2019-01-01

Stratigraphic Response Of The Differential Rise Of The Gypsum Valley Salt Wall, Jurassic Entrada Formation, Paradox Basin, Colorado

Rafael Andres Delfin
University of Texas at El Paso

STRATIGRAPHIC RESPONSE OF THE DIFFERENTIAL RISE OF THE GYPSUM VALLEY SALT WALL, JURASSIC ENTRADA FORMATION, PARADOX BASIN, COLORADO

RAFAEL A. DELFIN

Master's Program in Geological Sciences

APPROVED:

____
Richard Langford, Ph.D., Chair

____
Katherine Giles, Ph.D., Co-chair

____
Elizabeth Walsh, Ph.D.

____
Stephen Crites, Ph.D.
Dean of the Graduate School

Dedication

To my parents, who have been my biggest supporters and have helped guide me onto the path of success.

STRATIGRAPHIC RESPONSE TO THE DIFFERENTIAL RISE OF THE GYPSUM VALLEY SALT WALL, JURASSIC ENTRADA FORMATION, PARADOX BASIN, COLORADO

by

RAFAEL A. DELFIN, B.S. Geology

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Geological Sciences
UNIVERSITY OF TEXAS AT EL PASO
December 2019

Acknowledgements

I'd like to give a special thanks to Dr. Langford who has played a crucial role in shaping me into the sedimentologist that I am today. I'd also like to thank the University of Texas at El Paso and the department of Geological Sciences for preparing me for my future career.

Abstract

The effect of halokinetic processes on fluvial and marine depositional environments adjacent to salt diapirs have been well established through extensive research, however eolian systems in similar geologic settings have not been documented. This has left a void in our understanding of eolian depositional environments adjacent to salt diapirs. This study is aimed at providing new knowledge and a solid foundation on eolian systems and diapiric processes. Despite our limited understanding of theses interactions, there has been a recent interest in deep water prospectively in the Gulf of Mexico. Successful tests of the Norphlet Formation prove that eolian sandstones deposited adjacent to salt bodies can be economic reservoirs. Utilizing this study as a potential analogue will aid in the future development of deep-water prospects and expand upon our understanding of salt sediment interactions.

The Paradox Basin is largely an Ancestral Rocky Mountain structure where salt tectonism influenced sedimentation patterns from the Permian through the Jurassic. A series of northwest – southeast trending salt walls emerged and began to interact with sediments, which were deformed through the process of halokinesis. The Gypsum Valley salt wall found in southwestern Colorado was part of this series and is the focus of this study. During the late Jurassic Period the eolian Entrada Formation was deposited and began to interact with the Gypsum Valley salt wall.

Gypsum Valley spans for approximately 38 km and is split into two distinct geomorphic regions; towards the northwest is Little Gypsum Valley, which represents a portion of the salt wall that was buried under Entrada strata. The second portion is Big Gypsum Valley found towards the southeast and is interpreted to have had passive diapiric rise that thinned the Entrada Formation along its flanks. This study documents the irregular thickness and facies variations

within the Entrada Formation found along strike of the Gypsum Valley salt sediment interface. Documentation of these variations was accomplished through a series of measured sections and interpreted panoramic photographs taken along the northern flank of the salt wall. These sections show a dramatic change in thickness from what is documented regionally. The Entrada Formation is thickest at the northwest portion of the study area at 55 m and thins to 30 m toward the southeast. A total of 11 lithofacies were identified and include: trough cross-stratified sandstone, structureless sandstone, wave ripple cross stratified sandstone, recessive siltstone, wind-rippled sandstone, flaser bedded sandstone, burrowed sandstone, current rippled sandstone, gravel lag deposits, soft sediment deformation and avalanche deposits.

Five facies associations were documented and include: tidal deposits, wet inter-dune deposits, large eolian dunes, small eolian dunes and horizontally bedded structureless sandstone. The Entrada Formation can be broken up into 4 map units that have similar characteristics to those documented by Shawe et al. (1968). However, internally these units have variable lateral facies distributions unlike those documented within the regionally extensive Entrada Formation. These units include the following, in ascending order: Basal Tidal Unit, Wet Inter-Dune Unit, Cross-Bedded Unit and the Horizontally Bedded Unit.

The Basal Tidal Unit is mainly composed of tidal facies and has a uniform thickness across the study area. The contact with the unit above is sharp and marked by a laterally continuous bed of small eolian dunes. The Wet Inter-Dune Unit has an uneven thickness distribution that is the result of diapiric rise in the southeast coupled with rotation and erosion of diapir flanking sediments. This produced a southeast thinning trend of the Wet Inter-Dune Unit. The Cross Bedded Unit is primarily made up of both large and small eolian dune deposits that display southeastward thinning trend. This trend is the result of the same processes that affected the Wet Inter-Dune Unit found below. The Horizontally Bedded Unit composes the top of the Entrada Formation and is dominated by structureless sandstone facies. Its thickness trend is different than the other units in that it thins towards the northwest.

A total of 10 stratal packages were identified with in the Entrada Formation. Stratal packages 1, 2 and 3 are part of the basal tidal unit; collectively they produce a uniform thickness across the study area suggesting erosion near the end of deposition of the tidal unit that beveled the underlying sequences. Stratal packages 1 and 2 show the evidence of diapiric rise concentrated in the southeast based of lateral truncations and facies assemblages. Package 3 is the result of a shift of diapiric rise towards the northwest. Stratal packages 4, 5 along with portions of 6 and 7 make up the Wet Inter-Dune Unit.

These packages all pinch-out towards the southeast and display the effects of a progressive shift of diapirism back towards the southeast. Portions of packages 6 and 7 along with packages 8 and 9 make up the Cross-Bedded Unit. This unit represents the continuation of greater diapiric deformation in the southeast and is capped by sequence 8. Between these areas of diapiric rise, sediments were rotated and truncated by erosional processes. Packages 9 and 10 make up the Horizontally Bedded Unit, which thins towards the northwest unlike the other stratigraphic units. These packages may define onlap of the underlying dune field, or a more broad subsidence in the Big Gypsum Valley area that allowed greater accumulation of strata.

Table of Contents

List of Figures

Chapter 1: Introduction

To date, few studies have documented the effect of halokinetic processes on eolian depositional environments adjacent to salt diapirs (Giles and Lawton, 2002), although the effects of halokinetic processes on fluvial and marine depositional environments adjacent to salt diapirs have been well established through extensive research (Giles and Lawton, 2002; McFarland, J.C, 2016; Heness, A.H, 2016; Mathews, 2007). This has left a void in our understanding of depositional environments adjacent to salt diapirs. This study is aimed at providing new knowledge and a solid foundation on eolian systems and diapiric processes, specifically regarding the thickness and facies variations that are common at various scales within diapir-proximal depocenters. Documentation of such changes is key to understanding potential hydrocarbon reservoir distributions and deformational history. Despite our limited understanding of theses interactions, there has been a recent interest in deep-water prospectivity in the Gulf of Mexico. Successful tests of the Norphlet Formation prove that eolian sandstones deposited adjacent to salt bodies can be economic reservoirs. Utilizing this study as a potential analogue will aid in the future development of deep-water prospects.

Gypsum Valley is located in the Paradox Basin of southwest Colorado, USA (Figure 1.1, Figure 1.2), and exposes an elongate diapir, or "salt wall". For approximately 18 km along its northern margin are exposures of the salt-sediment interface between the Jurassic Entrada Formation and the Gypsum Valley salt wall. Gypsum Valley is divided into 2 geomorphic areas (Figure 1.2): the northwest end is Little Gypsum Valley and the southeast end is Big Gypsum Valley. The study area is focused in Big Gypsum Valley, which contains exceptionally well-exposed cliffs of the Entrada Formation that are easily accessibly on foot. In this area, the Entrada displays thickness and facies variations at or near the salt wall margin that are more dramatic when compared to uniform thickness of the outboard Entrada stratigraphy. At Gypsum Valley, the Entrada's thickness is more abbreviated with a maximum thickness of 50 m. Previous studies on salt related interaction with the Entrada Formation have been focused on structural frameworks in which the focus has been exclusively on faulting of stratigraphic units (Doelling 1987; Cruikshank and Ayden 1993).

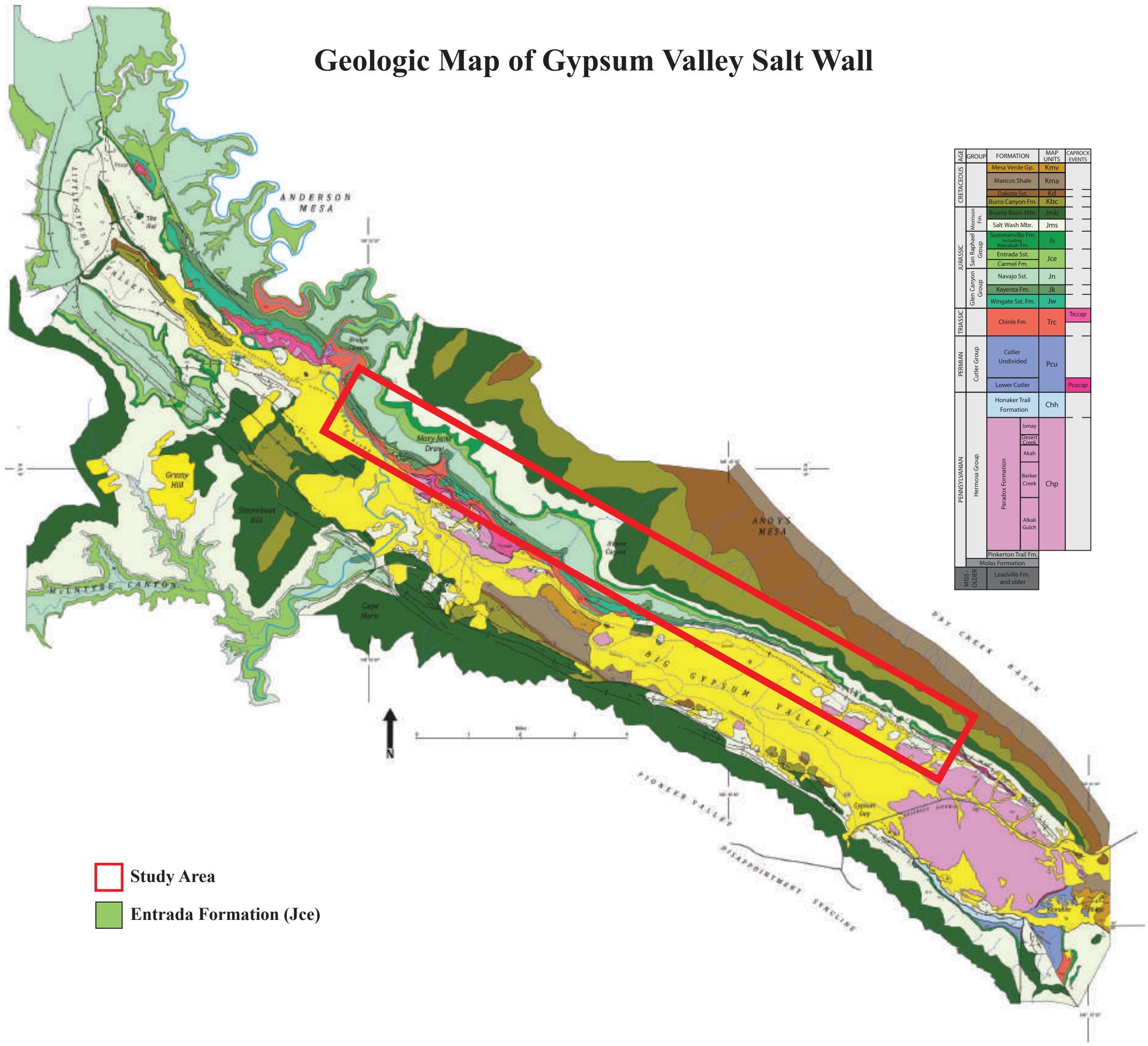


Figure 1. Geologic Map of Gypsum Valley. The red box represents the extent of the study area along the northern flank of the diapir. The Jurassic Entrada Formation (Jce) is represented by a shade light green-yellow (modified from Escosa et. al, 2016).

1.1 Background and Geologic Setting

1.1.1 Paradox Basin

The Paradox Basin is located in the southwestern portion of the United States and spans four different states (Figure 1.2). The basin began forming during the Pennsylvanian as a foreland basin associated with the Ancestral Rocky Mountain orogeny (White and Jacobson 1983; Barbeau 2003). The Ancestral Rocky Mountain orogeny can be characterized as a series of intracratonic block uplifts that nucleated in the southwestern portion of the North American craton (Hite 1960; Barbeau 2003). The resulting uplifts had substantial relief along near vertical faults, where Paleozoic strata along with Precambrian igneous and metamorphic basement (Hite 1960) were subsequently eroded, generating large amounts of coarse-grained clastic sediments that filled the surrounding basins.

The Uncompahgre Uplift located in the northeastern portion of the Paradox Basin is bound by a high angle thrust fault to the southwest (Figure 1.1). Flexural subsidence took place during the early Desmoinesian through the mid-Permian (Barbeau 2003). Circulation was restricted by the four corners platform to the southeast, this limited ocean circulation was ideal for the deposition of thick evaporite sequences though out the Desmoinesian (Hite & Gere 1958; Peterson and Hite 1969; Carter & Liming 1972; Baars & Stevenson 1981).

The compressional regime associated with the Ancestral Rockies caused the Paradox Basin to subside and reactivate basement structures (Barbeau 2003; Peterson 1989). Subsidence coupled with doming and faulting produced the Uncompahgre Uplift flanked by the Eagle Basin in the northeast and the Paradox Basin in the southeast (Baars & Stevenson 1981; Peterson 1989; Nuccio & Condon 1996). The initial fill forms the Paradox Formation, which is primarily made up of interbedded dolomite, shale and evaporites that have a max thickness of ~2500 m at the foredeep of the basin (Trudgill 2011). Conversely, the basin forebulge was home to reefal carbonate buildups along the distal western margin (Peterson & Hite 1969; Baars & Stevenson 1981; Trudgill 2010). Within the central portion of the basin there are approximately 40 cycles of evaporite-shale and dolomite deposits documented by Peterson & Hite (1969) and Peterson (1989). Cyclic deposition is understood to have been caused by a variety of factors such as eustasy, sediment supply, and subsidence (Nuccio & Condon 1996; Peterson 1989).

Diapirism within the Paradox Basin was initiated by differential loading of evaporites caused by the sediment overburden of a southeasterly prograding alluvial wedge that was deposited during late Pennsylvanian to Early Permian (Barbeau 2003; Trudgill and Paz 2009). The extent of this wedge is what has been accepted as the boundary and geographic extent of the Paradox Basin (Condon 1997). The result of this prograding wedge was a series of northwest trending salt-cored anticlines that parallel the Uncompahgre Uplift (Trudgill and Paz 2009). During the Late Jurassic and into the Early Cretaceous these salt bodies were initially buried and continued to be buried on through the Paleogene (Rasmussen 2014). During the Neogene period, these salt bodies were exhumed and later during the Pleistocene are thought to have collapsed as a result of extensive erosion and dissolution (Rasmussen 2014; Nuccio and Condon 1996).

