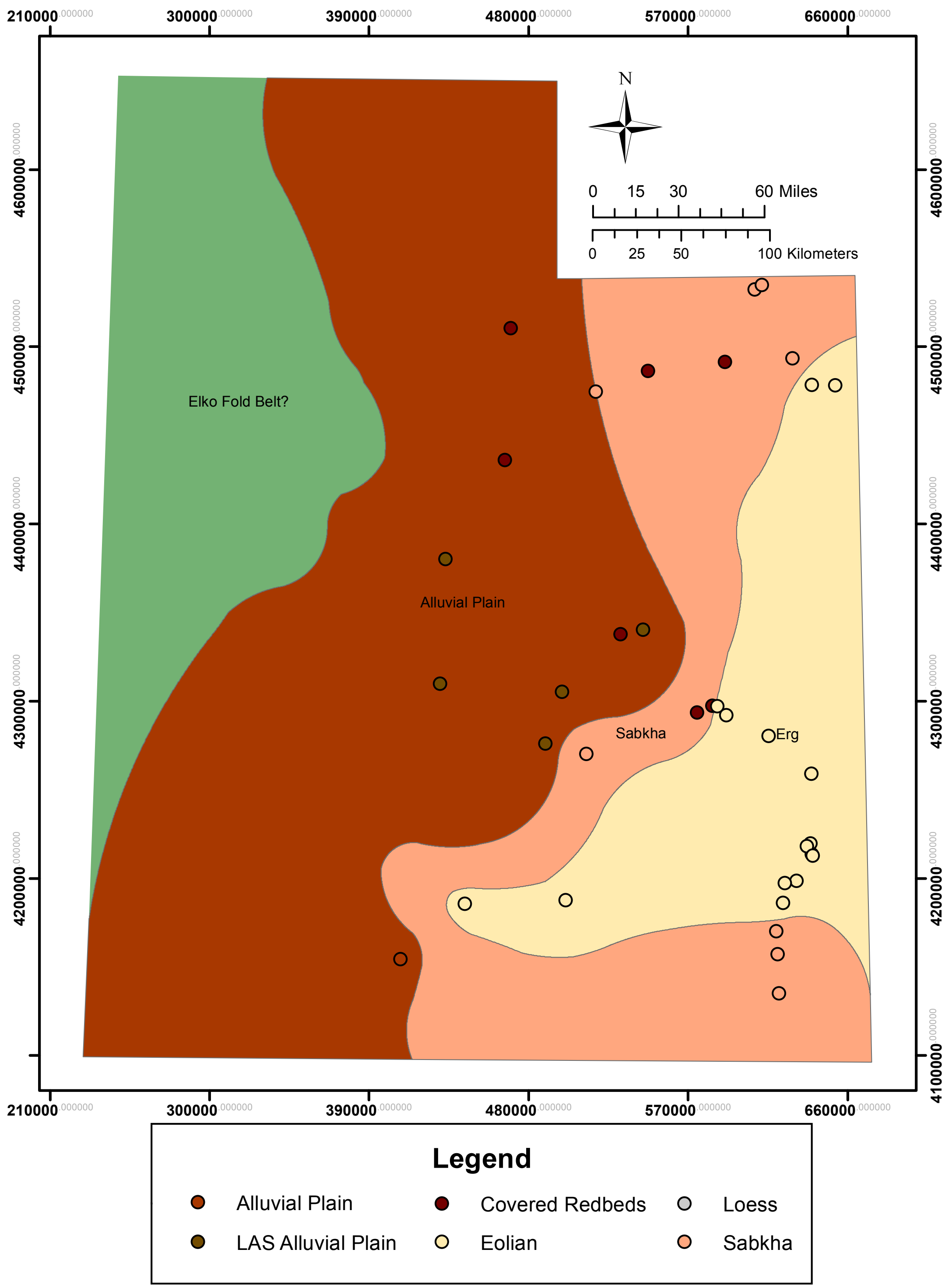


Figure 16: Paleogeographic reconstruction illustrating the facies directly above Sequence Boundary 2. The erg has once again retreated significantly and stacked channel facies, representative of a low accommodation system (LAS), in the alluvial sections have moved eastward.

Dead Oil in the Entrada Sandstone

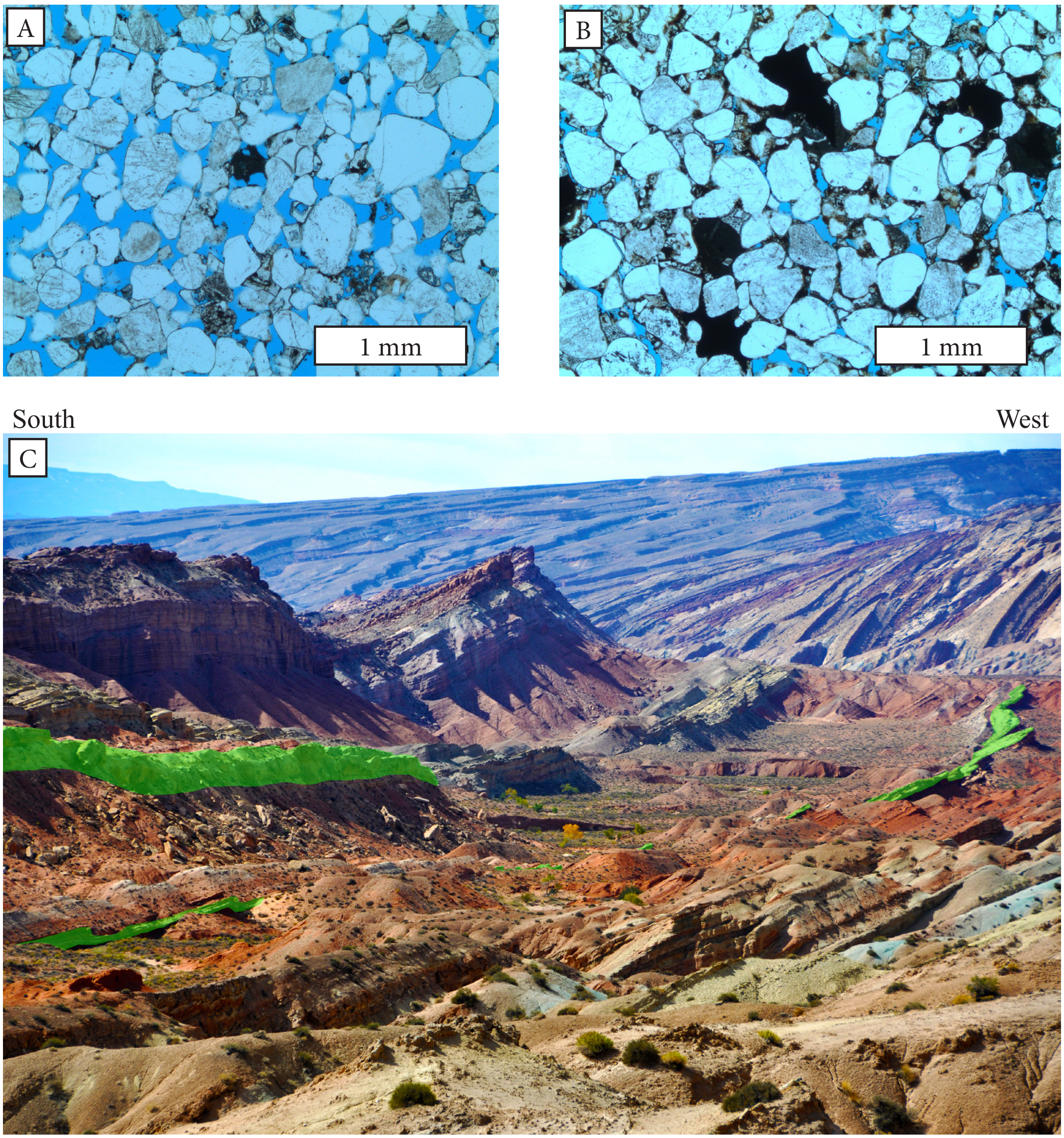


Figure 17: Tar sands from the upper (A) and lower (B) eolian units in section 23. SE-SRS. Note the pore-filling residual tar. The stratigraphic pinch-out of the eolian units in this section into muddy redbeds on the San Rafael Swell (C) creates combination hydrocarbon traps in the Entrada Sandstone. Photograph C is annotated to illustrate eolian sandstones, highlighted in green. Note that while the lower sandstone continues westward, the upper sandstone pinches out.