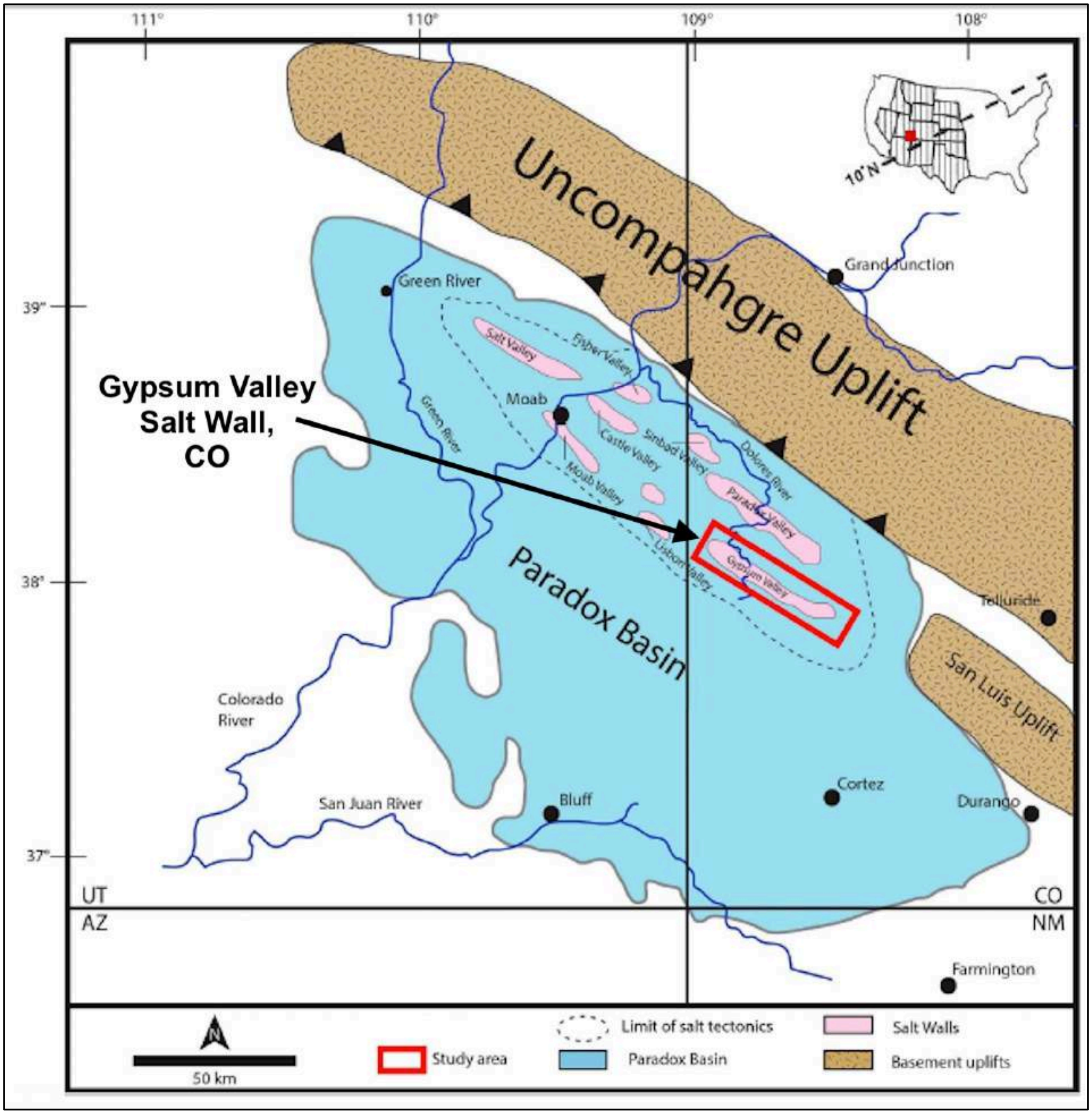


Figure 1.2. Map displaying the extent of the Paradox Basin and major uplifts and salt bodies (Modified from Shoemaker, et al. 1958). Gypsum Valley Salt Wall spans across portions of southwest Colorado and is outlined in red.

1.1.2 Gypsum Valley Salt Wall

Gypsum Valley (Figure 1.1) is a salt wall located in southwest Colorado. It has a NW-SE trend and is approximately 35 km long and 3 km wide. The Paradox Formation evaporite deposits that form the salt wall are exposed along the valley floor as modern, mostly gypsic caprock forming smooth hills across the valley. There is no halite present at the surface, however wells in the adjacent Andy's Mesa and Double Eagle oil fields have encountered halite in the subsurface (Cater, 1970). The valley walls are made up of Pennsylvanian, Permian, Triassic and Jurassic sediments that dip away from the valleys center towards the Dry Creek mini-basin in the northeast and the Disappointment mini-basin towards the southwest (Stokes and Phoenix 1948; Cater 1970) (Figure 1.2).

Gypsum Valley can be broken up into two distinct regions that are separated by the Dolores River that cuts across the valley. Towards the northwest of the river lies Little Gypsum Valley and to the southeast lies Big Gypsum Valley (Stokes & Phoenix 1948). Big Gypsum Valley is the larger of the two and home to highest abundance of exposed stratigraphy (Figure 1.2). Little Gypsum Valley has been thought to be a late-stage dissolutional collapsed portion of the salt body where collapsed blocks of the Morrison Formation rest on the valley floor (Cater 1970) (Figure 1.2).

1.1.3 Entrada Sandstone

The Entrada Sandstone (Figure 1.3 & Figure 1.4) is a Jurassic-aged eolian sandstone that forms part of the San Raphael Group, found across the western United States (Shawe, et al. 1968). In the Gypsum Valley area, it overlies the Navajo Formation and underlies Summerville Formation at the top (Shawe, et al. 1968). Regionally, the formation is composed of 3 distinct members, in ascending order: the Dewey Bridge Member, the Slick Rock Member and the Moab

Member (Shawe et al., 1968). The Dewey Bridge Member found at the base is the partial time equivalent to the Carmel Formation found in Utah (Shawe et al., 1968). The two are commonly referred to interchangeably based on lithological similarities and stratigraphic position. The Dewey Bridge Member is dominantly composed of slope forming red siltstones and fine grain sandstones (Figure 1.3). The Slick Rock Member is regionally ~30 m thick and is a fine-grained sandstone that produces shear cliff faces of various shades of tan and red. The Slick Rock Member is subdivided by Shawe et al. (1968) into 3 stratigraphic units (ascending order): the Massive Unit, the Cross-Bedded Unit and the Horizontally Bedded Unit (Figure 1.3). Capping the Entrada Sandstone is the Moab Member, which is not present at Gypsum Valley. The Moab Member is described by Wright et al. (1962) as a white cliff forming sandstone containing large sweeping cross beds. Regionally, the Entrada maintains a fairly constant thickness of 70-75 m, but to the northeast, it thins toward the Uncompahgre Uplift (Shawe et al. 1968; O'Sullivan 1986; O'Sullivan 1991). In general, the Slick Rock Member thins to the east, and the Dewey Bridge Member thickens to the east, reaching a maximum of 33 m near Uravan Colorado (O'Sullivan, 1991).

The Entrada Formation was mainly sourced from a shoreline north of the Paradox Basin and was bounded by a combination of shallow marine and sabkka deposits towards its north and west (Dickinson and Gehrels 2003). The Entrada sand sea migrated towards the west through time, where it inter-tongued with strata of the Carmel Seaway (O'Sullivan 1981). This regression, followed by a major transgression caused marine and sabkha deposits to onlap onto the Entrada eolian sands (Pipiringos & O'Sullivan 1978). Paleowind directions based on cross bedding suggest a dominant NW-SE wind direction, however, workers have suggested different parts of the Entrada erg experienced variability in wind direction (Mckee 1956; Kocureck 1981).

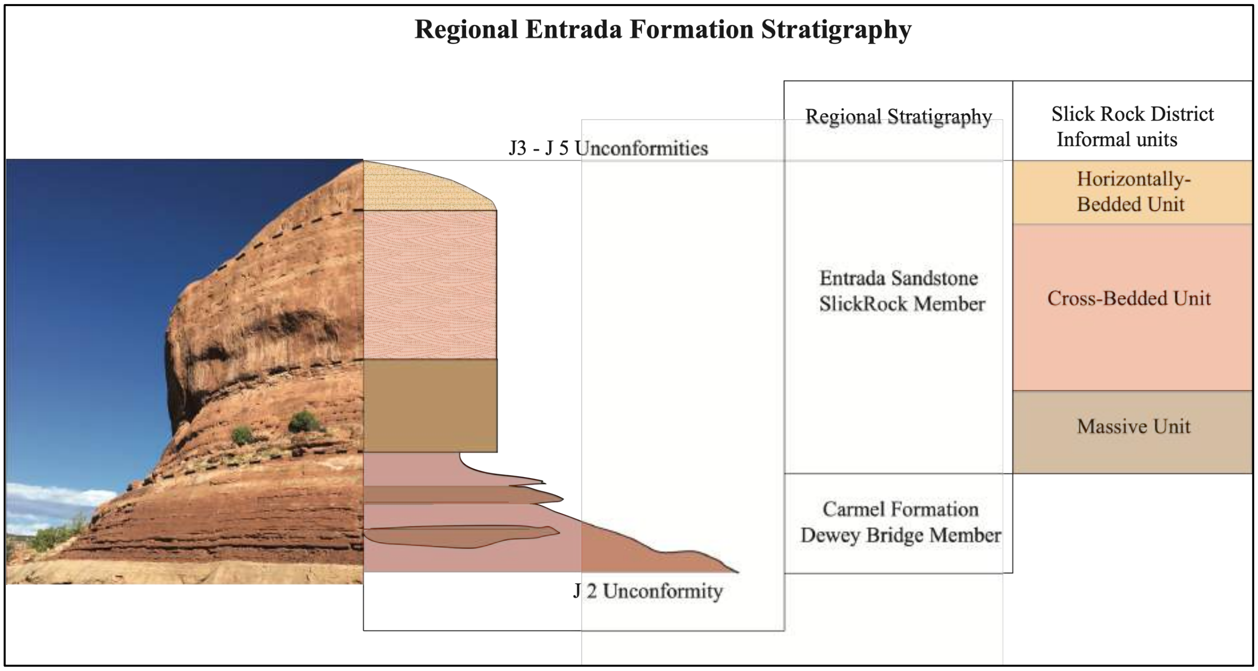


Figure 1.3. Regional Entrada Formation Stratigraphy. Section is 75m thick. Stratigraphic Units are named using the nomenclature of Doelling (1998) who separates Carmel and Entrada into two conformable and inter-tonguing formations. The Entrada Formation consists of a single formal unit, the Slick Rock Member (Wright & others 1962). The overlying Moab Member of the Entrada Formation is absent due to erosion, which also superimposes the J3 and J5 unconformities recognized by Pipiringos & O'Sullivan (1978). Regionally, the Slick Rock Member is subdivided into 3 informal units: Massive Unit, Cross-Bedded Unit and the Horizontally Bedded Unit (Shawe et al. 1968).

1.2 Methods

Stratigraphic analysis of the Entrada Sandstone involved 6 measured sections extending from the base of the Entrada Formation to the base of the Summerville Formation across the northern flank of Big Gypsum Valley (Figure 1.4). Sections vary in thickness from 55 m down to 30 m. A Jacob's staff was used to measure sections and bed thickness. Lithofacies, strike/dip, sedimentary structures, grain size, sorting, angularity, color, and thickness were documented where units changed. A Brunton Compass was used to measure strike/dip of beds and contacts. A Garmin 64st handheld GPS unit was used to collect GPS data of measured section locations. While measuring sections individual beds were described and photographed in detail and transcribed onto data sheets. Where possible, beds were traced laterally to document stratal geometries and correlate measured sections.

Measured sections were compiled and digitized utilizing Adobe Illustrator software in order to make structural and stratigraphic cross-sections. GPS points collected in the field provided the top and base elevation of measured sections. These cross-sections were used to produce lithofacies correlations, lithostratigraphic correlations, and a structural reconstruction of the Entrada Formation. The lithofacies correlation was utilized to develop the halokinetic sequence architecture within the Entrada Formation.

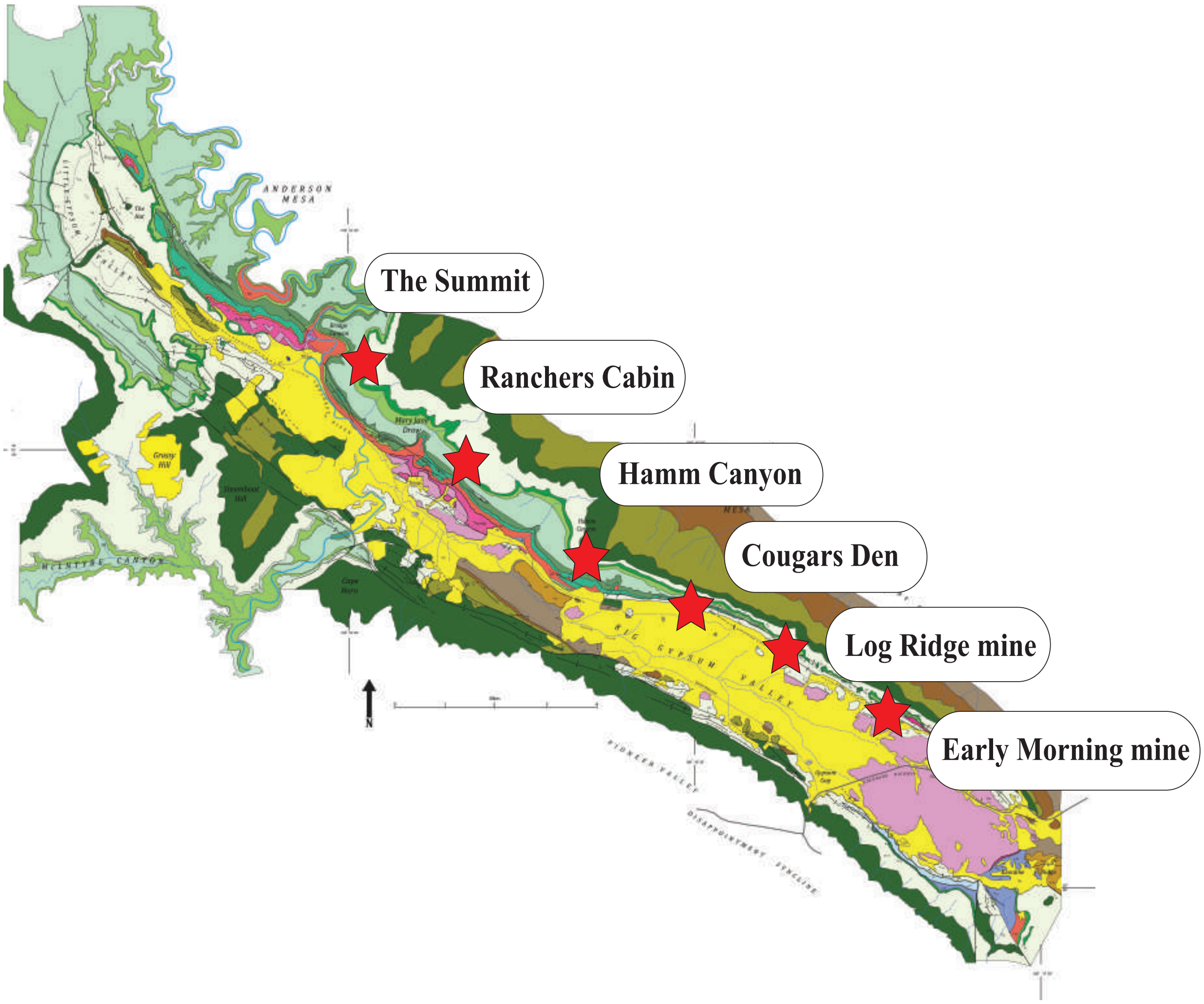


Figure 1.4 Geologic Map of the Gypsum Valley Salt Wall. Red stars represent locations of measured sections and corresponding names (modified from Escosa et. al, 2016).

Chapter 2: Entrada Lithofacies and Facies Associations

2.1 Lithofacies

Within the Entrada Sandstone at Gypsum Valley a total of 11 lithofacies were identified based on lithological composition and sedimentary textures. Lithofacies vary laterally across the study area in both abundance and composition. The 11 lithofacies are: trough cross-stratified sandstone, structureless sandstone, wave ripple cross stratified sandstone, recessive siltstone, wind-rippled sandstone, flaser bedded sandstone, burrowed sandstone, current rippled sandstone, gravel lag, soft sediment deformation and avalanche deposits.

2.1.1 Trough Cross-Stratified Sandstone

Trough cross-stratified sandstone is the most common facies seen at the Gypsum Valley salt wall. Grain size ranges from fine to medium-grain and sandstones are typically well sorted and well rounded. Trough cross-stratified beds vary in thickness from fifty centimeters to several meters thick and have sharp erosional contacts at the top and bottom (Figure 2.1B**)**. Beds are multiple shades of red-orange, tan and white in color. Coarse-grained sand can be found on top of individual trough cross beds as grain flow deposits (Figure 2.1.1D**)**. A key identifying feature of the beds that make up much of the Entrada Formation is the presence of granular sized chert grains referred to by Wright et al. (1962) as "Entrada Berries".