Desert Facies Associations

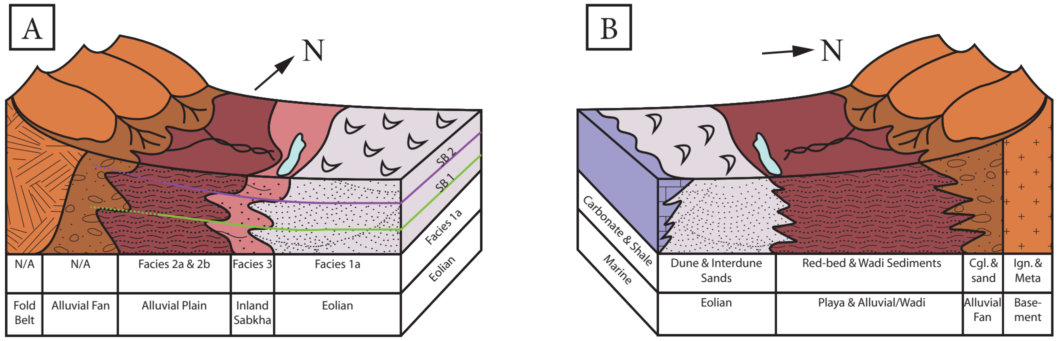
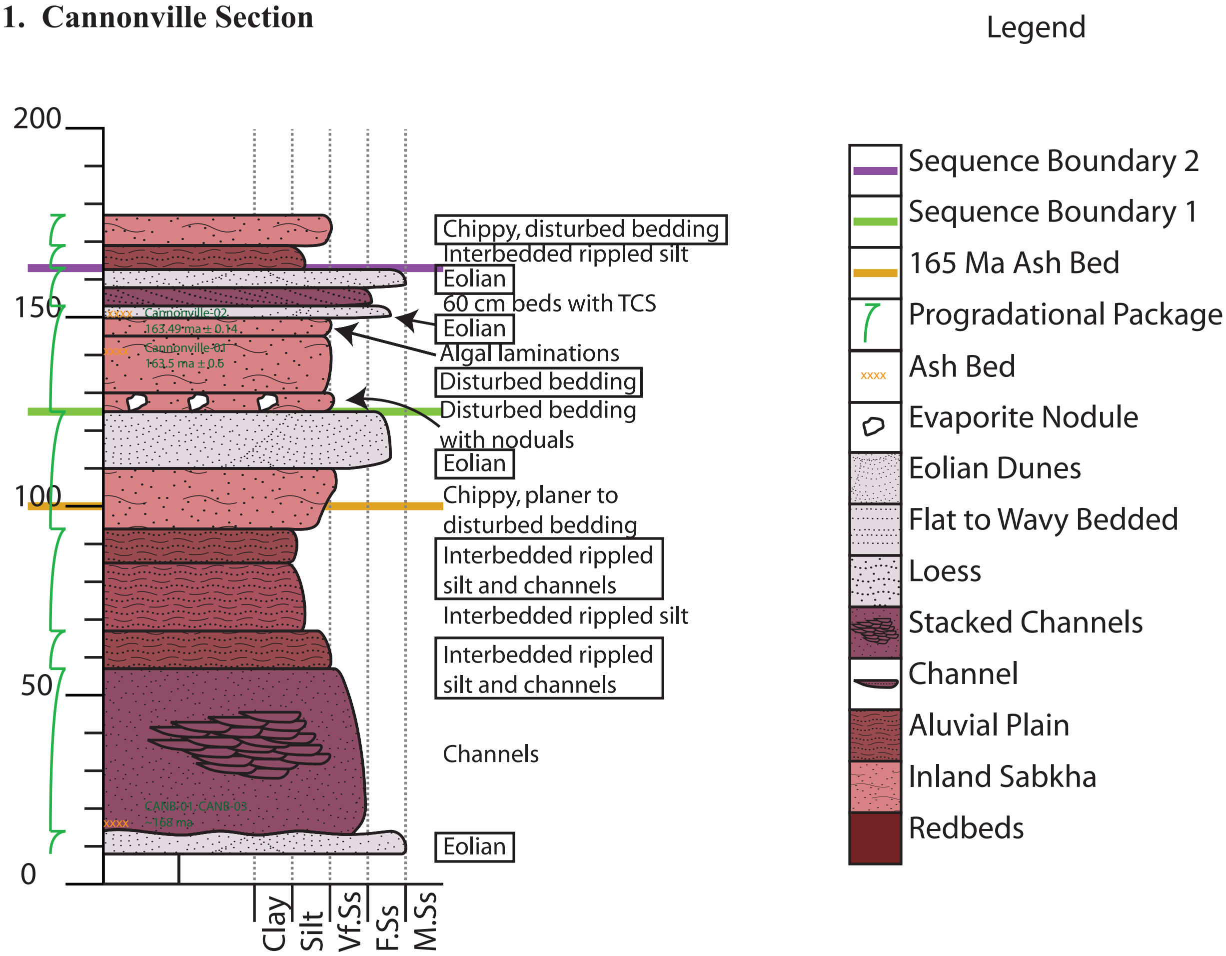


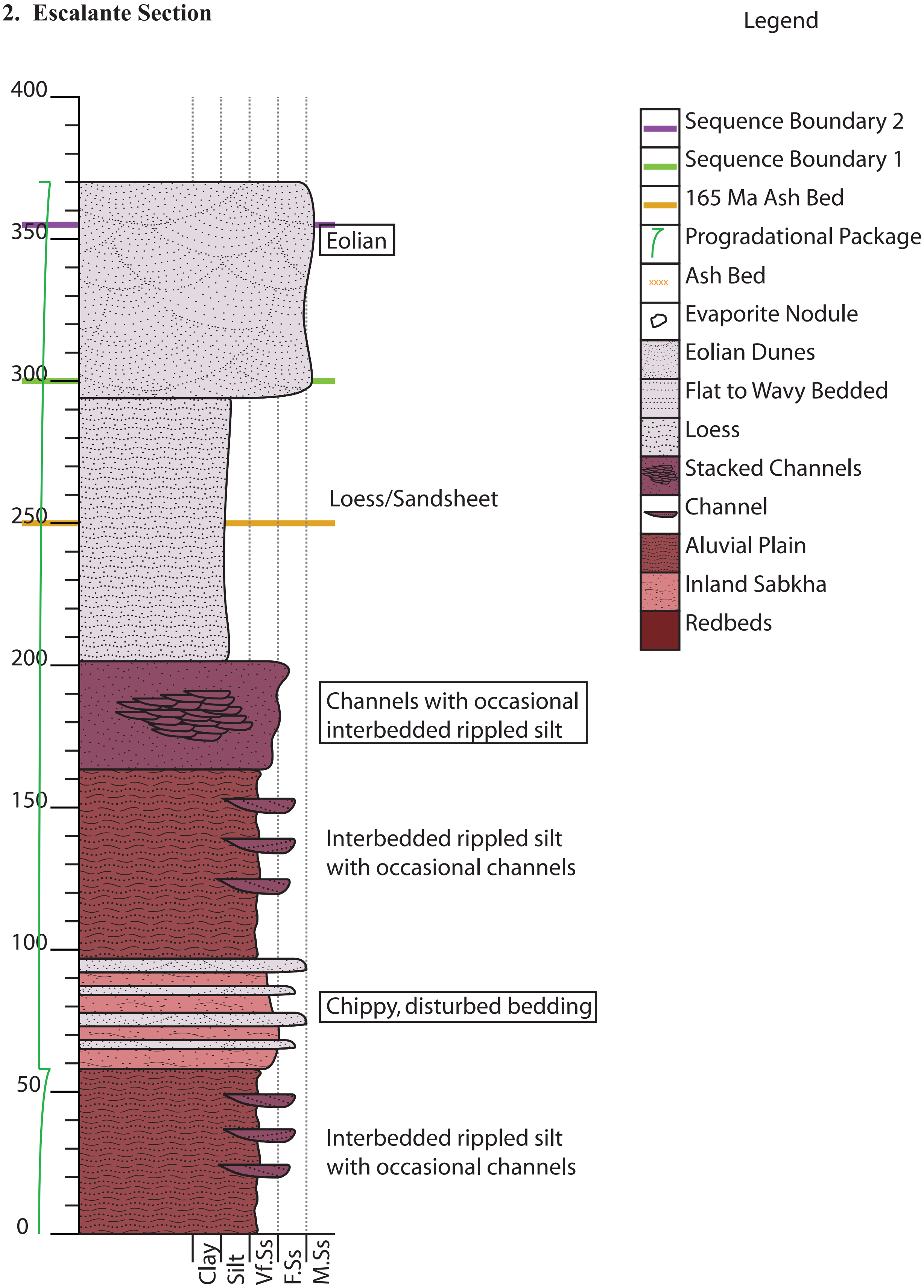
Figure 18: Generalized facies comparison between the Entrada Sandstone (A) and the Norphlet Formation (B). The Norphlet Formation block diagram is modified from Mancini et al. (1985), and Marzano, et al. (1988). In the Entrada Sandstone (A) note the expansions of the erg below sequence boundaries 1 & 2. The pinch-out of eolian facies into the muddy portion of the Entrada Sandstone creates a potential stratigraphic or combination trap. Similar traps may be present in the petroliferous Norphlet Sandstone (B) in the Gulf of Mexico.

APPENDIX A: MEASURED SECTIONS

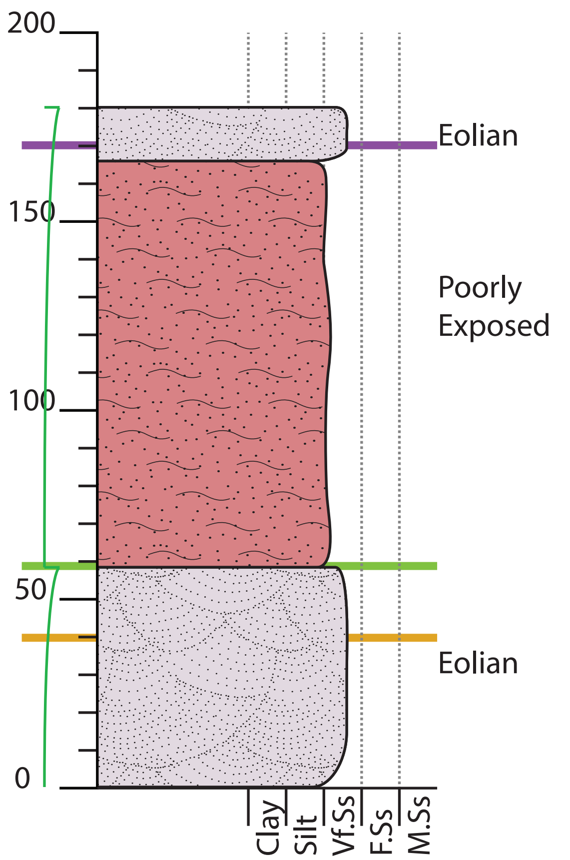
1. Cannonville Section

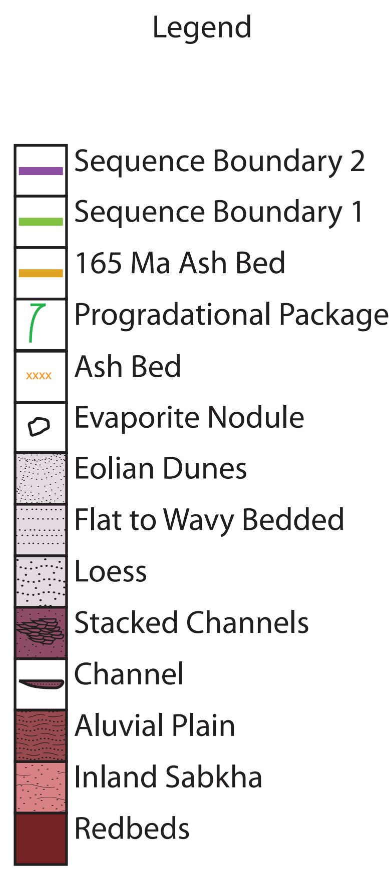


2. Escalante Section

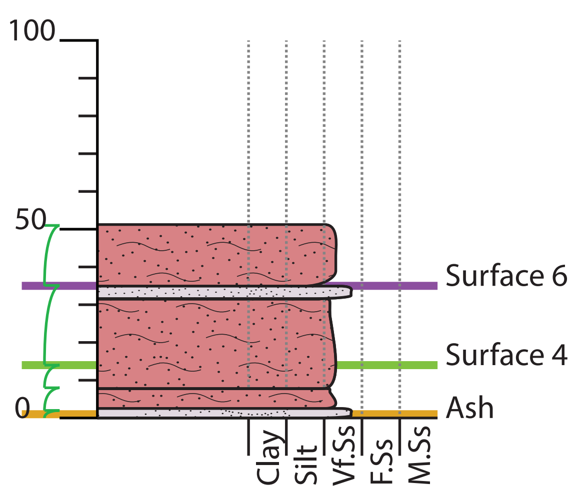


3. South Capitol Reef

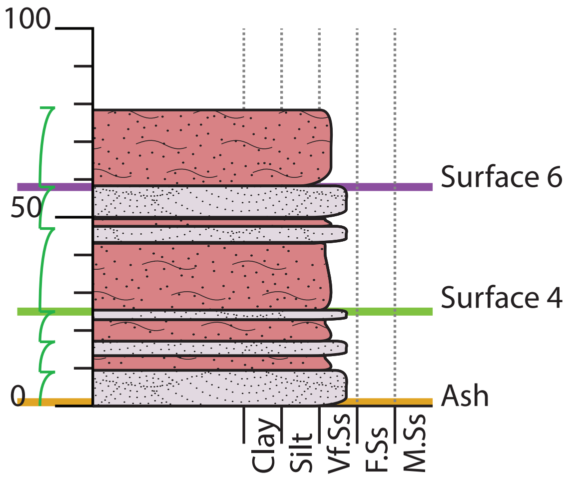




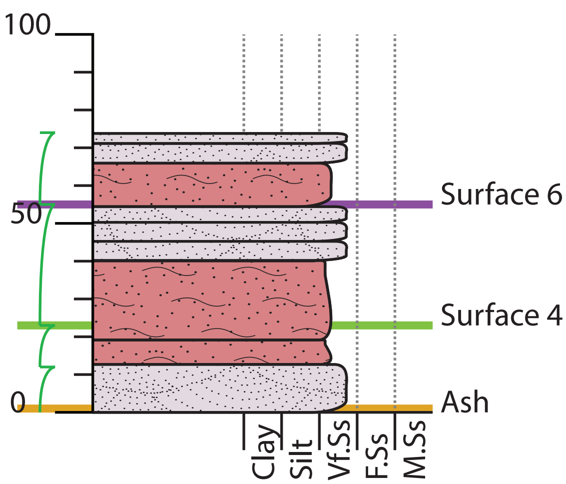
4. Butler 13



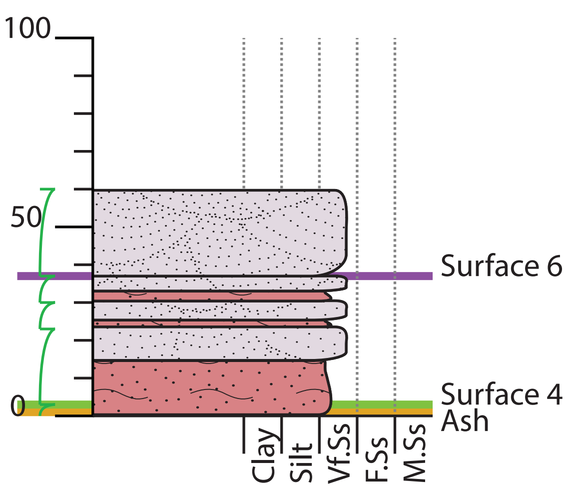
5. Butler 4

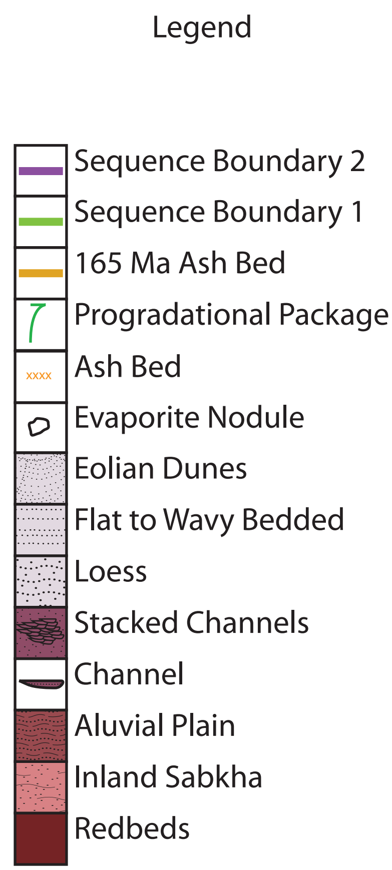


6. Black Steer Knoll

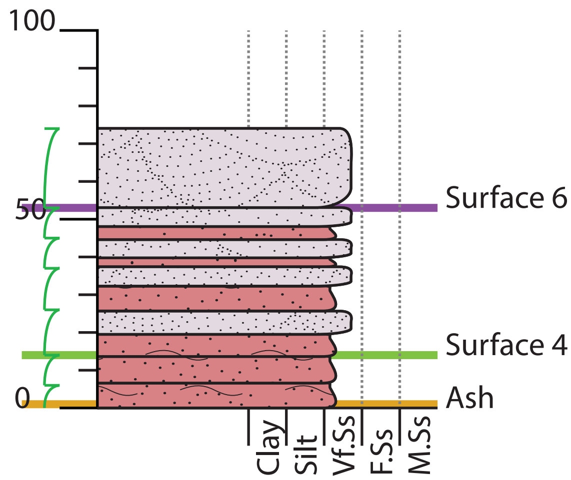


7. Mt. Linneaus

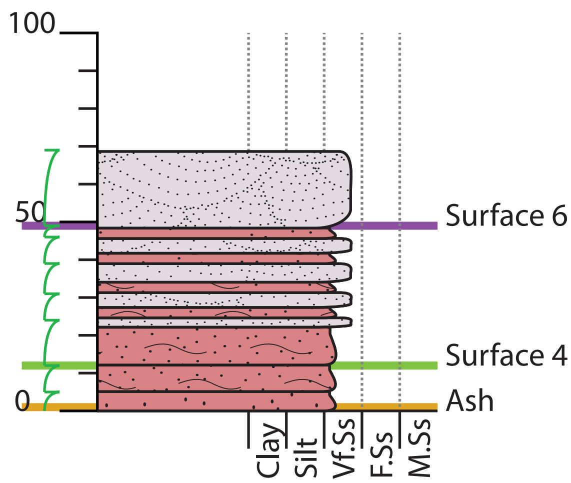




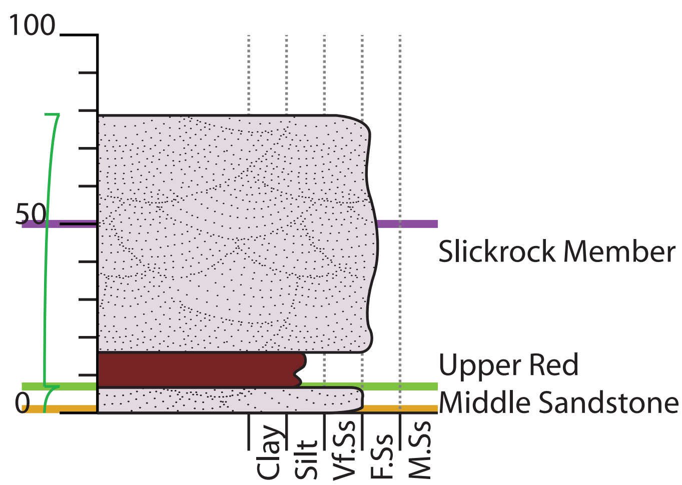
8. Shay Mountain



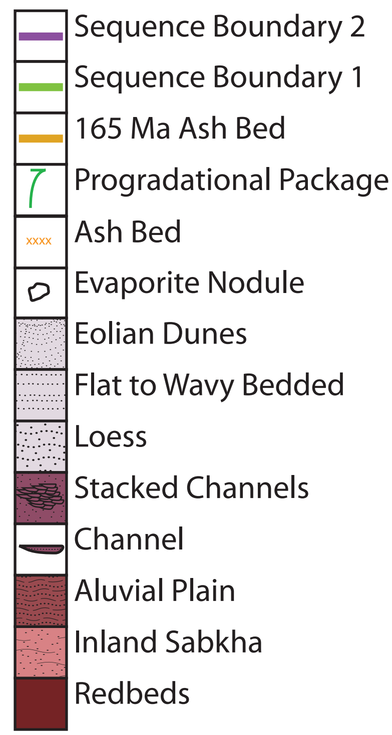
9. Indian Creek E.