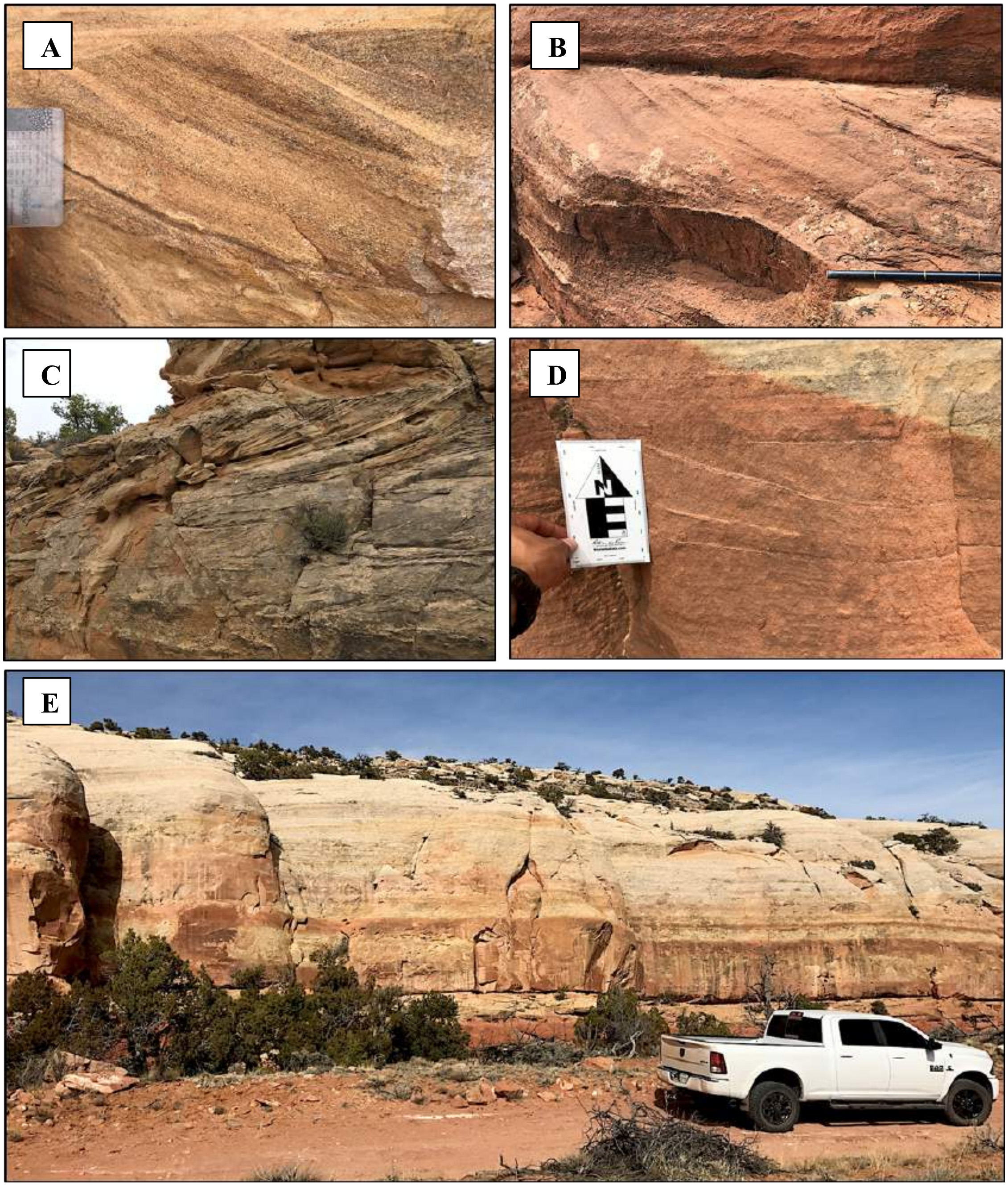


Figure 2.1.1 – Trough Cross-Stratified Lithofacies A) Twenty centimeter thick bed of trough cross-stratified sandstone with tan coarse-grained trough cross beds and scattered Entrada Berries. **B)** Red meter thick trough cross-stratified sand with sharp erosional contact with the bed above. **C)** Large white meter scale trough cross-stratified sandstone. **D)** Small scale trough stratification with individual coarse-grained troughs. **E)** Outcrop expression of large scale trough cross stratified sandstone

2.1.2 Structureless Sandstone

The base of the Entrada Formation is composed of bulbous beds of fine-grained sandstone that is well sorted and well rounded. The upper and lower contacts of this unit are sharp and erosional. This unit is bounded above by trough cross-stratified sandstone from within the Entrada Formation and below, by the eolian Navajo Formation. Because both contacts are sharp they can be easily recognized by the contrasting colors (Figure 2.1.2 A&B**)**. This basal unit of the Entrada Formation is always a shade of reddish-orange and always contains white chert grains known as "Entrada Berries" (Wright *et, al.* 1962). These beds lack sedimentary structures and can be best described as being massive (Figure 2.1.2). The structureless sandstone lithofaces is broken up into two distinct beds separated by a thin recessive siltstone (Figure 2.1.2 C).

2.1.3 Wave Ripple Cross-Stratified Sandstone

Wave ripple cross-stratified sandstones are beautifully preserved throughout the Entrada Formation found along the northern flank of the Gypsum Valley salt wall (Figure 2.1.3). Grains are typically fine grained, well rounded and moderately well sorted. Individual beds vary in thickness from approximately ten centimeters to half a meter thick. Bedding contacts vary locally from gradational to sharp contacts. Gradational contacts are most common where wave rippled sandstones grade into laminated sandstone beds. When sharp erosional contacts are present individual beds are thin and are bounded above and below by different facies. The color of this sandstone is commonly a shade of reddish tan on fresh surfaces and a dark brown to black color on weathered surfaces (Figure 2.1.3). Symmetrical ripple cross-stratification can also be identified in outcrop (Figure 2.1.3).

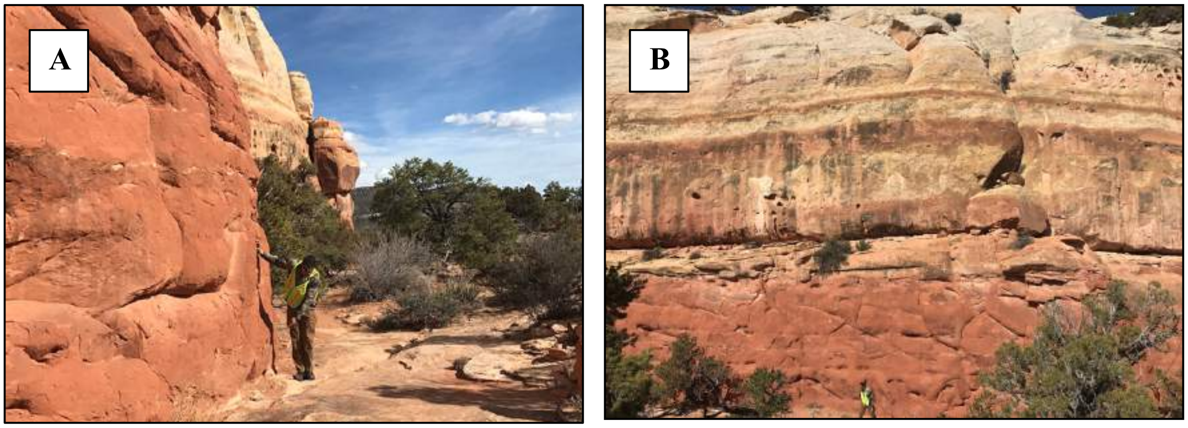


Figure 2.1.2 – A) Example of the structureless Sandstone Lithofacies. Sharp erosional contact with the red basal Entrada Formation and the tan colored Navajo Formation (Photo taken southeast of Ranchers Cabin section). **B)** Upper contact between the red basal Entrada unit and a trough cross-stratified sandstone bed above (Photo taken south of Ranchers Cabin section). **C)** Basal unit broken up into two thick beds separated by a red recessive mudstone (Photo Taken at the base of the Summit section).

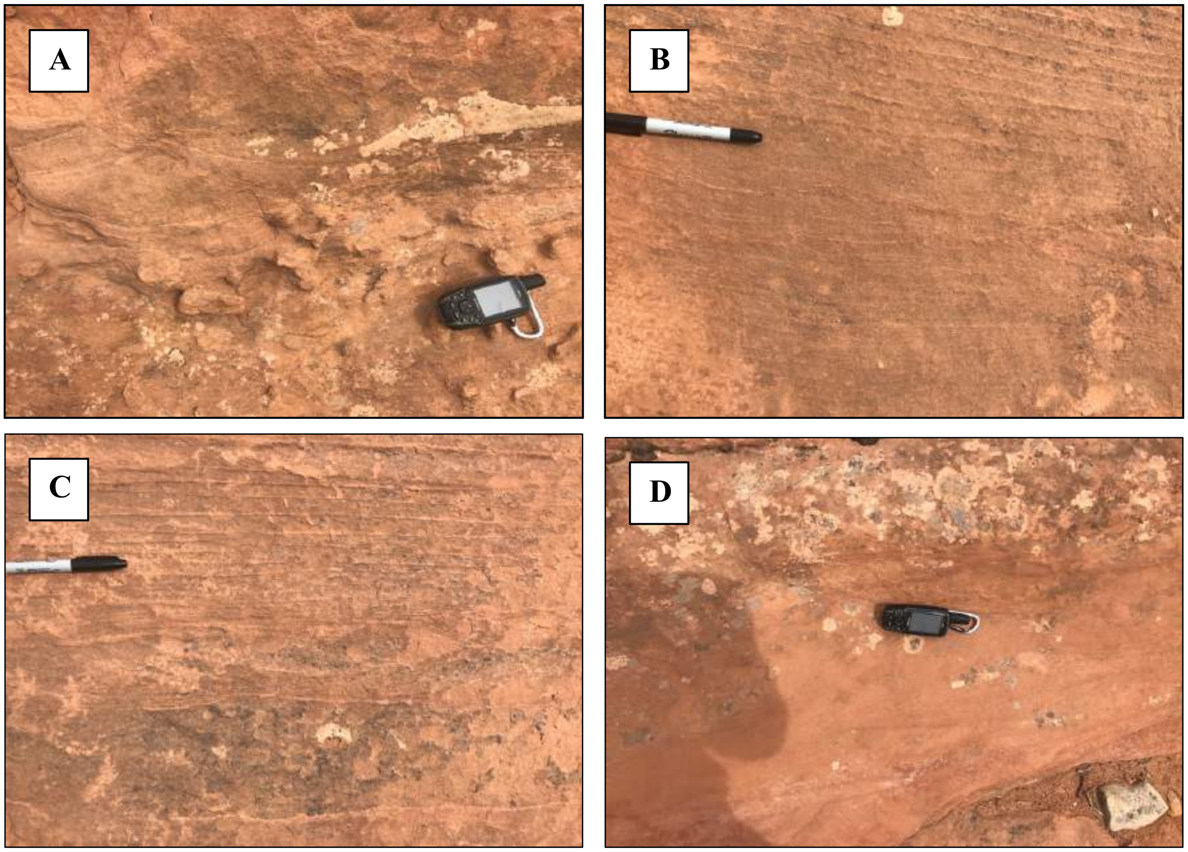


Figure 2.1.3 – **A)** Wave ripple cross-stratified sandstone bed twenty centimeters thick, weathered surfaces displaying a dark brown-black oxidized color (Photo taken at the Hamm Canyon section). **B)** Gradational contact with lamination sandstone above and below a 5 cm thick bed of wave rippled sandstone (Photo taken at the Hamm Canyon section). **C)** Sharp contacts with trough cross-stratified sandstone above a 50 cm bed of wave rippled sandstone (Photo taken at the Hamm Canyon section). **D)** Sharp contact below a wave rippled sandstone and gradational contact above with laminated sandstone (Photo taken at the Log Ridge Mine section).

2.1.4 Recessive Siltstone

A very distinctive although not common facies found at Gypsum Valley salt wall is best described as a recessive siltstone. This unit is predominantly made up of silt-sized grains and thin tabular ribbons of very fine sands. These thin siltstone beds are roughly twenty - fifty centimeters thick and are various shades of red and pink. This unit is only found separating beds of the strucureless sandstone within red beds that make up the base of the Entrada Formation. Within individual siltstone beds are horizons that are white in color and laterally extensive (Figure 2.1.4 B). This facies is identical to Ronson's (2018) white reduced siltstone horizon and is found at the same stratigraphic level.

2.1.5 Wind-Rippled Sandstone

Wind-rippled sandstone found within the Entrada Formation are fine grained, well sorted and well rounded. Beds are typically no more than one meter thick and are flat and horizontal. The contacts with the units above and below are sharp and erosional with trough cross-stratified sandstone above and structureless sandstone below (Figure 2.1.5**)**. The color of these beds is variable, from multiple shades of red and white-tan. Laminae were identified based on key features such as inverse grading and sparse ripple forset laminae. These laminae are approximately 2 mm thick and composed of scattered granules of chert grains referred to as "Entrada Berries" by Wright,et al. (1962).

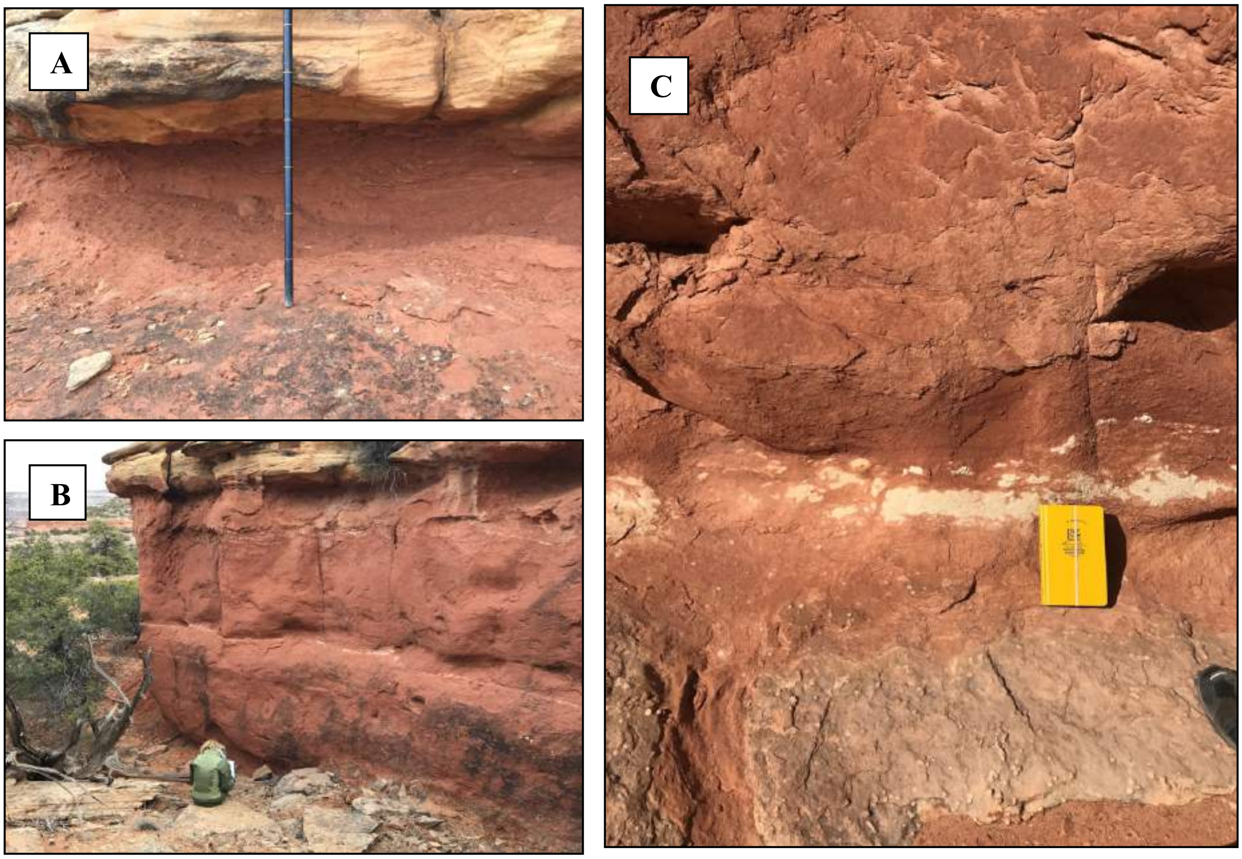


Figure 2.1.4 – A) 40 cm thick recessive siltstone bed with thin sand ribbons that appear wavy and irregular (Photo taken at the Summit section). **B)** Recessive siltstone beds with white horizons interbedded with featureless siltstone beds found at the base of the Entrada Formation (Photo taken at the Hamm Canyon section). **C)** Close up view of white horizons within the recessive siltstone bed (Photo taken at the Summit section).