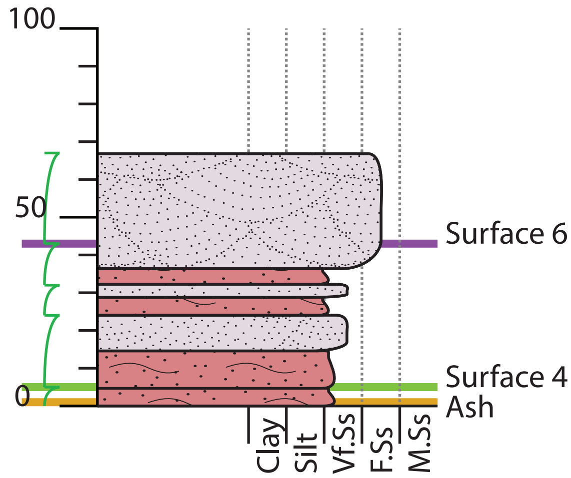
10. Photo Gap South



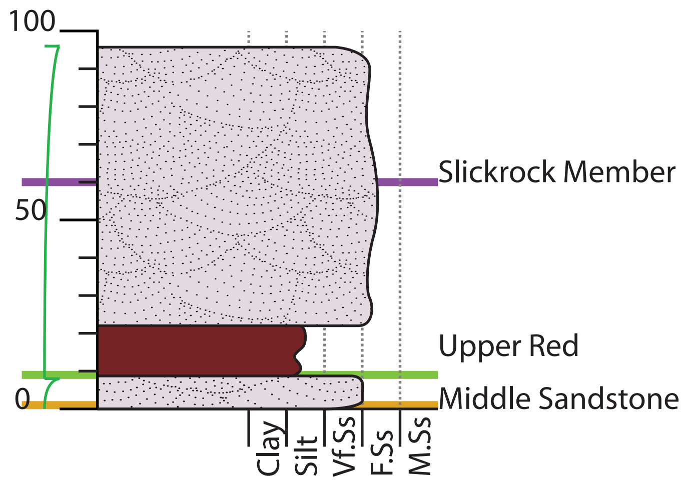
Legend



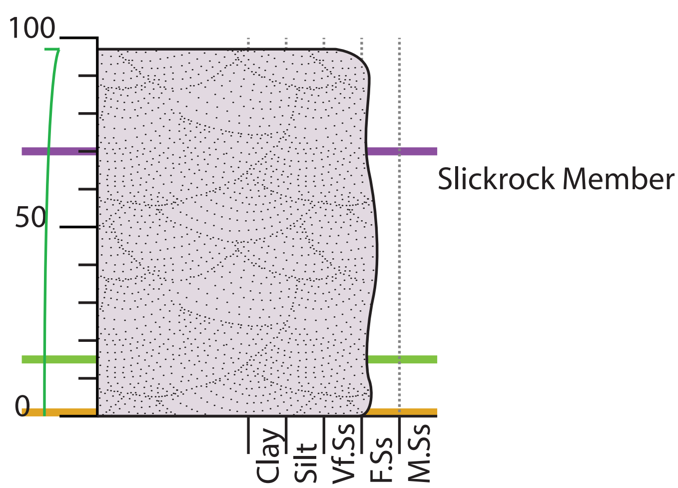
11. Photo Gap

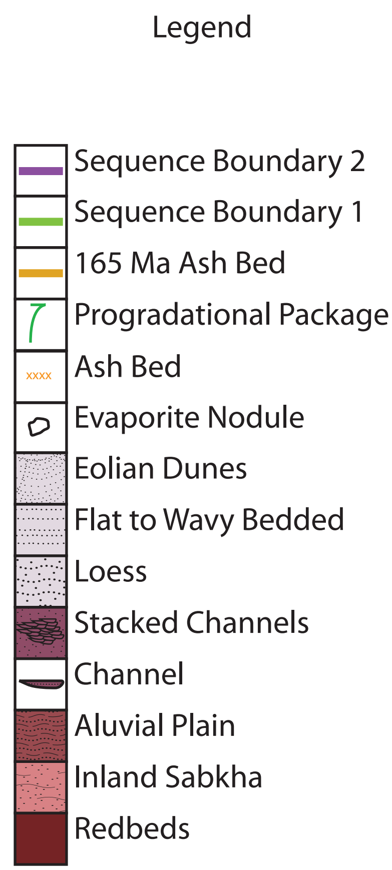


12. Lone Cedar

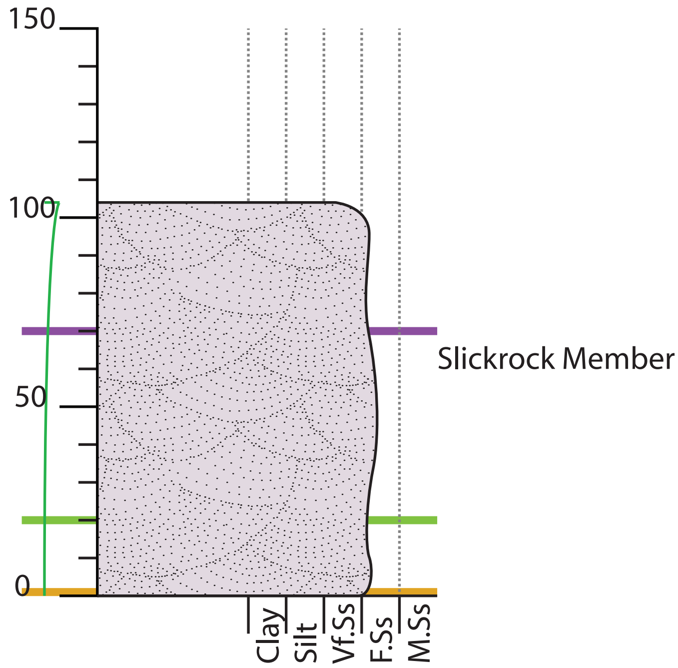


13. Lightning Draw North

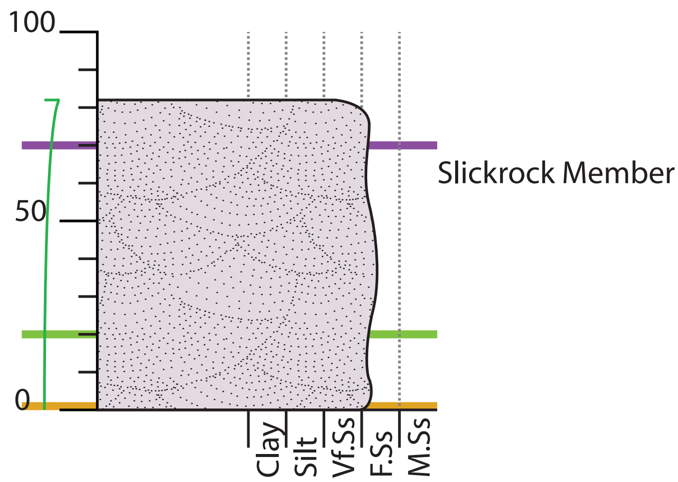


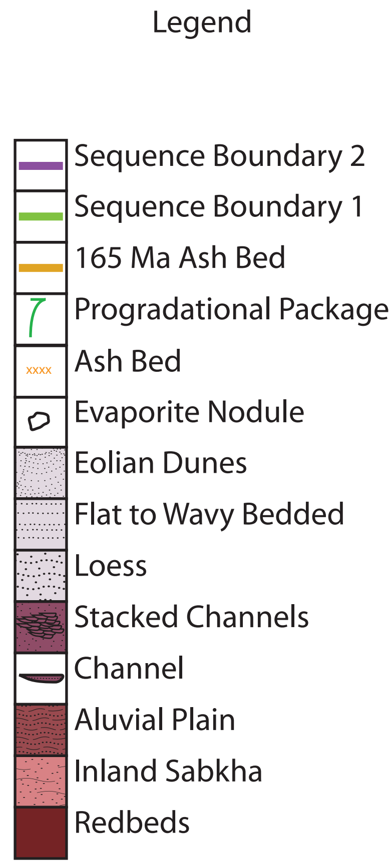


14. Spanish Valley South