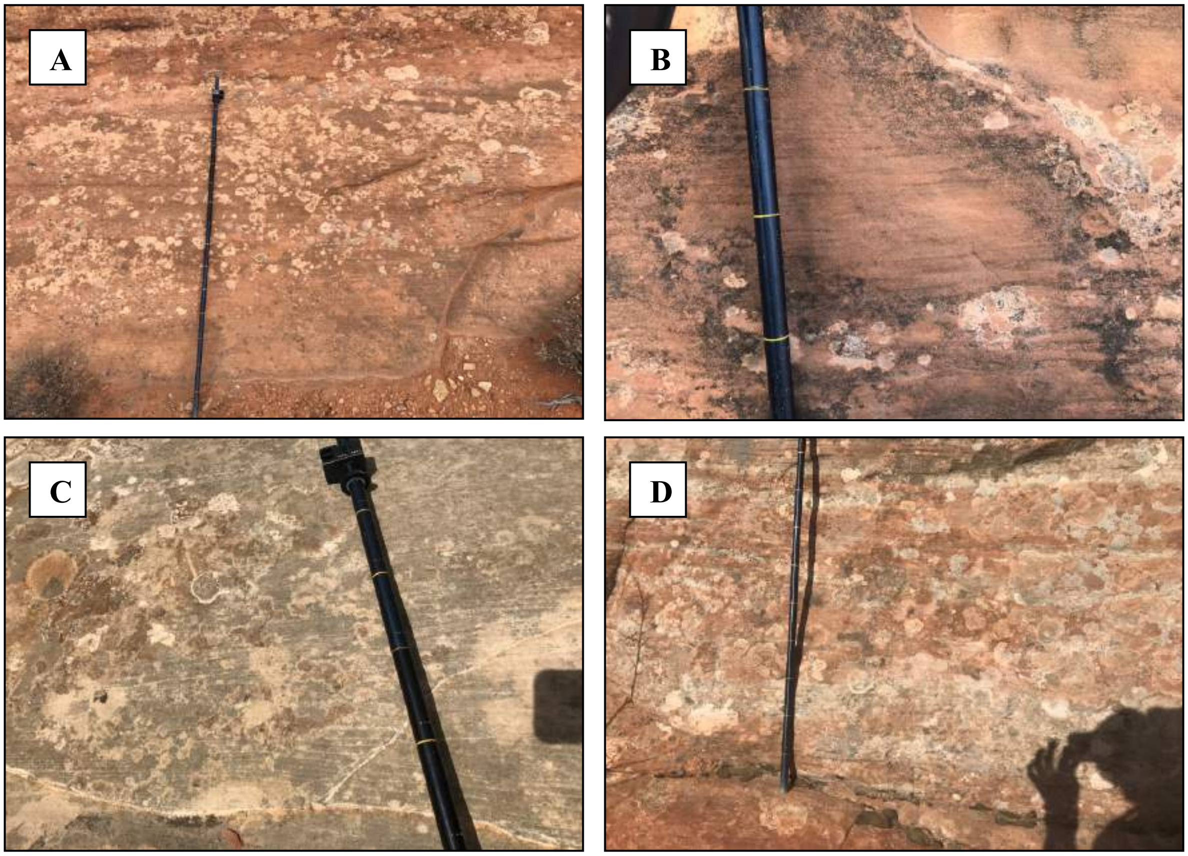


Figure 2.1.5 – A) One-meter-thick wind rippled sandstone with trough cross-stratified sandstone above separated by a sharp erosional contact (Photo taken at the Hamm Canyon section). **B)** Small scale discontinuous ripples within a 40 cm thick bed (Photo taken at the Hamm Canyon section). **C)** White-tan colored wind rippled sandstone with 2 mm thick laminae (Photo taken at the Cougars Den section). **D)** 1 m thick bed of wind rippled sandstone with bands of red and white color and massive red sandstone below (Photo taken at the Ranchers Cabin section).

2.1.6 Flaser Bedded Sandstone

Flaser bedded sandstones are commonly found within the base of the Entrada Formation and are identical to the flaser-bedded sandstone facies identified by Ronson (2018) at the northwest end of Gypsum Valley. Sand grains are typically fine grained and a light red color. Finer grains are easily seen by their dark red color shown in Figure 2.1.6A. Thin muddy and discontinuous laminae drape the troughs a top of ripples. Individual beds are relatively thin and range from ten centimeters to forty centimeters in thickness. Contacts with the units above and below are always sharp, wavy and irregular. It is also common to find scattered chert grains called "Entrada Berries" (Wright et. al., 1962) throughout these beds and centimeter scale lags of "Entrada Berries" at their base

2.1.7 Burrowed Sandstone

Burrowed sandstone is one of many facies that is both laterally extensive and commonly found at Gypsum Valley (Figure 2.1.7). The burrowed sandstone is fine grained, well rounded and well sorted. Individual beds consistently vary between 1 m to 1.5 m thick, laterally continuous and slightly wavy and irregular at the top and bottom. Beds are predominantly red in color, although it is not uncommon to find white burrowed beds in Ham Canyon (Figure 2.1.7A). Any sedimentary structures that may have been present can no longer be seen due to the abundance of bioturbation. This facies can be easily distinguished in outcrop by its modeled appearance and irregular bedding planes. Burrows are evident in scattered outcrops and are inferred to be the cause of the mottling in the rest of the facies (Figure 2.1.7B and C).

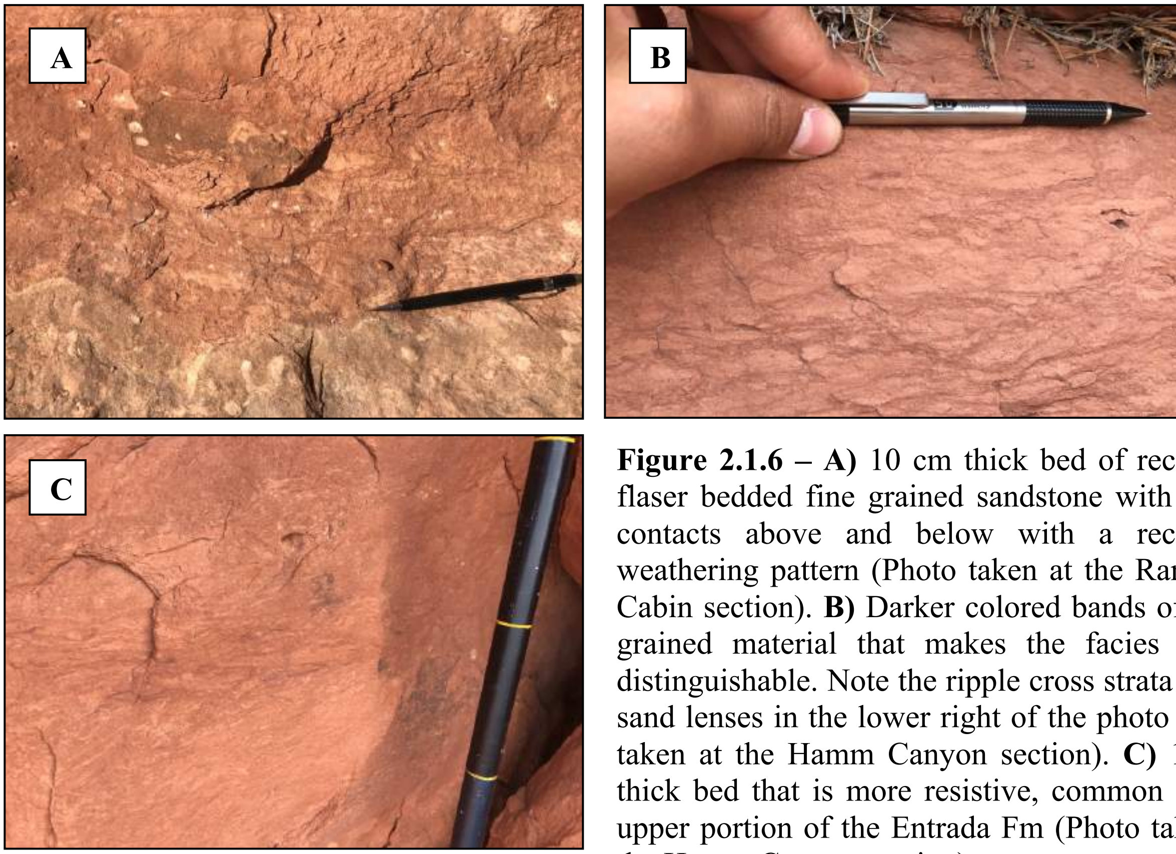


Figure 2.1.6 – A) 10 cm thick bed of recessive flaser bedded fine grained sandstone with sharp contacts above and below with a recessive weathering pattern (Photo taken at the Ranchers Cabin section). **B)** Darker colored bands of finer grained material that makes the facies easily distinguishable. Note the ripple cross strata in the sand lenses in the lower right of the photo Photo taken at the Hamm Canyon section). **C)** 15 cm thick bed that is more resistive, common of the upper portion of the Entrada Fm (Photo taken at the Hamm Canyon section).

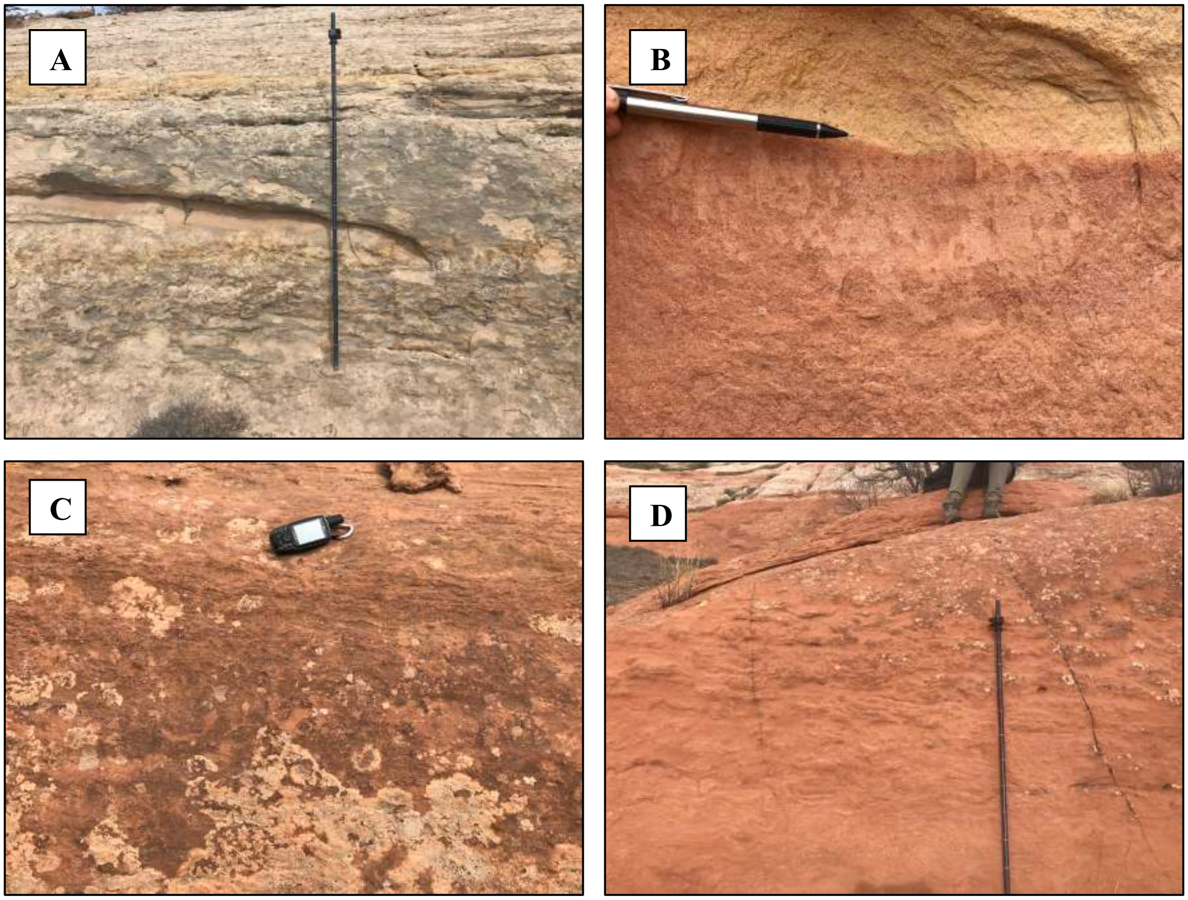


Figure 2.1.7 – A) Meter scale beds of white bioturbated sandstone (Photo taken at the Hamm Canyon section). **B)** Individual bed of well defined vertical burrows in contact with a bed of featureless sandstone above (Photo taken at Little Gypsum Valley). **C)** Close up view of burrowed sandstone lichen cover (Photo taken at the Log Ridge Mine section). **D)** Red-peach colored bed of bioturbated sandstone (Photo taken at the Ranchers Cabin section).

2.1.8 Current Rippled Sandstone

Current rippled sandstone is only found at the top of the Entrada Formation in one stratigraphic unit at Gypsum Valley. Current ripples were identified in these sands are medium grained, well sorted and well rounded. Outcrop surfaces are covered with 5mm cemented clumps of sand grains. These similar clumps have previously been noted by Ronson (2018) who referred to them as popcorn in a different facies within Little Gypsum Valley (Figure 1.1) (Figure2.1.8B**)**. The basal contact is sharp and erosional into the underlying featureless sandstone. This bed is approximately ten centimeters thick and exclusively a tan-buff color in outcrop (Figure2.1.8A**)**.

2.1.9 Gravel Lag Deposits

Gravel lag deposits are found in isolated occurrences around Gypsum Valley and mark the unconformable contact between the Glen Canyon group and the San Raphael group (Figure 2.1.9). Clasts tend to vary in size but are more commonly pebble sized. These clasts are dominantly composed of chert that varies in color from red-orange to green-gray. Grain edges are usually varied from rounded to subangular in nature and are supported by fine grain tan-red sandstone. Sedimentary structures associated these deposits are typically subhorizontal laminations and ripple cross stratification. A well-exposed example is found where the Entrada Formation onlaps the megaflap at the southern end of the diapir (Figure 1.1).

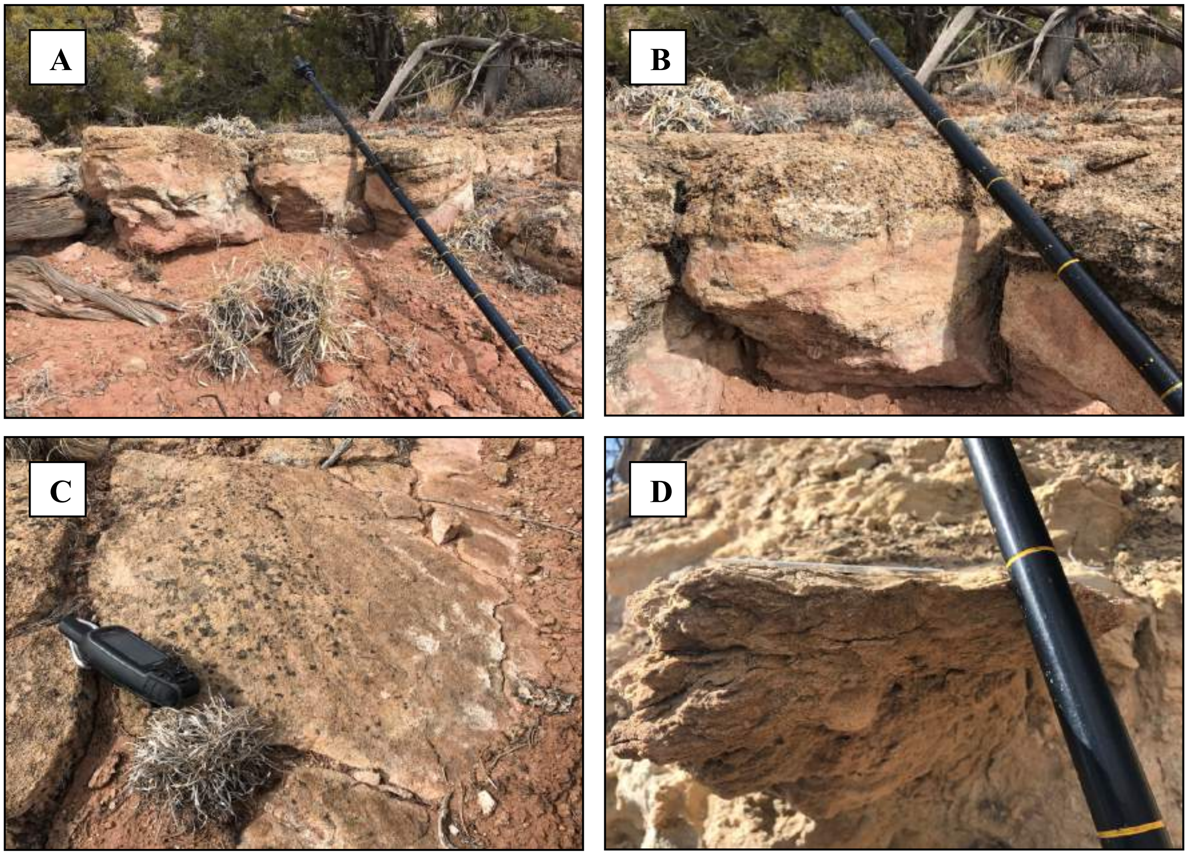


Figure 2.1.8 – A) Sharp irregular contact with a featureless sand stone below (Photo taken at the Hamm Canyon section). **B)** 5mm sized sediment clumps similar to what was seen by Ronson, 2017 (Photo taken at the Hamm Canyon section). **C)** Bed top view of current ripples (Photo taken at the Hamm Canyon section). **D)** Cross sectional view of current ripples asymmetrical geometry (Photo taken at the Log Ridge Mine section).