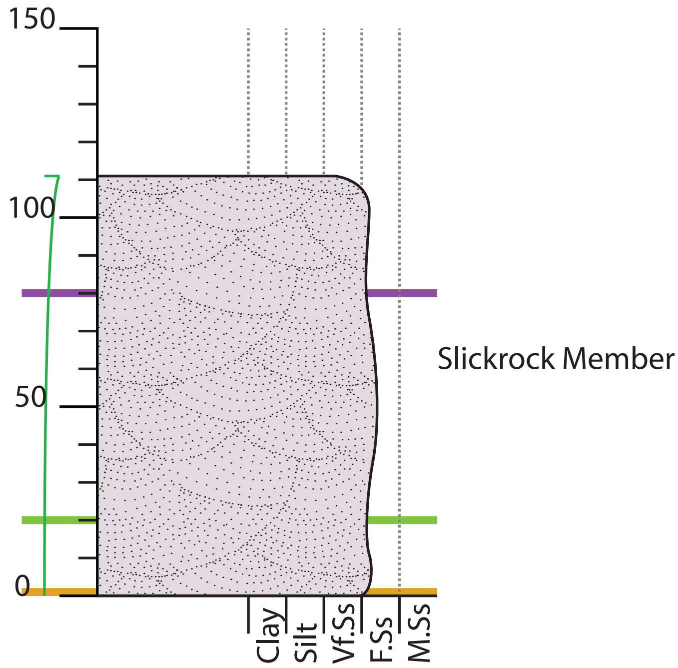


15. Sevenmile Canyon

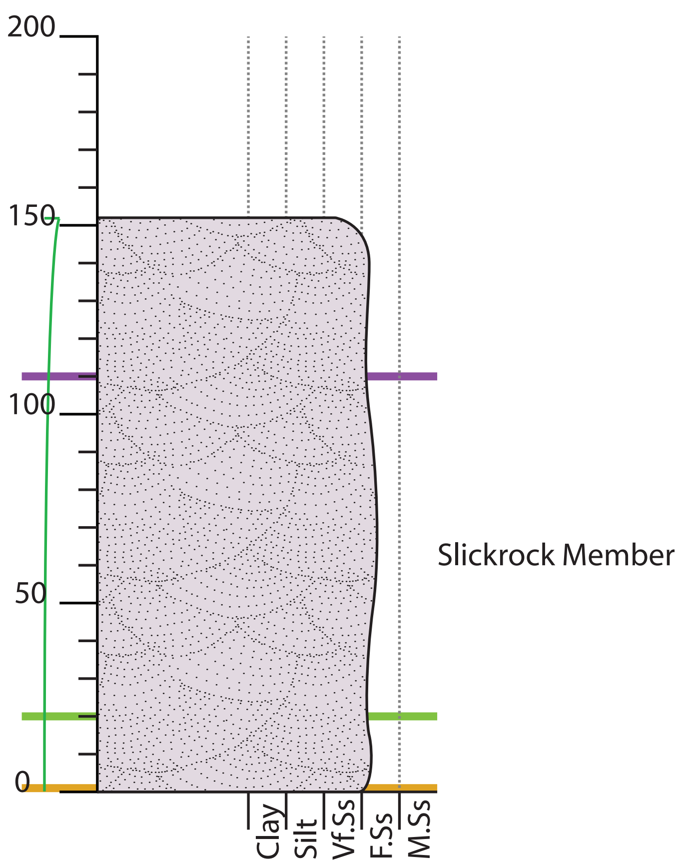




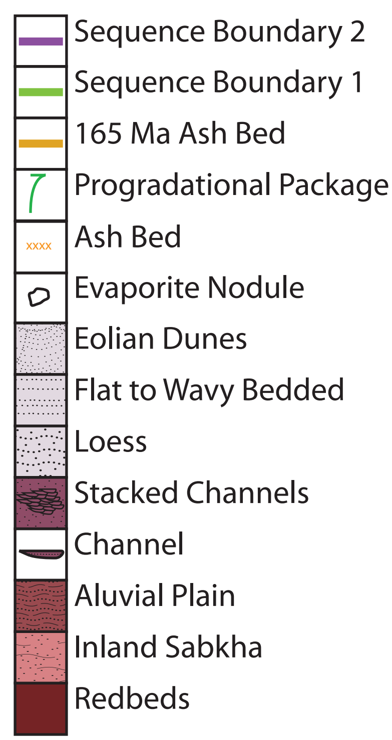
16. Tenmile Canyon West



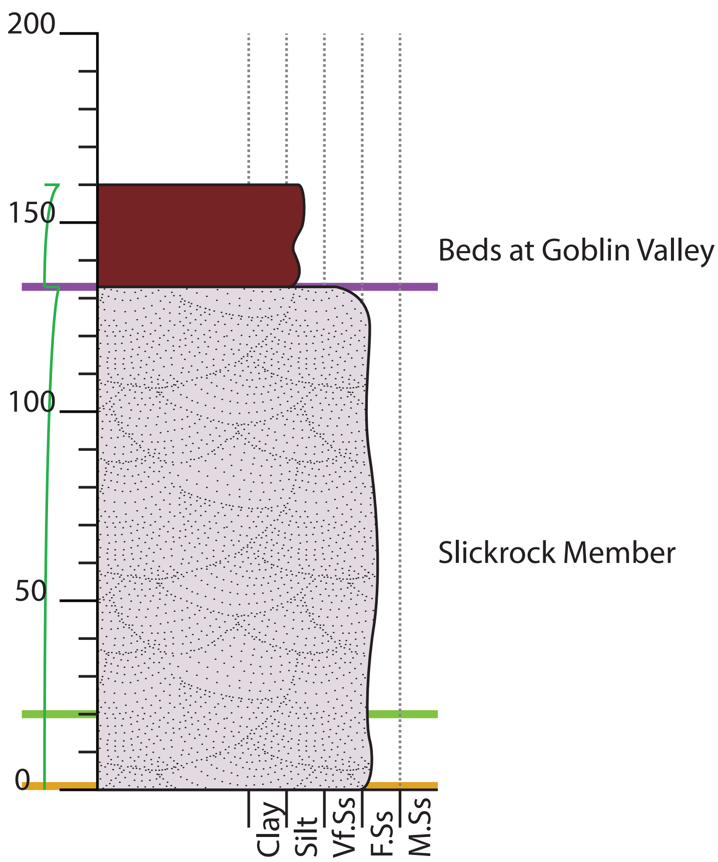
17. White Wash C

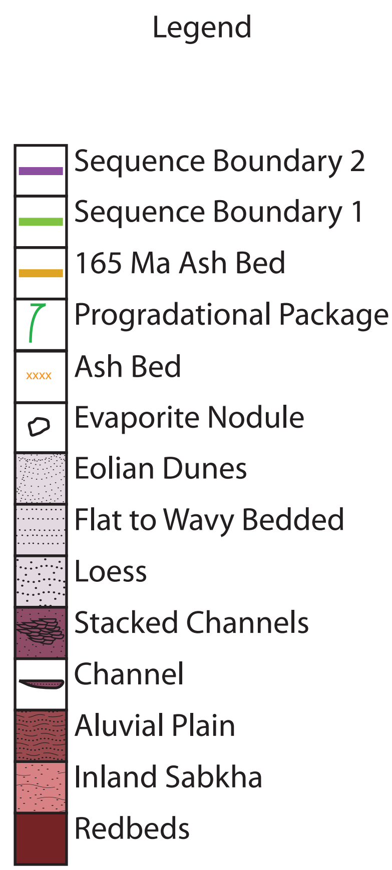


Legend

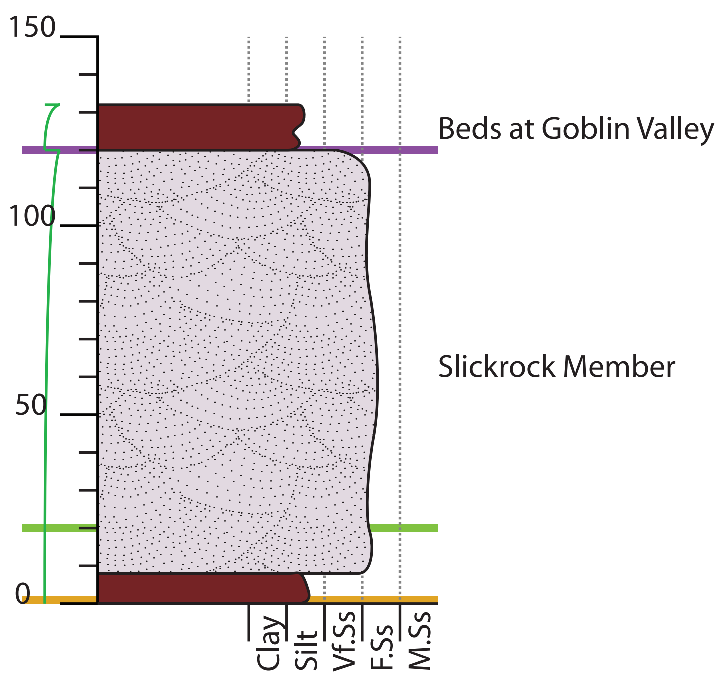


18. White Wash A

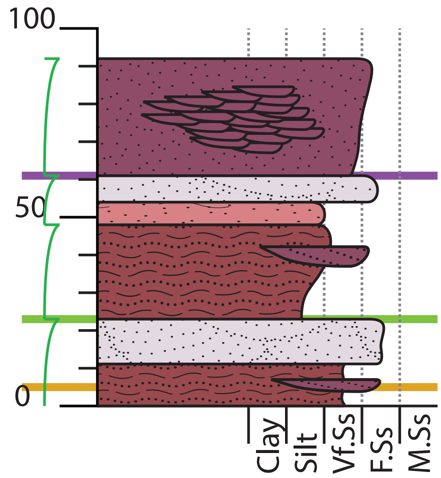