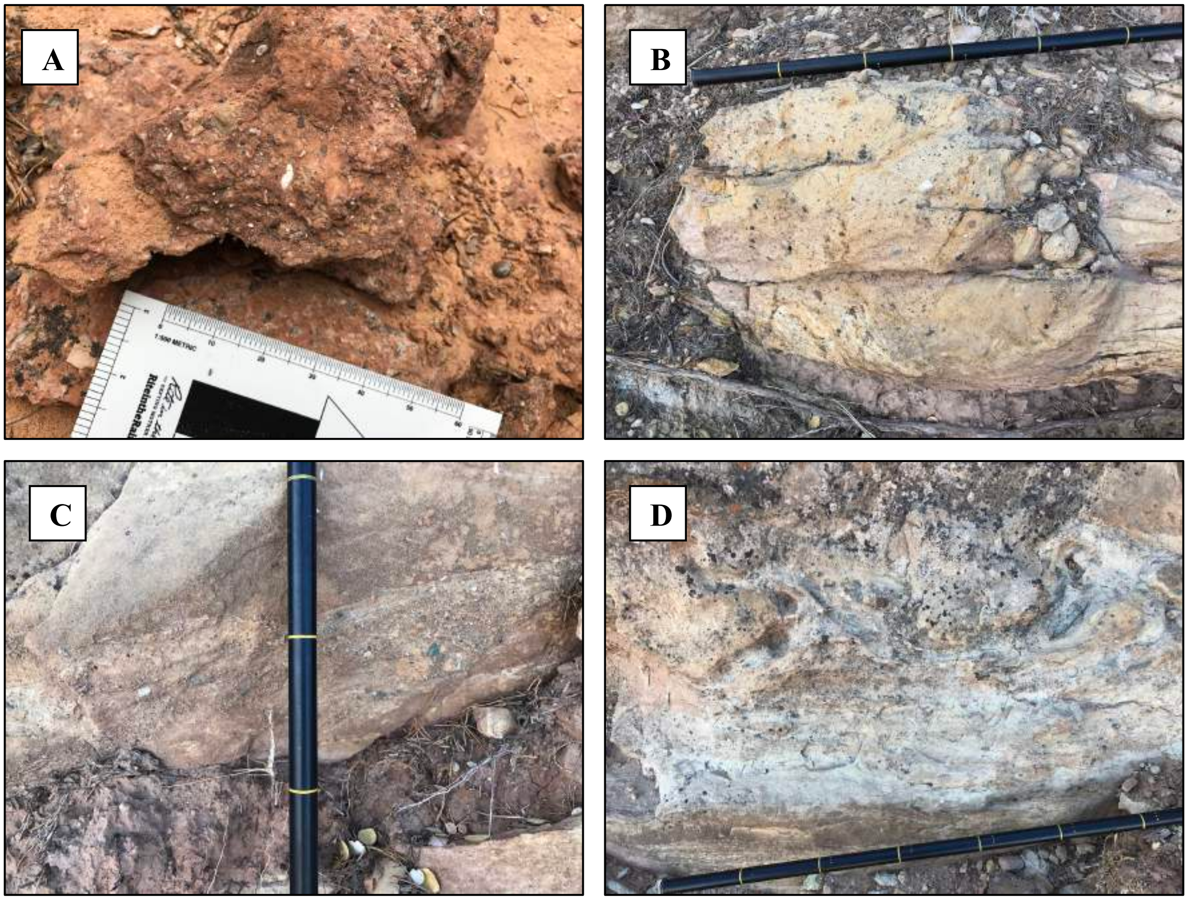


Figure 2.1.9 – A) Red gravel lag deposit commonly found at the base of the Carmel/Entrada Formations. Gravel is composed of pebble-sized clasts of chert that vary in color and shape (Photo take at Little Gypsum Valley). **B)** Tan colored bed of pebble sized gravel composed of varying shapes and colors (Photo taken at the MegaFlap area). **C)** 10 cm bed of granule sized clasts of chert (Photo taken at the MegaFlap area). **D)** Gravel bed with soft sediment deformation (Photo taken at the MegaFlap area)**.**

2.1.10 Soft Sediment Deformation

Occurrences of soft sediment deformation are commonly found along the lower half of the Entrada Formation found at the Gypsum Valley salt wall. These structure include ball and pillow structures and dish structures (Figure 2.10). Grain size is dominantly fine grain sand; grains are rounded to well-rounded and well sorted. These occurrences are found in generally in 0.5m-thick beds that are interbedded with wave rippled sandstone and massive sandstone and occasionally interbedded with trough-cross stratified sandstone.

2.1.11 Avalanche Deposits

Avalanche deposits are commonly found throughout the Entrada Formation both regionally and locally at the Gypsum Valley salt wall. These deposits are found along individual foresets of trough cross beds (Figure 2.1.11). Grain size ranges from fine to medium grain throughout the section and vary in color from tan, red to white (Figure 2.1.11). Avalanhe deposits forms tongues 2-7 cm thick in the lower parts of large foresets. They teypicall have abrupt noses at the bottoms, and taper gradually at the top. They are identical to foresents interpreted as avalange, or grain flow strata by Rubin and Hunter (1977).

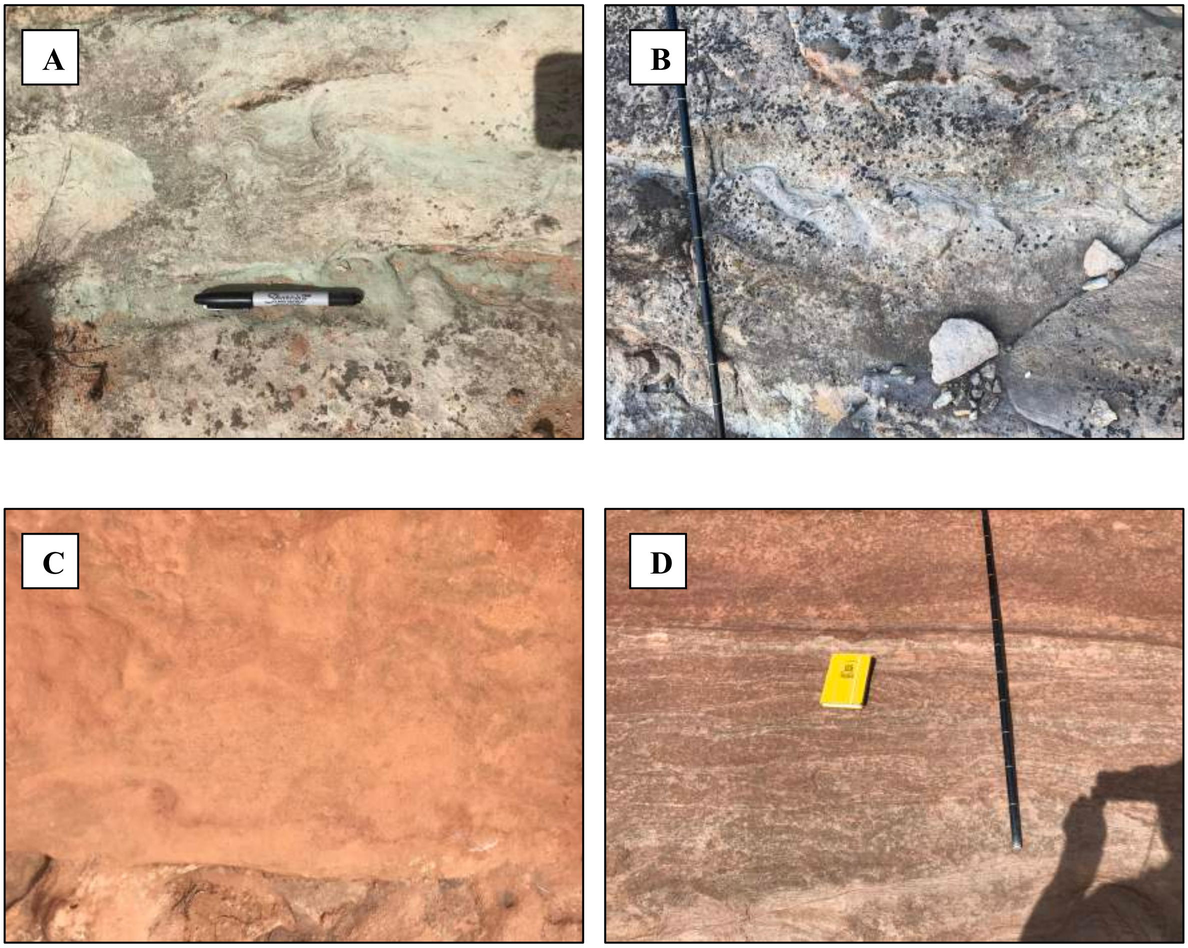


Figure 2.1.10 – A) White fine grain sandstone only found at the Cougars Den section with dish structures. **B)** Exposure of gravel lag deposits found at the base of the Entrada Formation, example of ball and pillow structures (Photo taken at the Mega Flap). **C)** Fine grain sandstone found in the bottom half of the Entrada Formation containing soft sediment deformation (Photo taken at the Ranchers Cabin). **D)** Bed of red fine grain sandstone with abundance of dish structures (Photo taken at the Log Ridge Mine section).

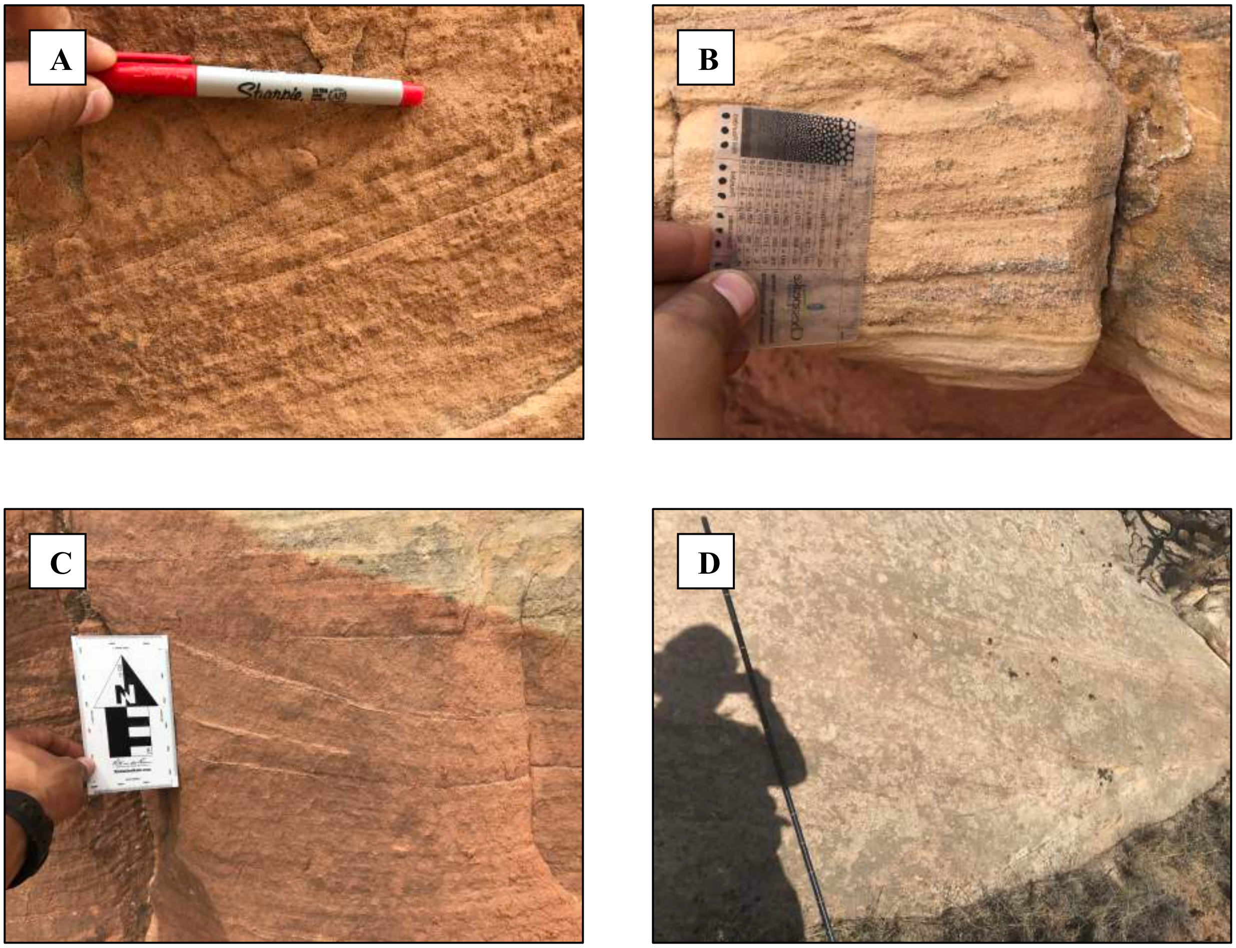


Figure 2.1.11 – A) Millimeter scale avalanche deposits along the foresets of small trough cross beds (Photo taken at the Cougars Den section). **B)** Milimeter scale avalanche deposits along shallow foresets (Photo taken at the Summit section). **C)** Centimeter scale avalanche deposits along foresets (Photo taken at Little Gypsum Valley). **D)** Meter scale avalanche deposits (Photo taken at the Hamm Canyon section).

2.1.12 Lithofacies Distribution

The study area can be split in half between the Hamm Canyon and Cougars Den measured sections based on the distribution of lithofacies (Figure 2.1.10). In the north at the Summit section, Ranchers Cabin and Hamm Canyon sections the dominant facies are dry eolian facies, mainly large eolian dunes (2.1.10). South of Hamm Canyon at the Cougars Den, Log Ridge Mine and Early Morning Mine sections wet facies are most abundant, primarily wave-rippled sandstone and bioturbated sandstone. (Figure 2.1.10)

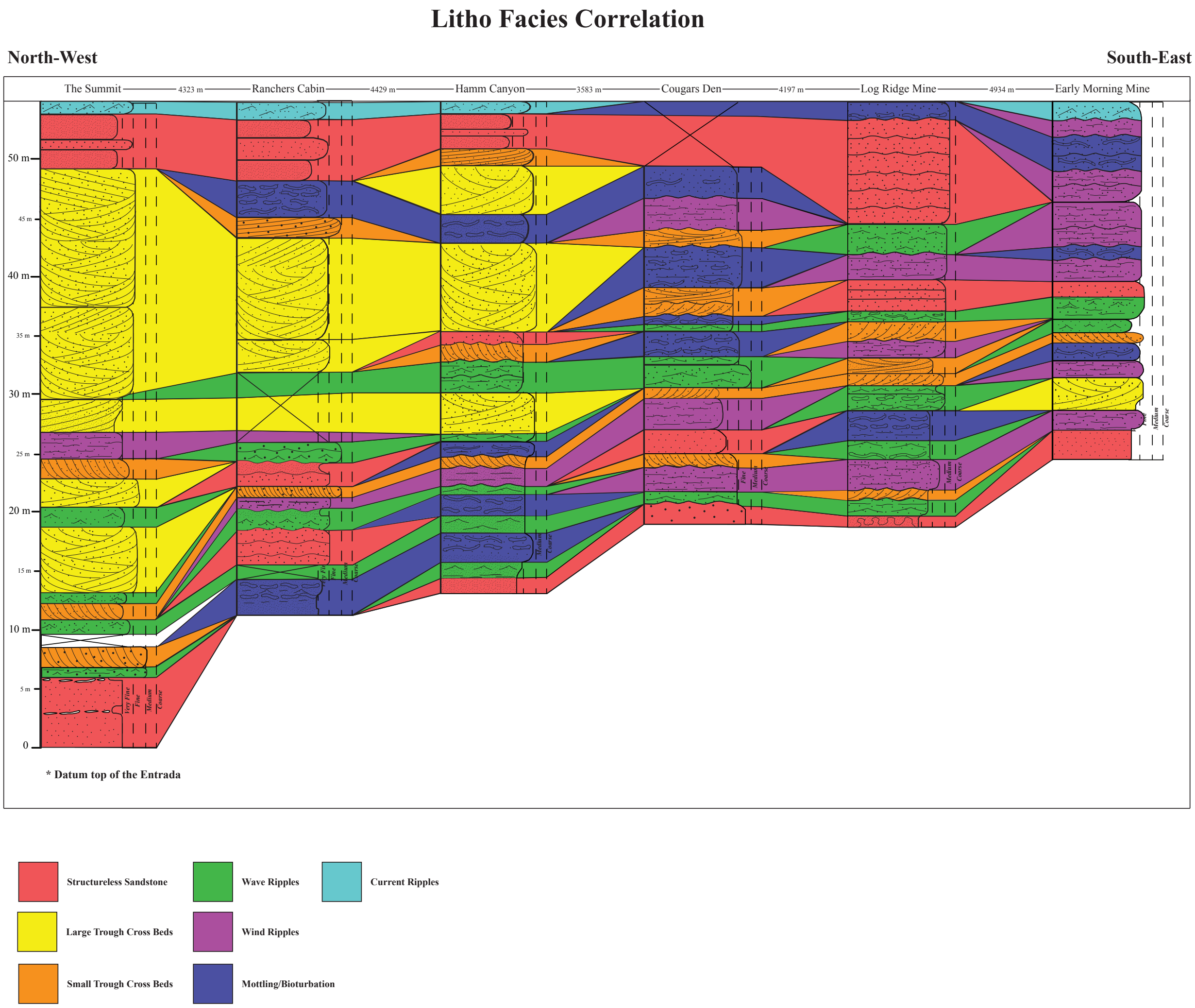


Figure 2.1.12 – Lithofacies correlation across the study area show the lateral distribution of thickness and facies across the study area. Section locations are shown in Figure 1.1.