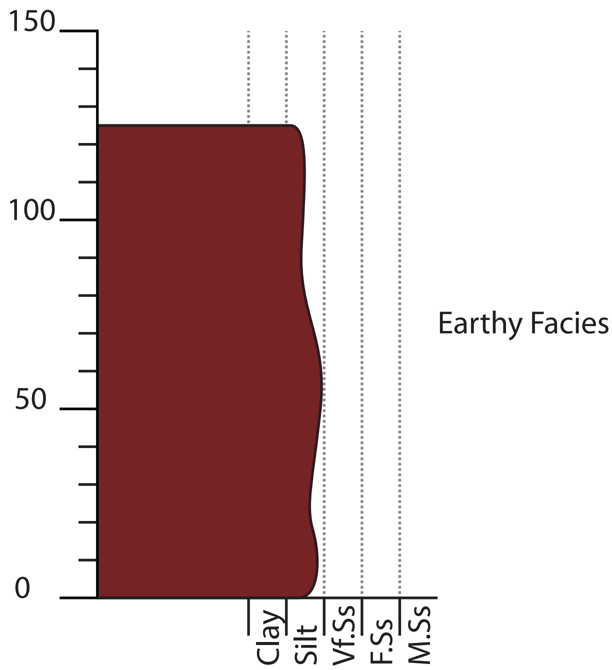
19. Green River

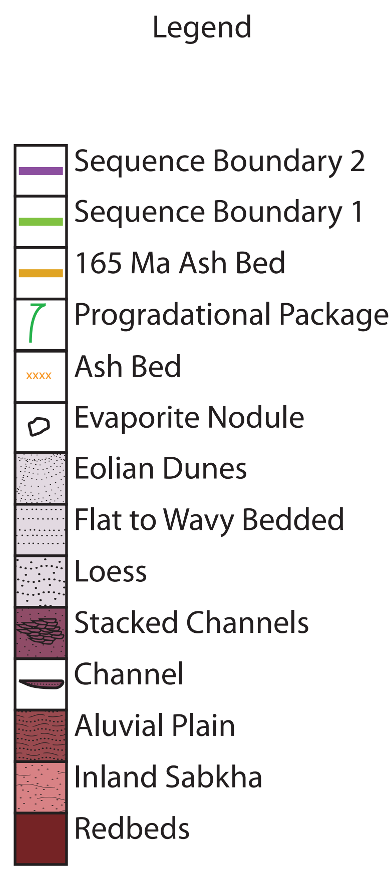


20. East Flank SRS Section

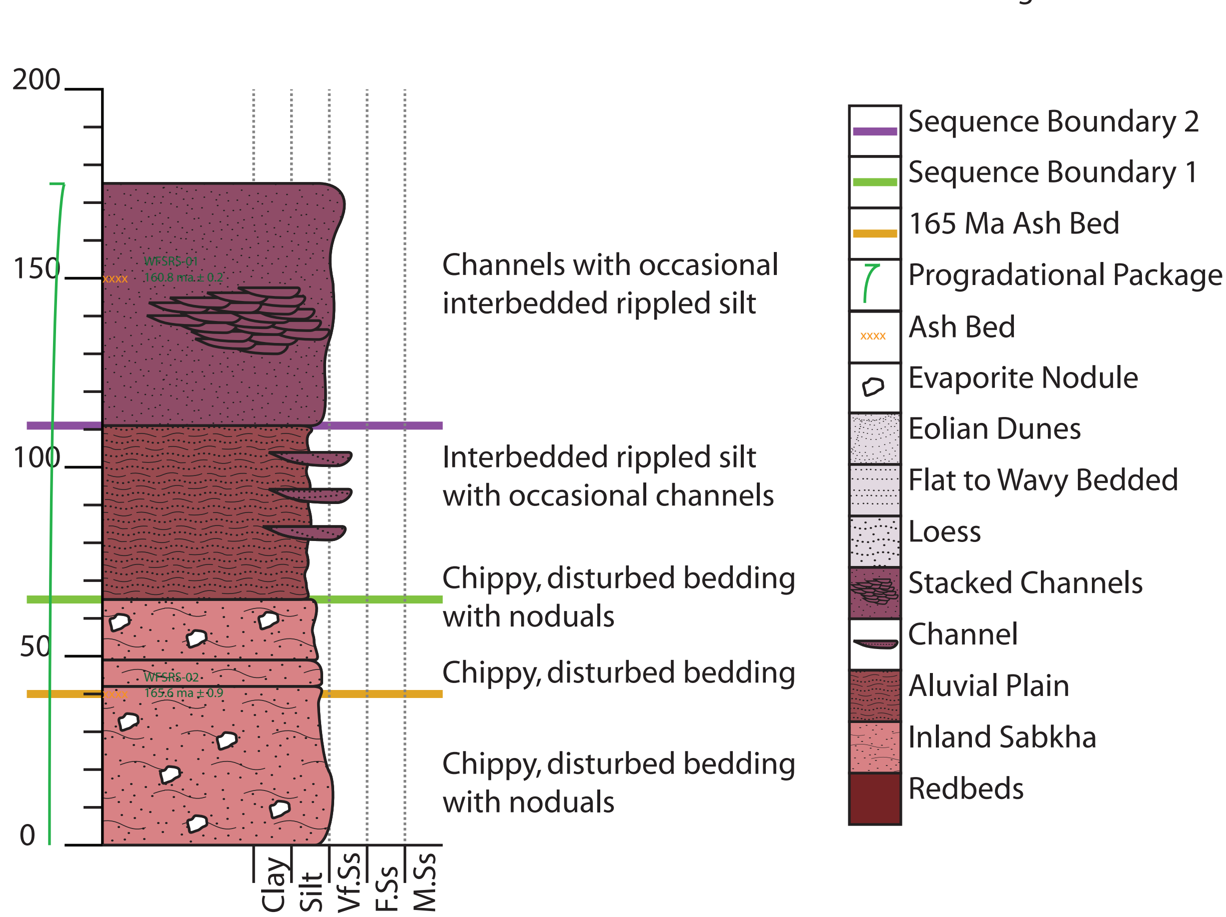


21. San Rafael Swell

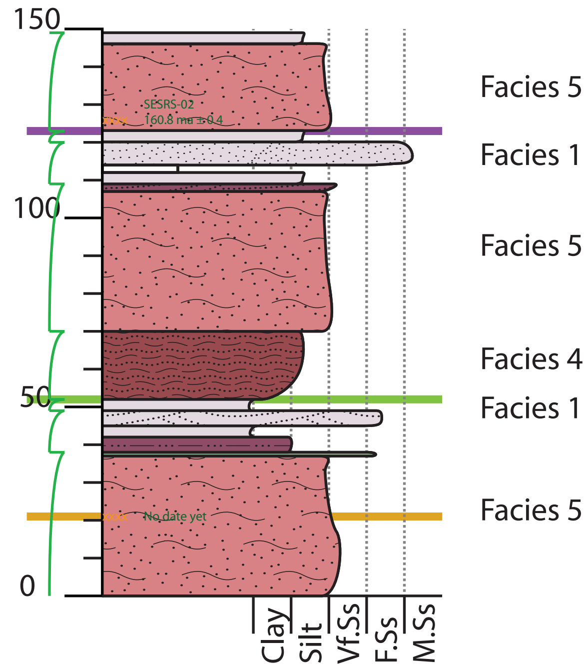




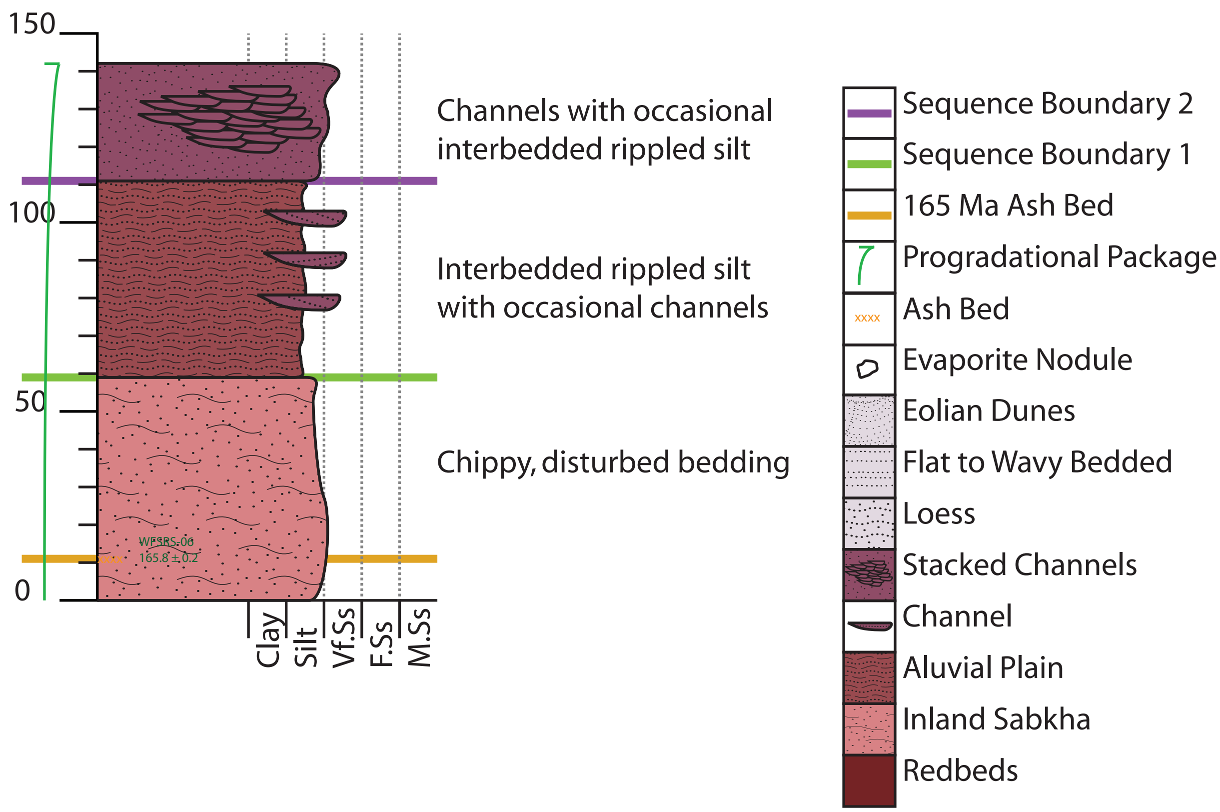
22. Moore Road Section



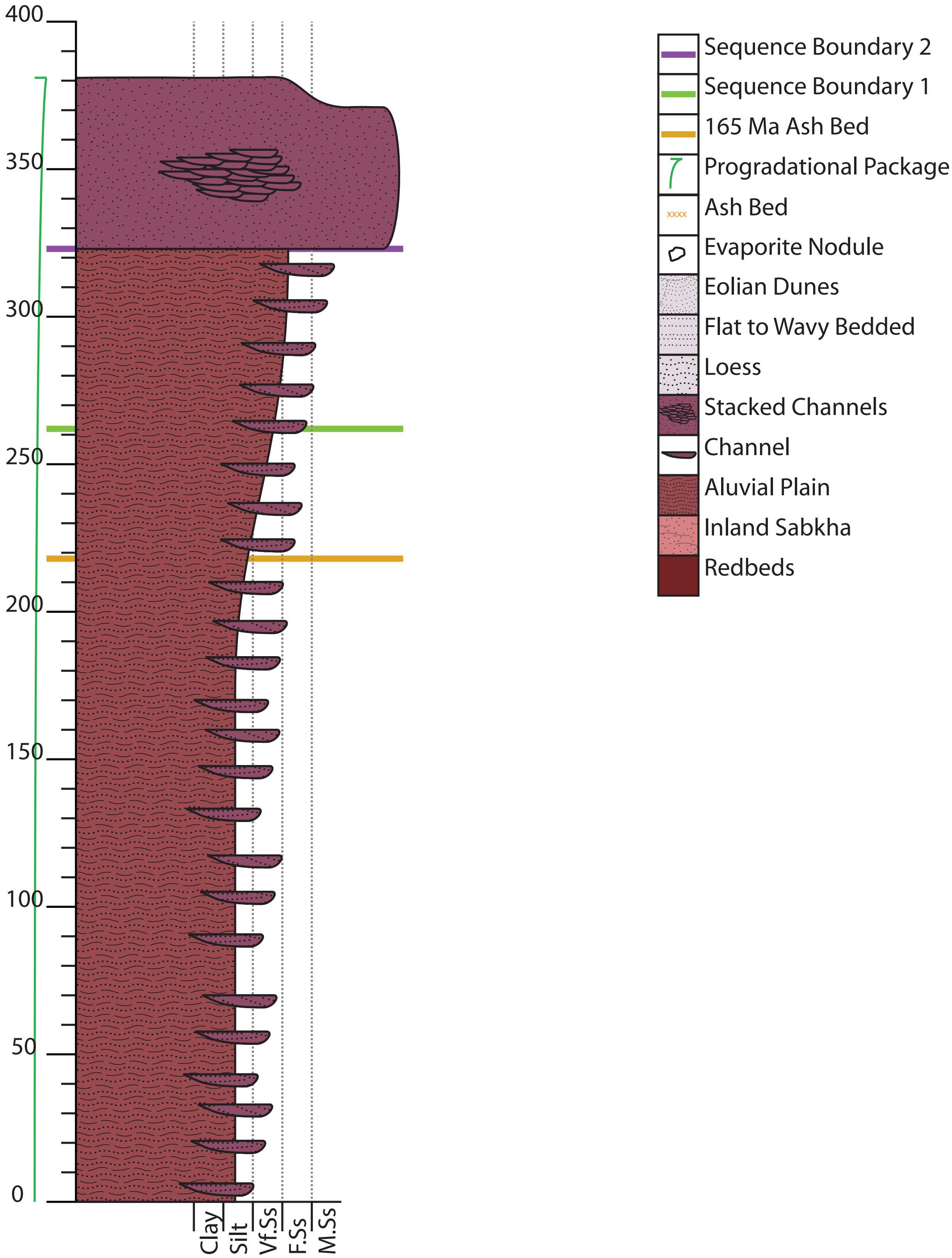
23. SE-SRS Section



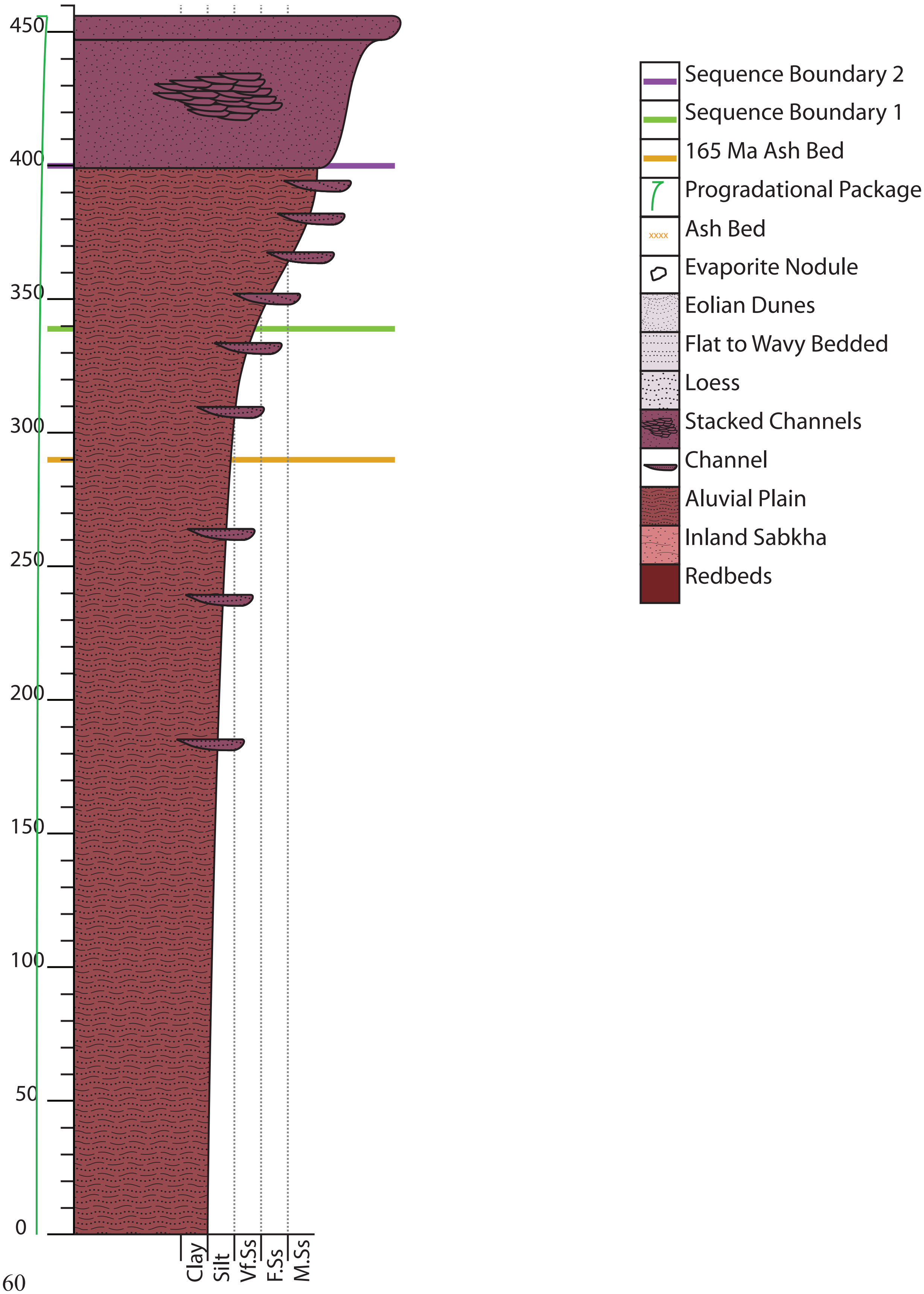