2.2 Facies Associations

During lithological correlation a total of 5 facies associations were identified. The 5 facies associations include: Tidal deposits, wet inter-dune deposits, large eolian dunes, small eolian dunes and horizontally bedded structureless sandstone. Facies associations loosely correlate to the stratigraphic units mentioned later in the text. The stratigraphy documented in this study is more complex and will be discussed later.

2.2.1 *Facies Association 1: Tidal Deposits*

2.2.1.1 Description

Tidal deposits are diagnostic of the basal portion of the Entrada Formation. These beds vary in thickness from 0.45 to 3 meters thick depending on the exposure (Figure 2.2.1 A). Tidal deposits are exclusively dark red in color and can be traced for kilometers. Contacts with the overlying units and the Navajo Sandstone below are sharp and scoured. Within these basal beds are two discrete zones separated by 5 cm thick bands of white blotches that are key markers found around the valley (Figure 2.2.1-A).

The two most dominant facies within the Tidal Flat Facies Association are the structureless sandstone and bioturbated sandstone. Flaser bedded sandstone, gravel lag deposits, and wave rippled sandstones are also found within this facies association. Very isolated occurrences of trough cross-stratified sandstones are also found within the Tidal Flat facies association. In ascending order, a typical tidal flat unit has a 1 – 1.5 m thick bed of structureless sandstone at the base, followed by amalgamated beds of bioturbated sandstone or wave-rippled sandstone that vary from 0.25 – 0.5 m in thickness. This facies association is occasionally capped by 0.5 – 1 m thick bed of trough cross-stratified sandstone.

Internal bedding is difficult to see due to the abundance of bioturbation and reworking of sediment (Figure 2.2.1-B). Grain sizes range from silt sized grains up to very fine sand that is well-sorted and well-rounded with the exception of coarse lag deposits and calcite crystals scattered throughout (Figure 2.2.1-C&D). Visible sedimentary structures include flaser bedded sands, horizontal laminations, aqueous ripples and massive sands (Figure 2.2.1-E&F).

2.2.1.2 Processes

The presence of coarse-grained lag deposits and silt-sized grains suggest that deposition occurred in a low energy environment coupled with marine ravinement during transgression (Cattaneo and Steel 2003). The prominent red color of these beds with the exception of the two 5 cm thick reduced horizons suggest that the sediments have been subjected to oxidation The abundance of flaser bedded sands, alternating sands and silts along with calcite crystals suggest that the sediments were exposed to fluctuations in current flow and occasional desiccation, indicative of tidal flat deposition (Reineck and Wunderlich 1968, Nio and Yang 1991). The presence of aqueous ripple cross-stratification and laminations with fine sandstones and siltstones suggest diminished current flow (Nio Yang 1991). The thin bedding suggests deposition in a tidal flat, and the low overall thickness suggests deposition in the upper, landward parts of the flat. Blakey et al. (1984) interpreted similar strata in their Redbed Facies of the Carmel Formation as upper tidal flat and Sabkha deposits. The isolated eolian cross-stratified sets indicate occasional desiccation of the tidal flat and migration of isolated eolian dunes across its surface

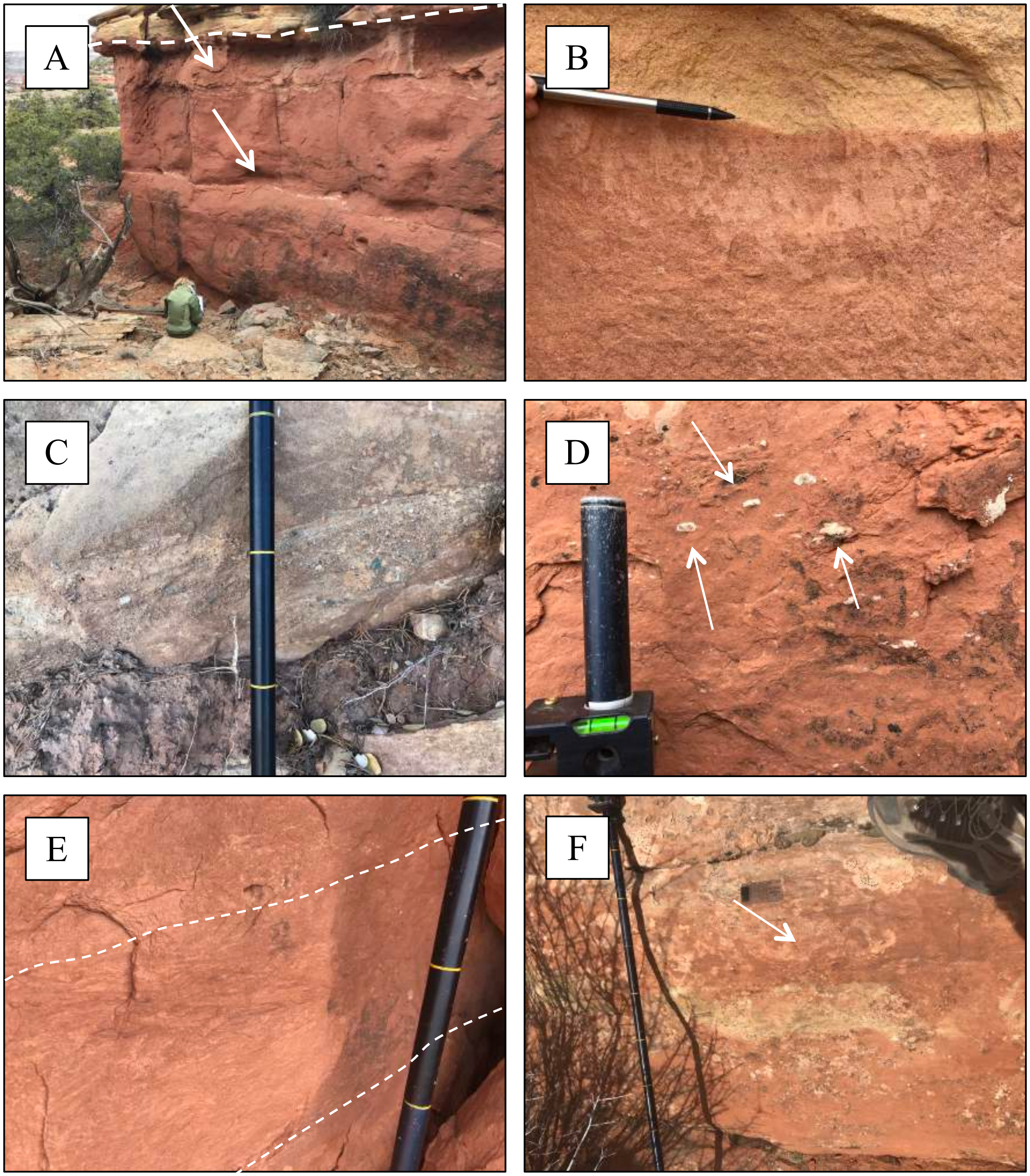


Figure 2.2.1 - Tidal Facies Association: **A**) Outcrop photo of tidal facies association displaying 5 cm white bands of blotches and sharp scoured contact with the unit above (Photo taken at the Summit section). **B**) Faintly laminated fine grain sandstone disrupted by bioturbation. **C**) Silt-sandstone with coarse pebble lag deposit (Photo from Little Gysum Valley). D) Centimeter sized calcite crystals(Photo from Hamm Canyon). **E**) Flaser bedded sandstone bed (Photo from Hamm Canyon section). **F**) Faint aqueous rippled sandstone (Photo from Ranchers Cabin section)

2.2.2 *Facies Association 2: Wet Inter-Dune*

2.2.2.1 Description

Wet interdune deposits are interbedded with dry eolian deposits throughout Gypsum Valley and are concentrated in the lower half of the Entrada Formation, stratigraphically above the tidal facies. Beds also vary in thickness from approximately 6 m – 12 m thick. These beds can be traced for kilometers. The most dominant lithofacies within the Wet Interdune Facies Association are wave-rippled sandstone, bioturbated sandstone, and soft sediment deformation. These beds vary from 0.25 – 1 m in thickness. The Wet Inter-Dune sequence contains variable lithofacies assemblages that typically have a wave-rippled sandstone at the base. These sequences are most abundant in the southeastern portion of Gypsum Valley, although there are scattered occurrences of wet interdune sequences in the northern portion of Gypsum Valley as well. An aqueous setting is interpreted based on the presences wave ripples (Figure 2.2.2-C) and varying degrees of soft sediment deformation (Figure 2.2.2-B) and bioturbation (Figure 2.2.2-A). An interdune setting is inferred from the presence of interbedded eolian trough cross stratification of the Small Eolian Dune Facies Association.

2.2.2.2 Processes

The variability in grain size from fine-grained sandstone up to medium-grained sandstone represents episodic flooding event into standing bodies of water (Viega, et al. 2002). The abundance of inter-bedded aqueous facies and eolian facies (Figure 2.2.2-D) indicates the presence of a high water table (Langford and Chan 1988). Any existing sedimentary structures are no longer visible as a result burrowing organisms, which reflects an aqueous environment favorable for life. The presence of soft sediment deformation is an indication of rapid sedimentation coupled with poorly consolidated sands that can readily be deformed. The presence of intercalated and surrounding eolian dune trough cross strata indicate an interdune setting. The Entrada Formation has been interpreted as a wet eolian system (Crabaugh and Kocurek 1993; Kocurek 1981). Strucureless sandstones and aqueously rippled sandstones have been interpreted as deposits of intermittently flooded interdunes (Cragaugh and Kocurek, 1993). The thin, parallel bedding has been interpreted as water table controlled interdunes surfaces (Crabaugh and Kocurek 1993).

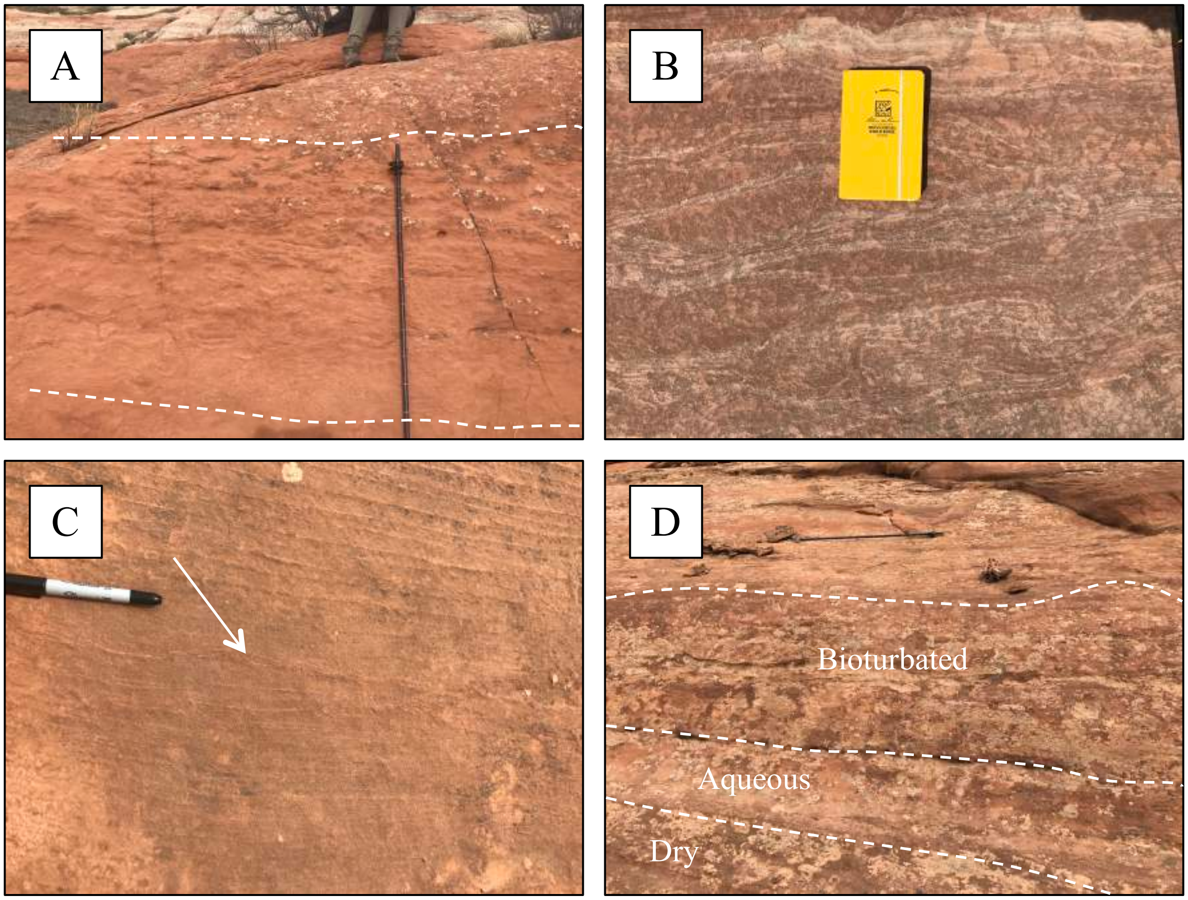


Figure 2.2.2 Wet inter-dune: **A**) Outcrop example of bioturbated-mottled sandstone (Photo from Ranchers Cabin section). B) Outcrop example of bed of soft sediment deformation with field book for scale (Photo from Earlt Morning Mine section). C) Wave rippled sandstone exposure (Photo taken at the Hamm Canyon Section). D) Outcrop example of inter-bedded wet inter-dune beds and dry eolian dune beds (Photo from the Early Morning Mine Section)

2.2.3 *Facies Association 3: Large Eolian Dunes*

2.2.3.1 Description

Large trough cross-stratified sands are the diagnostic feature of the Entrada Formation. Beds are a variety of shades of white-grey, tan, pink to red in color and have a distinct weathering pattern that produces vertical cliffs and smooth ledges (Figure 2.2.3). Individual beds vary in thickness from 1 m to approximately 2.5 m thick and are found in four of the six measured sections. A typical sequence of the Large Eolian Dune facies association contains amalgamated beds of wind-rippled sandstone and festoon cross-stratification. Festoon cross-stratification can be seen at both high and low angles with scattered occurrences avalanche deposits on their foresets (Figure 2.2.3-B & Figure 2.2.3-C). These sands are thickest towards the Summit section (Figure 1.1) in the northwest and generally thin towards the southeast.

2.2.3.2 Processes

Large trough cross-stratified sandstone with low and high angle trough cross-stratification is present and suggests a variability in sediment supply and wind speed (Werner 1995). These variables contributed to altering typical Entrada barchan dunes into a more transverse style of dune (Tsoar and Blumberg 2002) (Figure 2.2.3-D). The variability in the color of exposures represents varying levels of oxidation has taken place (Chan, et al. 2000). More variability within this facies associations is displayed by the different weathering patterns seen in outcrop, the shear cliffs are more resistant to weathering than the smooth ledges (Figure 2.2.3 - A&B). Crabaugh and Kocurek (1993) interpreted this facies in Entrada exposures northwest of the study area as deposits of complex dunes, with smaller dunes migrating obliquely across lareger dune forms.

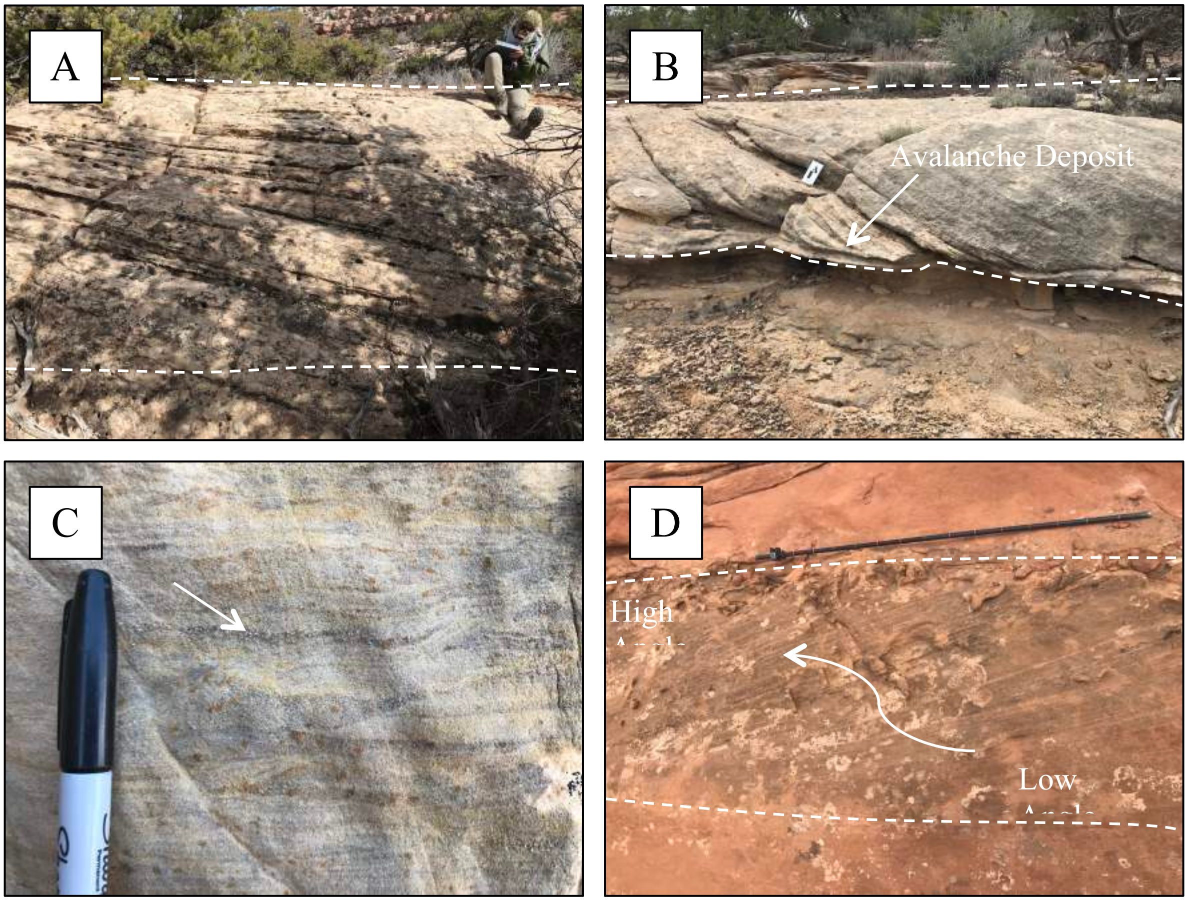


Figure 2.2.3 Large Eolian Dune Facies Associations: **A)** Cliff face with low angle trough cross-stratified sandstone (Photo taken at the Summit section). **B)** Smooth ledge outcrop of white low angle trough cross-stratified sandstone and more resistive avalanche deposit (Photo taken at Little Gypsum Valley). **C)** Close up view of a coarse-grained wind ripple (Photo taken at Little Gypsum Valley). **D)** Cliff face of red sandstone with low angle trough cross-beds that transition to high angle (Photo from the Log Ridge Mine section).

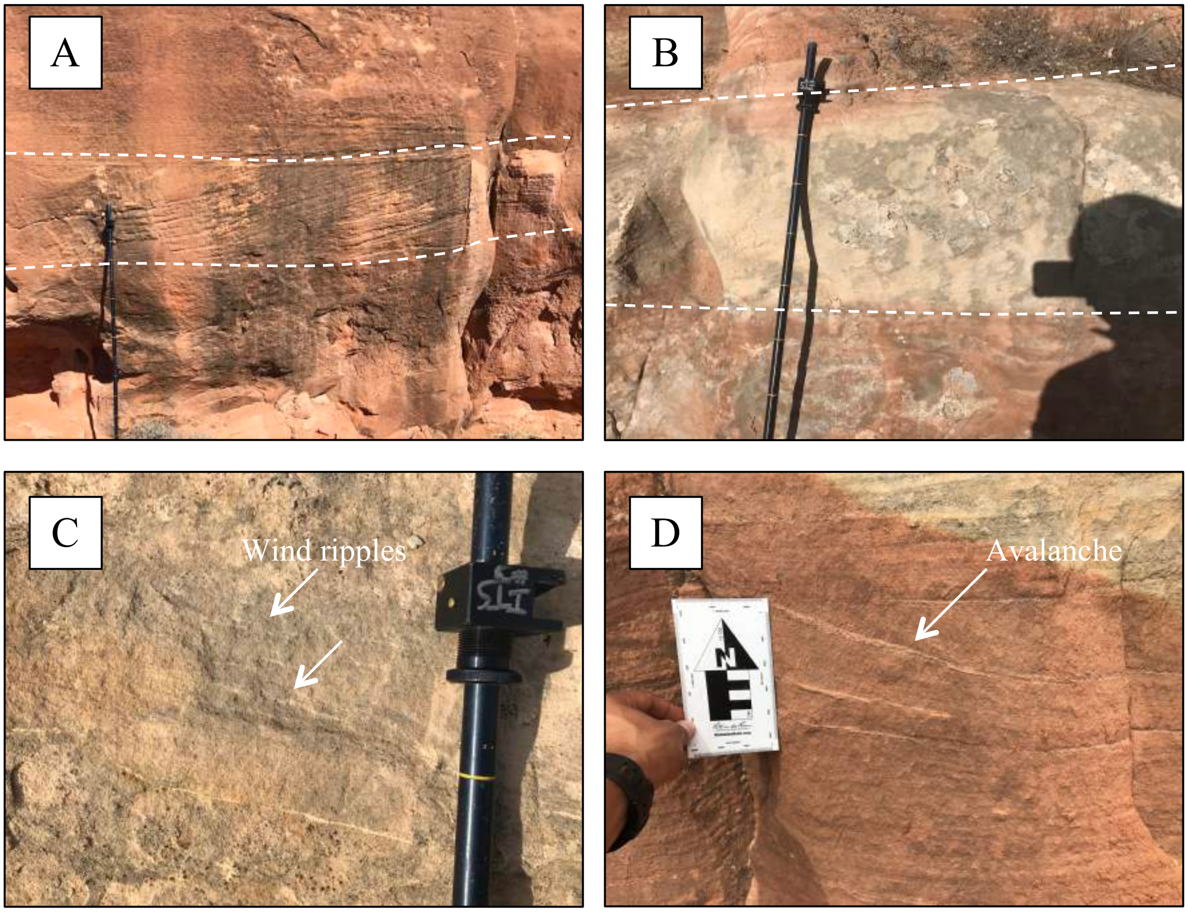
2.2.4 *Facies Association 4: Small Eolian Dunes*

2.2.4.1 Description

Small trough cross-stratified sandstones can be found in the lower two thirds of the Entrada Formation and can be traced across the study area (Figure 2.1.10). These beds range in thickness from 0.25 m up to a maximum of 0.5 m consistently. Typically, a sequence of the small eolian facies association contains amalgamated beds of trough cross-stratified sandstones with scattered occurrences of avalanche deposits on their foresets and wind-rippled sandstone.

2.2.4.2 Processes

Small trough cross-stratified sandstones are very similar to the large eolian dune facies association mentioned earlier and only differ in the size of cross-beds and slight variations in grain size. Subtle variation in grain size is seen in outcrop as coarse grain ripples (Langford, et al. 2016). The smaller size of individual cross beds suggest reduced sediment supply, yielding small-scale barchan dunes that potentially had a less dense distribution of dunes (McKee and Bigarella 1979; Lancaster 1988). The abundance of barchan dunes present is evidence for unidirectional wind flow (Ford, et al. 2010). Similar smaller dune forms have been inferred as representing migration of dunes during episodes of high water table, where sand supply is limited (Loope et al. 1992; Crabaugh and Kocurek 1993).



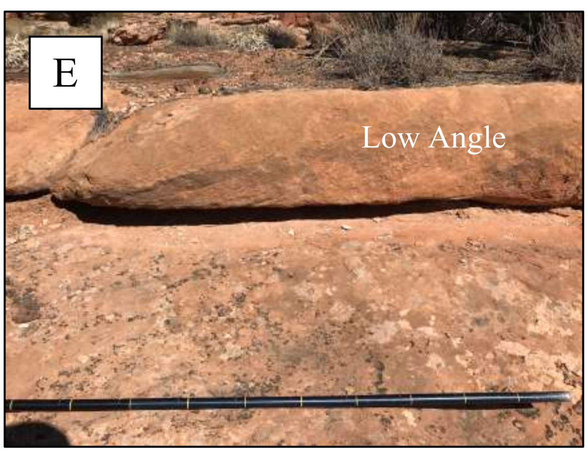


Figure 2.2.4 Small Eolian Dune Facies Association
A) Red cliff face of small low angle trough cross-stratified sandstone (photo from Cougars Den). **B)** Smooth white outcrop of high angle trough cross-stratified (Photo from Log Ridge Mine). **C)** Close up view of coarse-grained wind ripples (Photo from Hamm Canyon). **D)** Close up view of coarse grain avalanche deposits. (Photo from Little Gypsum Valley **E)** Smooth ledge of small low angle trough cross-stratified sandstone (Photo from Hamm Canyon).

2.2.5 Facies Associations 5: Horizontally Bedded Structureless Sandstone

2.2.5.1 Description

This facies association comprises the top 6 m of the Entrada Formation and, when exposed, is overlain by the Summerville Formation. Bedding contacts are scoured and sharp. This facies association is characterized by distinct laterally extensive packages of white to pink, horizontally bedded sandstone with scoured contacts. Individual beds lack any easily distinguishable sedimentary structures with the exception of a few scattered occurrences of faint cross stratification (Figure 2.1.8).

2.2.5.2 Processes

A lack of identifiable sedimentary structures within this facies association makes inferring processes difficult. Throughout Big Gypsum Valley (Figure 1.1) these deposits vary in shades of white, tan, red and pink which is an example of varying degrees of oxidation (Chan, et al. 2000). The presence of wavy and irregular bedding combined with scours represents a variety of possible processes such as variable wind speeds, variable sedimentation rates, changes is moisture at the surface of sediments and potential changes in topography caused by salt movement (Trudgill et al. 2004).

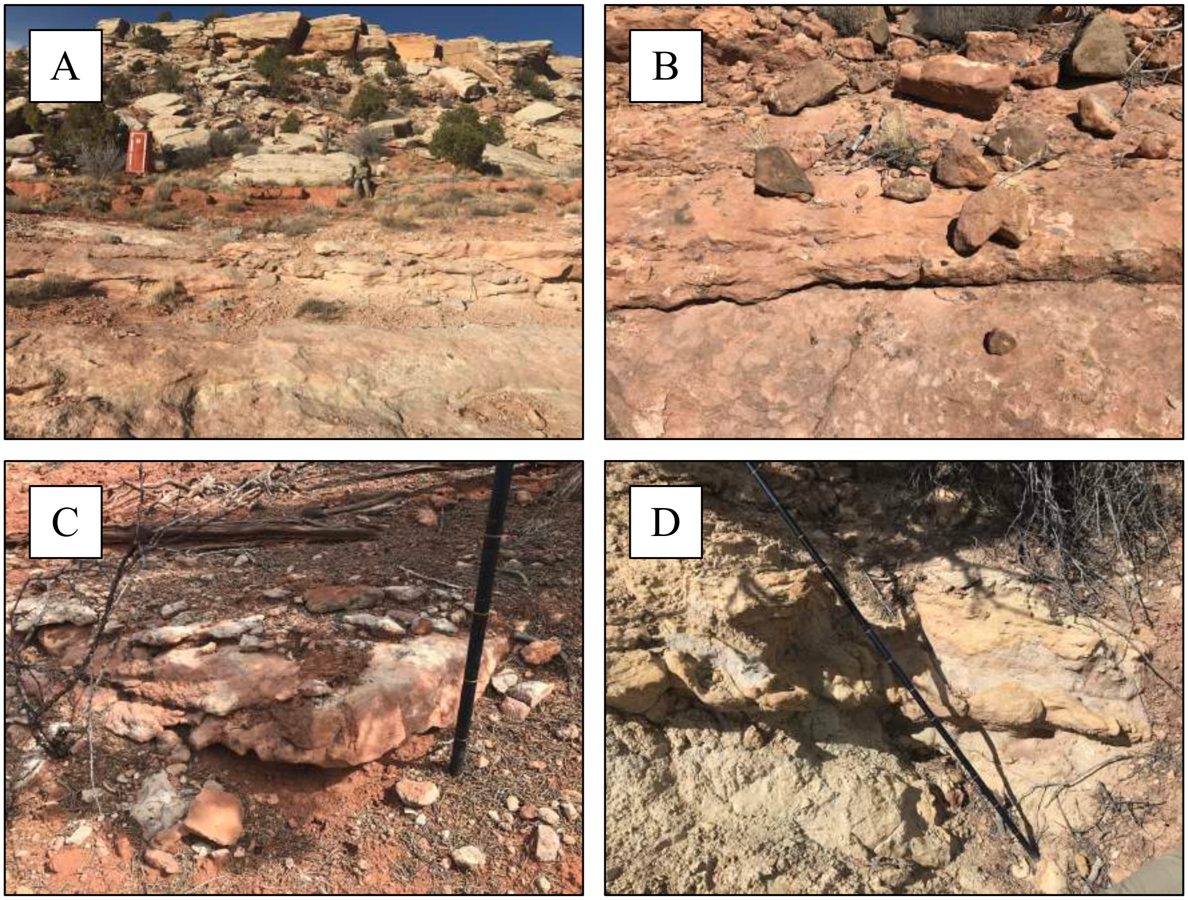


Figure 2.2.5 Scoured Eolian Facies Association: **A)** Outcrop exposure of small ledges of scoured eolian sediments that have a variety of colors produced by variability in oxidation (Photo from the Ranchers Cabin section). **B)** Close up view of a scoured bed lacking any sedimentary structures (Photo taken at the Hamm Canyon section). **C)** Example of varying degrees of oxidation (Photo taken at the Summit section). **D)** Small exposure of scoured sands that are white-tan in color (Photo taken at the Log Ridge Mine section).

Chapter 3: Stratigraphic Units

Four stratigraphic units similar to those documented by Shawe et al, (1968), were identified at Gypsum Valley during stratigraphic correlation (Figure 2.1.10). These units can be recognized regionally and mark changes in the environment. Beds on this flank of the salt wall strike northwest - southeast and dip to the northeast (Figure 1.1). Four stratigraphic units were identified during stratigraphic correlation: the Basal Tidal Unit, the Wet Inter-Dune Unit, the Cross-Bedded Unit, and the Horizontally Bedded Unit. The overall formation thickness ranges from 54 m at the Summit section to 23 m at Early Morning Mine section. Lateral thickness and facies composition within each unit vary across the study area. While these units are excellent for mapping the Entrada, in the study area the internal stratigraphy is much more complex.

3.1 Basal Tidal Unit

At the base of the Entrada Formation found at the Gypsum Valley salt wall lies the Basal Tidal Unit that is very similar to the Dewey Bridge Member recognized by Shawe et al. (1968). This unit has a consistent thickness of approximately 10 m across the entire study area (Figure 3.5). Exposures are dark red-pink in color and display a bulbous outcrop expression (Shawe et al. 1968). Contacts are sharp and erosional with the wet inter-dune unit above marked by a tan-buff colored bed of trough cross-stratified sandstone and the Navajo Formation below (Figure 3.1).

This unit is made up of amalgamated beds of structureless silt-fine grain sandstone, bioturbated fine grain sandstone, wave rippled sandstone, laminated fine grain sandstone and is capped by a thin trough cross stratified sandstone. This trough cross-stratified sandstone is a key marker bed for this unit and can be traced across the study area (Figure 3.1). Individual beds rarely exceed 0.50 m in thickness and tend to have bedding contacts that include sharp-erosional and gradational contacts.