24. Little Cedar Mountain Section



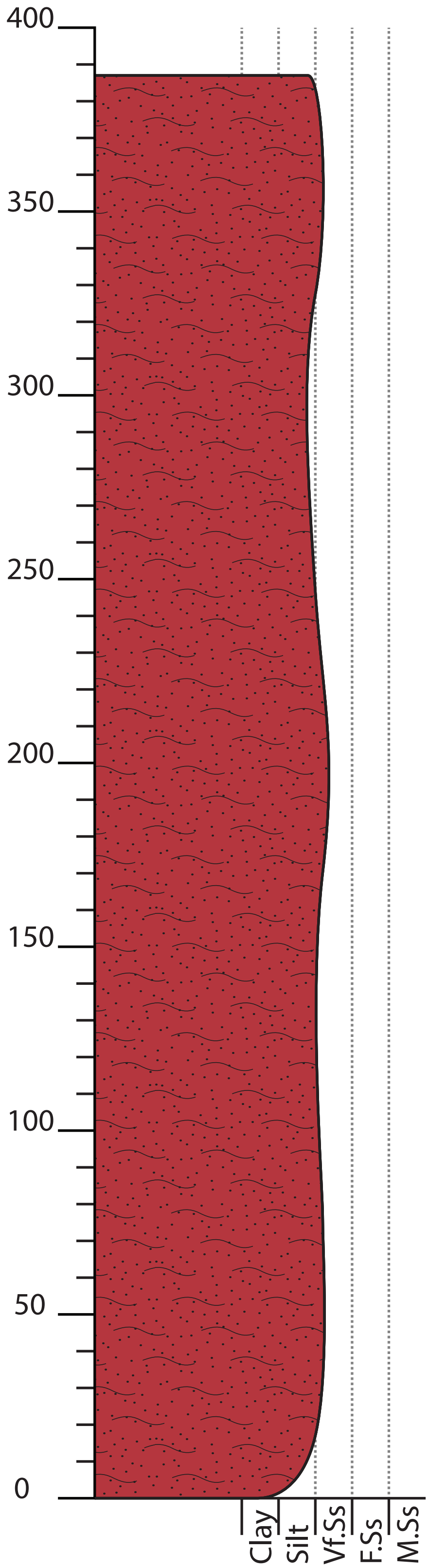
25. Salina Canyon Section

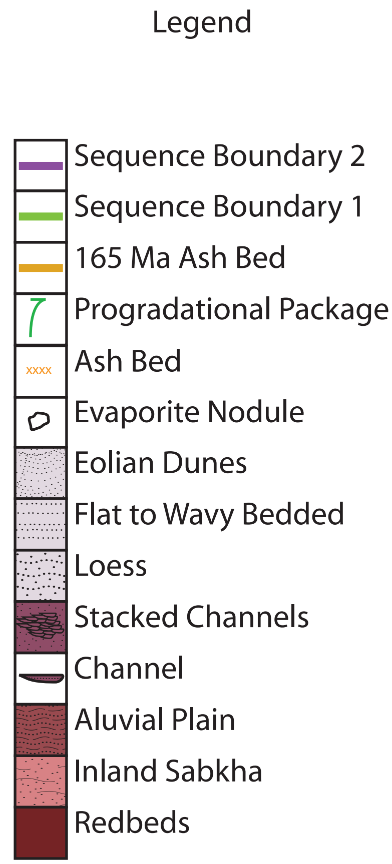


26. Pigeon Creek Canyon Section

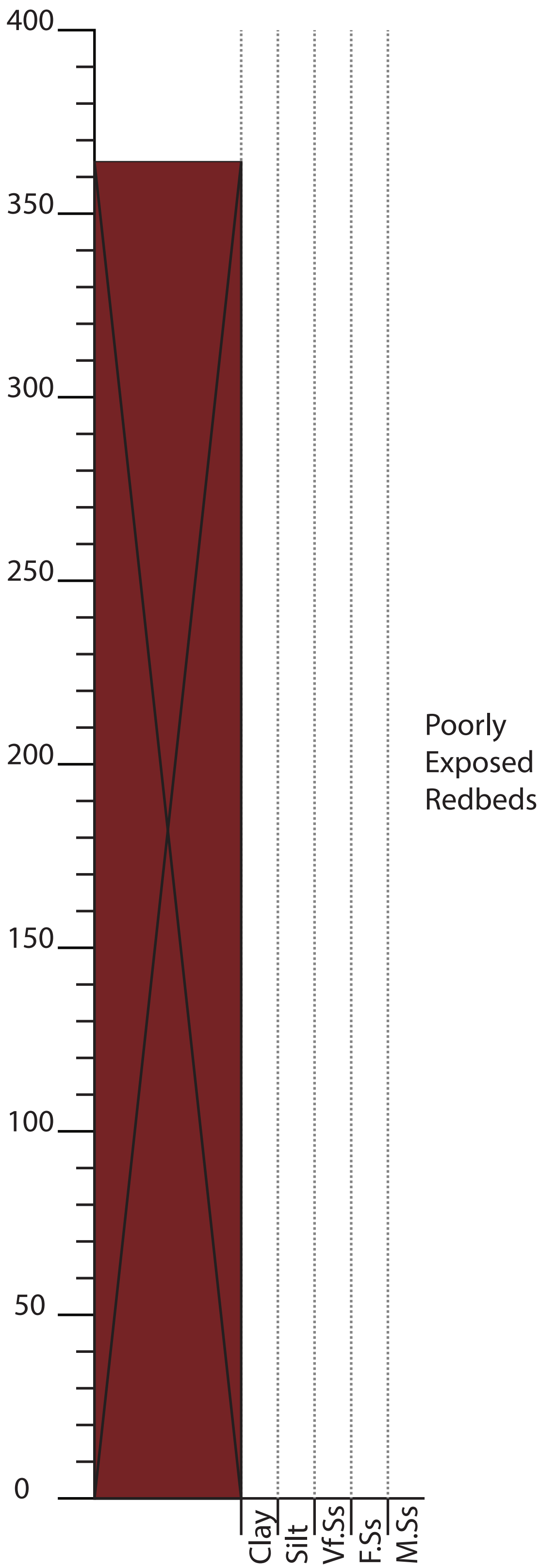


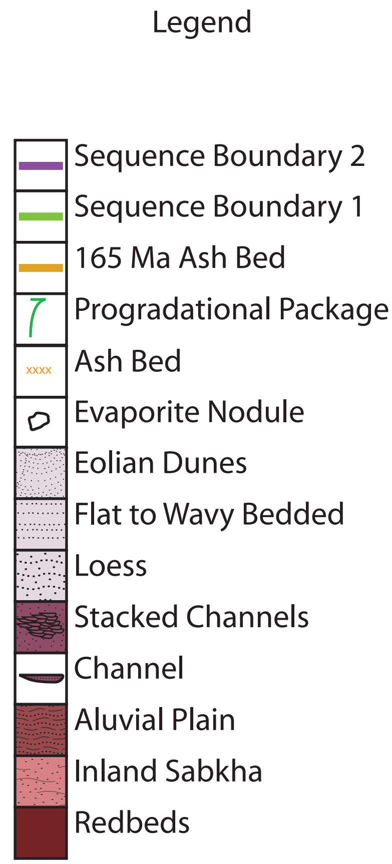
27. Monks Hollow



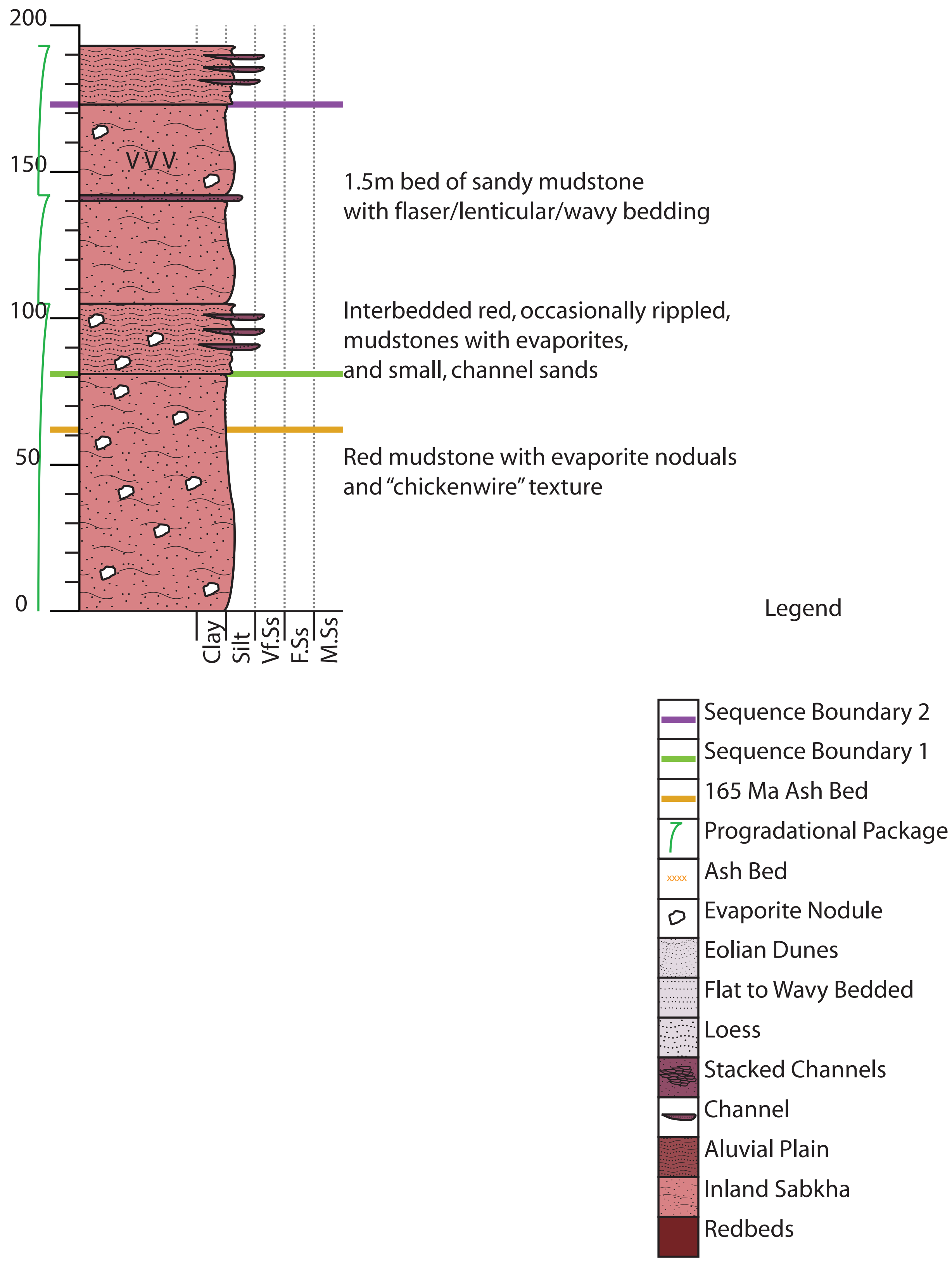


28. Peoa


400
350
300
250
200
150
100
50
0
Clay
Silt
Vf.Ss
F.Ss
M.Ss
Poorly
Exposed
Redbeds

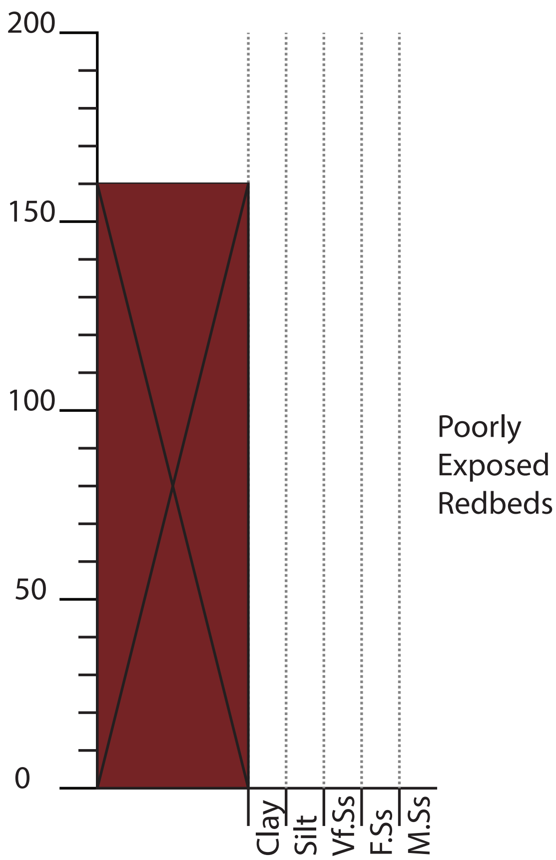

Legend
Sequence Boundary 2
Sequence Boundary 1
165 Ma Ash Bed
Progradational Package
Ash Bed
Evaporite Nodule
Eolian Dunes
Flat to Wavy Bedded
Loess
Stacked Channels
Channel
Aluvial Plain
Inland Sabkha
Redbeds

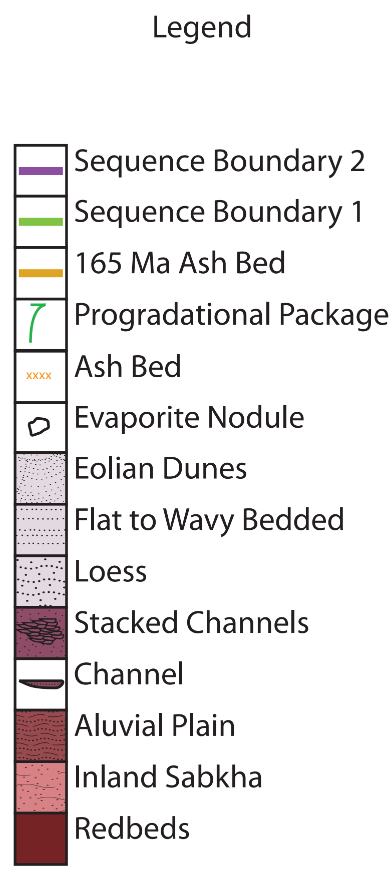
29. Hanna



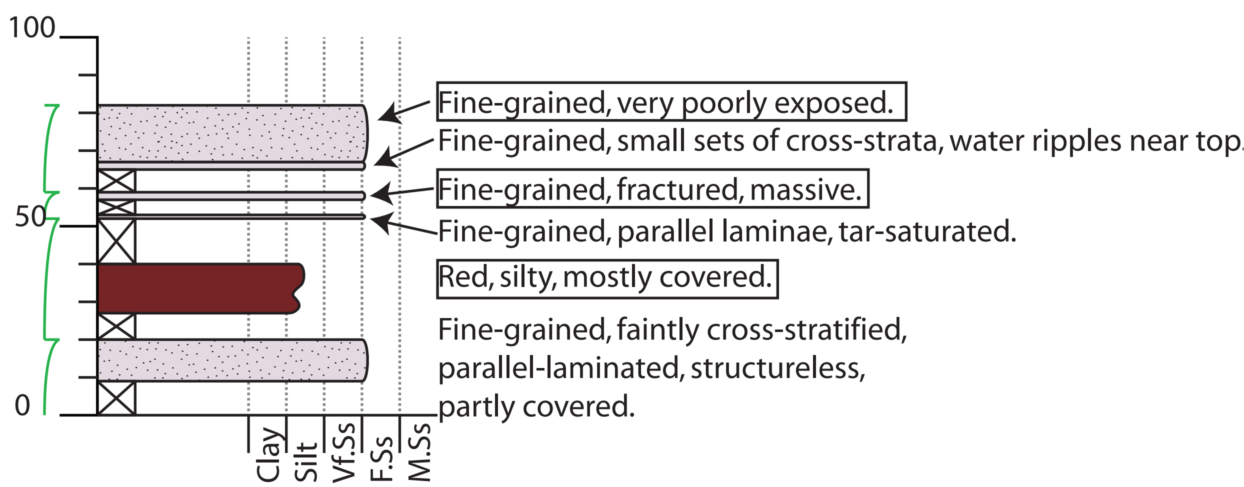
200
150
100
50
0
VVV
Clay
Silt
Vf.Ss
F.Ss
M.Ss
1.5m bed of sandy mudstone
with flaser/lenticular/wavy bedding
Interbedded red, occasionally rippled,
mudstones with evaporites,
and small, channel sands
Red mudstone with evaporite noduals
and "chickenwire" texture
Legend
Sequence Boundary 2
Sequence Boundary 1
165 Ma Ash Bed
Progradational Package
Ash Bed
Evaporite Nodule
Eolian Dunes
Flat to Wavy Bedded
Loess
Stacked Channels
Channel
Aluvial Plain
Inland Sabkha
Redbeds

30. Lake Fork Canyon

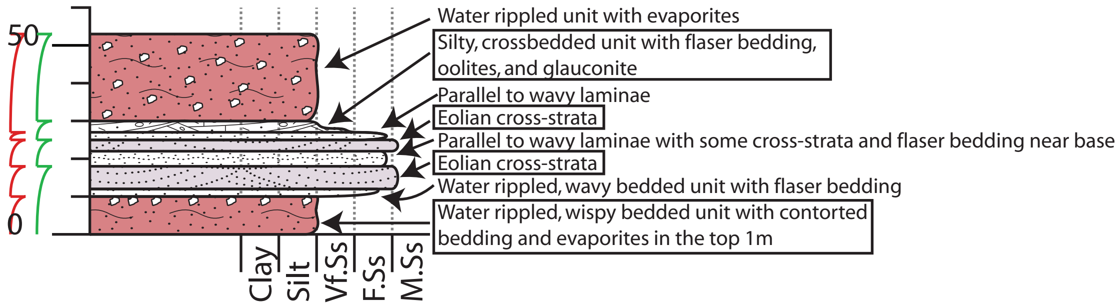




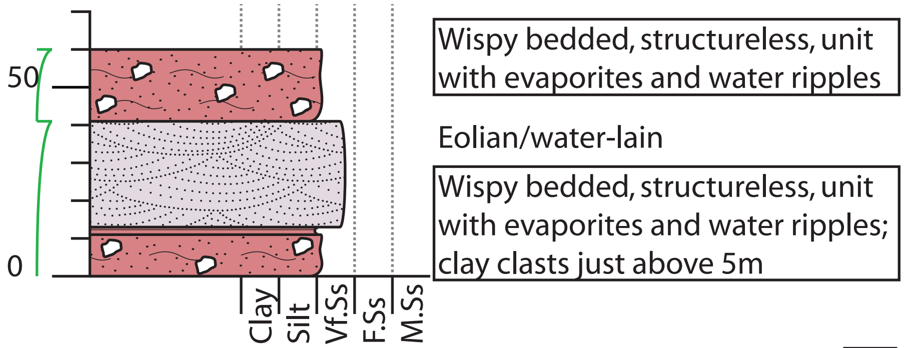
31. Whiterocks Canyon



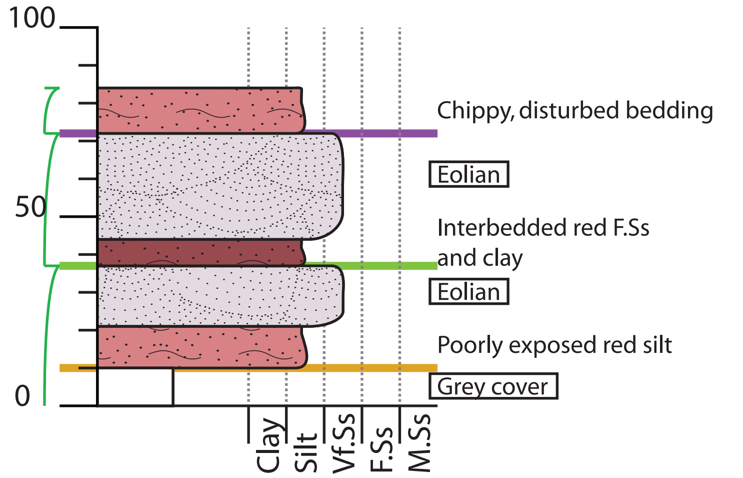
32. Sheep Creek Gap



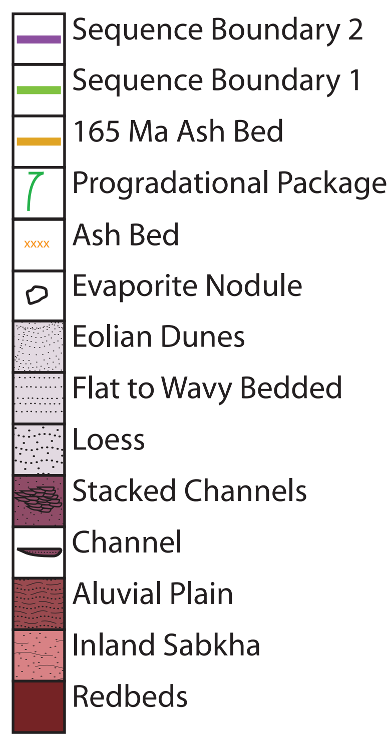
33. Daggett County Dump



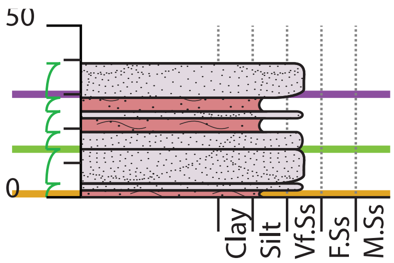
34. Vernal Section



Legend



35. Dinosaur National Monument



36. Area of Transverse