Lithofacies composition at the Summit section is a combination of structureless sandstone, small trough cross-stratified sandstone and wave-rippled sandstone. The bottom half of the unit pinches out at the Ranchers Cabin section 4.3 km away while the upper half is correlatable (Figure 2.1.10). At the Ranchers Cabin section, facies include bioturbated sandstone, structureless sandstone, wave-rippled sandstone, wind-rippled sandstone and trough cross-stratified sandstone. The upper half of the unit pinches out towards the northwest at the Summit section while the base is correlatable 4.4 km to the southeast. At the Hamm Canyon section this unit is mainly composed of bioturbated sandstone and wave-rippled sandstone. Less abundant facies include trough cross-stratified sandstone, wind-rippled sandstone and structureless sandstone. Beds found at this section can be correlated in both directions (Figure 2.1.10).

Approximately 3.5 km southeast of the Hamm Canyon section is the Cougars Den section. The Cougars Den section facies composition includes structureless sandstone, wave-rippled sandstone, wind-rippled sandstone and trough cross-stratified sandstone. Beds in this section tend to pinch out in both directions with the exception of the marker bed, a single bed of wave-rippled sandstone and a bed of structureless sandstone found at the base (Figure 2.1.10). Further southeast, at the Log Ridge Mine section the facies composition is mainly composed of wave-rippled sandstone and fewer beds of structureless sandstone, wind-rippled sandstone and trough cross-stratified sandstone. The top marker bed and a bed of structureless sandstone found at the base of the unit are correlable in both directions. The other beds pinch-out in both directions (figure 2.2.10). At the Early Morning Mine section the Facies are a mixture of structureless sandstone at the base followed by wind-rippled sandstone, trough cross-stratified sandstone, wind rippled sandstone and bioturbated sandstone (Figure 2.1.10).

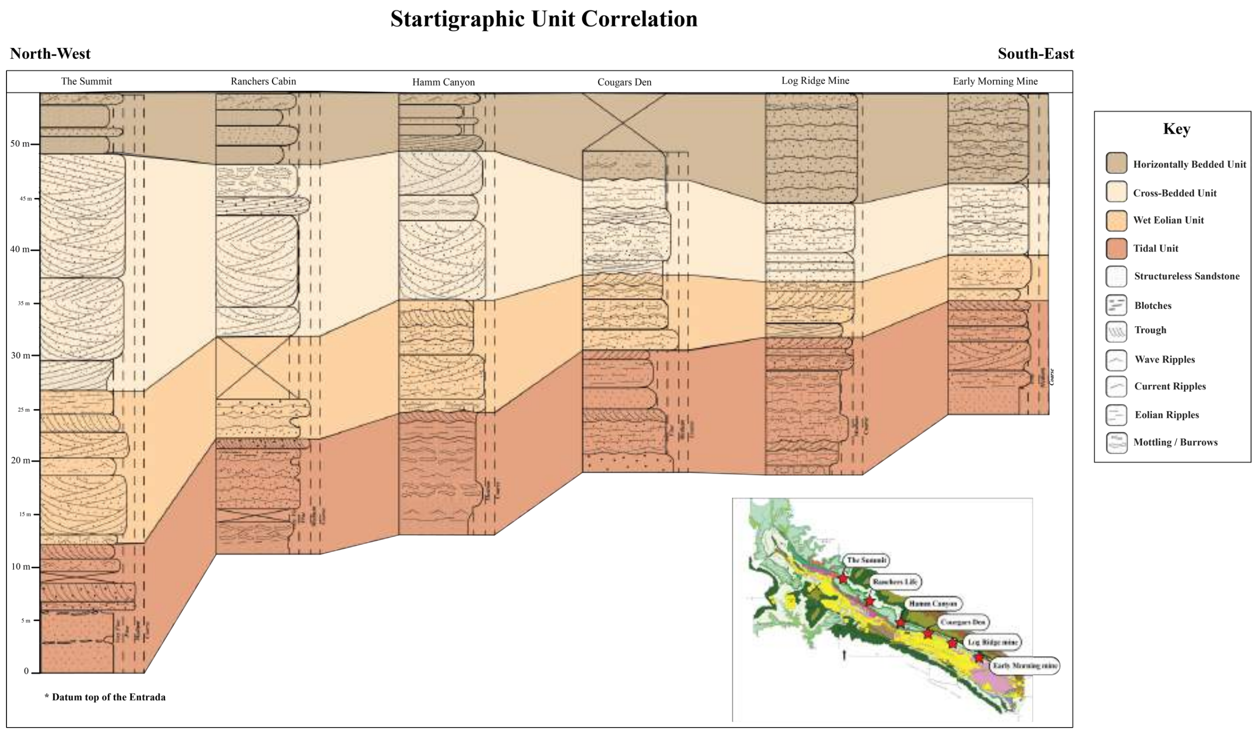


Figure 3.0 - Stratigraphic cross-section illustrating the lateral thickness distribution of individual stratigraphic units documented

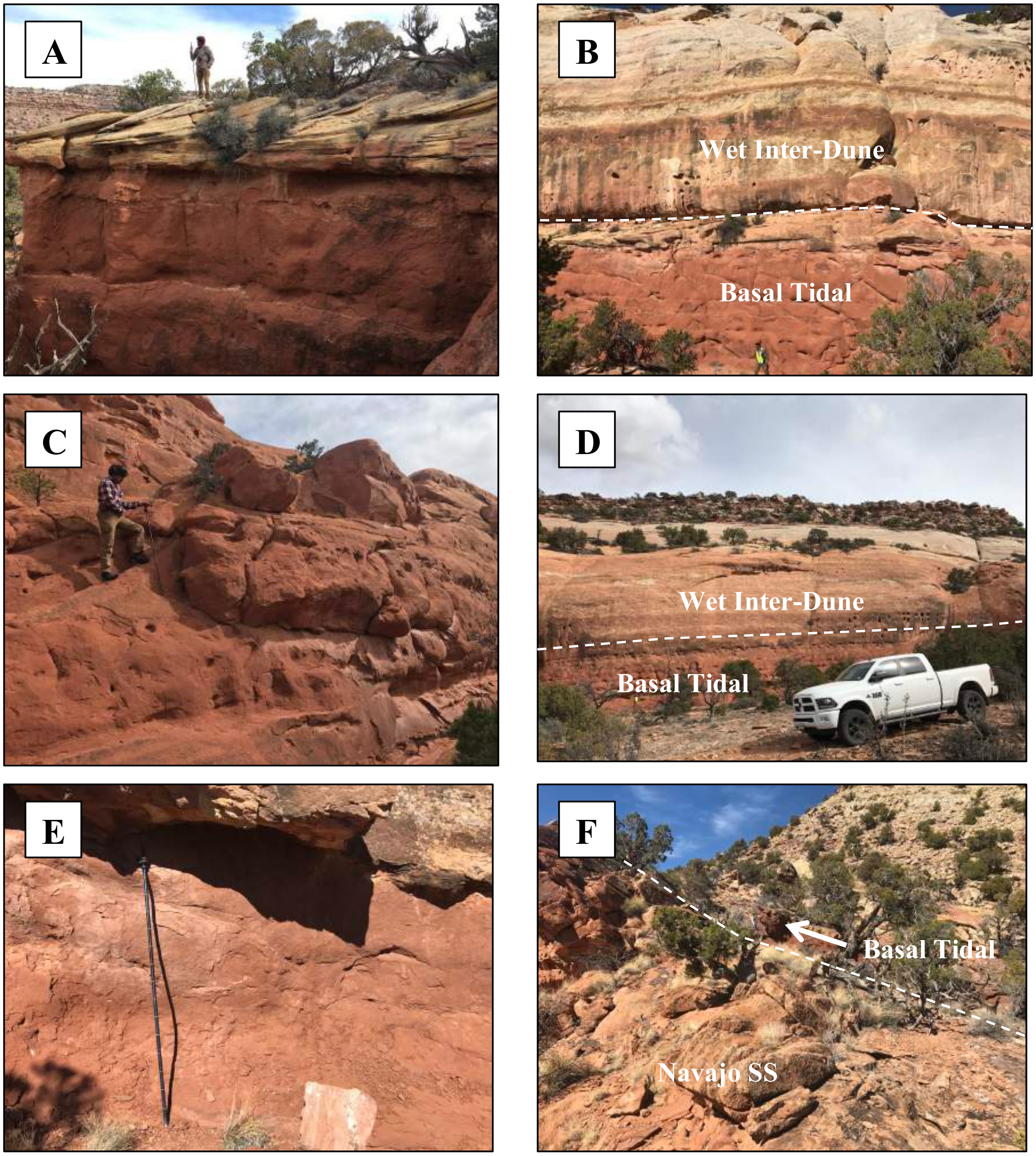


Figure 3.1 A) The Summit section exposure with shear cliff face and capping trough cross-stratified sandstone facies **B)** Cliff face between Ranchers Cabin and Hamm Canyon sections. **C)** Humpy outcrop expression at the Hamm Canyon section. **D)** Hamm Canyon cliff face with upper contact highlighted. **E)** Representaive exposure from Log Ridge Mine. **F)** Photo taken at Early Morning Mine showing the Basal Tidal Unit contact with the Navajo Sandstone.

3.2 Wet Inter-Dune Unit

The Wet Inter-Dune Unit is a cliff forming tan-buff colored fine grain sandstone found at the base of the Slick Rock Member identified by Shawe et al. (1968) (Figure 1.3). Regionally, this unit is described as massive, where as in the Gypsum Valley area, it is described as a wet inter-dune unit. This unit contains a sharp erosional contact with cross-bedded unit above and the Basal Tidal unit below (Figure 3.5). In the northwest at the Summit Section its thickness is 15 m (Figure 3.5). Towards the southeast at the Early Morning Mine section it thins to 4 m thick (Figure 3.5). This unit is composed of similar facies as the Massive Unit described by Shawe et al. (1968), however they differ in lateral facies distribution. Wet facies such as wave rippled sandstone and bioturbated sandstone are more common in the southeast than in the northwest. The exposures of this unit in the southwest of the study area ranged from 7 to 15 m (Shawe et al., 1968) Beds within this unit vary in thickness from 0.25 m to 0.50 m thick and include wind-rippled sandstone, trough cross-stratified sandstone, wave rippled sandstone and structureless sandstone facies (Figure 3.2).

At the Summit section in the northwest this unit makes up 15 m of the section and is mainly composed of dry eolian facies such as large eolian dunes, small eolian dunes, wind-rippled sandstone and a single bed of wave-rippled sandstone (Figure 2.1.10). A majority of these facies pinch-out 4.3 km towards the southeast at the Ranchers Cabin section. At the Ranchers Cabin section 4.3 km southeast the unit is approximately 9 m thick. The upper portion is eroded back and mostly covered by modern alluvium. Two facies were identified here and include structureless sandstone and wave-rippled sandstone (Figure 2.1.10). The Hamm Canyon section is mainly composed of wave-rippled sandstone followed by lesser amounts of trough cross-stratified sandstone and structureless sandstone.

At the Cougar Den section the unit thins to 7 m and is composed wave-rippled sandstone, bioturbated sandstone and trough cross-stratified sandstone at the top. The bottom half of the unit pinches out at the Log Ridge Mine section and is correlable to the Cougars Den section towards the northwest. The upper portion pinches out towards the northwest at the Cougars Den and is correlable to the log Ridge Mine section in the southeast (Figure 2.1.10). The thickness at the Early Morning Mine section is 5 m and is composed of 3 facies. These facies include trough cross-stratified sandstone, wind-rippled sandstone and wave-rippled sandstone. All of these beds pinch out in both directions with the exception of the wave-rippled sandstone at the top, which is correlable in both directions to the next stratigraphic sections (Figure 2.1.10). At the Early Morning Mine section this unit is 4 m thick and exclusively made up of wave rippled sandstone and structureless sandstone, which are correlable to the northwest (Figure 2.1.10).

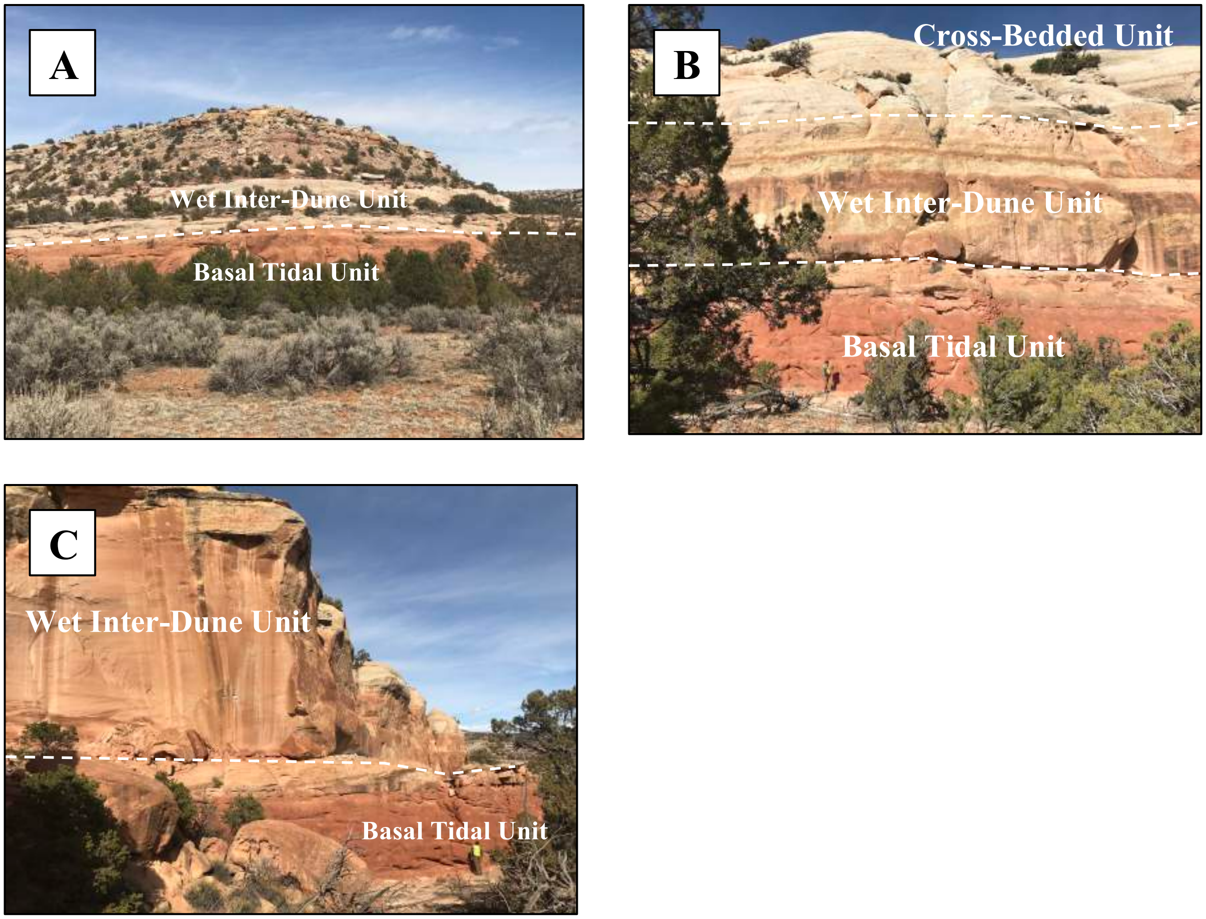


Figure 3.2 A) Photo taken near the Summit section illustrating the outcrop pattern in the northwest. **B)** Cliff face located southeast of the Ranchers Cabin section that is representative of shear cliff out crop pattern and stratigraphy. **C)** Photo taken in the northern portion of Hamm Canyon Showing the sharp contact between the Basal Tidal Unit and the Wet Inter-dune Unit.

3.3 Cross-Bedded Unit

The cross-bedded unit makes a portion of the upper half of the Entrada Formation at Gypsum Valley. This unit it identical to the cross-bedded unit described by Shawe et, al (1968) both in stratigraphic position and facies composition (Figure 1.3). However, the internal facies distribution of the cross-bedded unit is not uniform; festdune cross-stratification is dominant in the northwest unit while small trough cross-stratified sandstone and wind-rippled sandstones are dominant in the southeast. It forms steep cliff faces that can be found in various shades of white and tan. This unit is dominantly trough cross-stratified sandstone with fewer beds of wind-rippled sandstones, and bioturbated sandstone (Figure 2.1.10). At the Summit section in the northwest it is 21 m thick and thins towards the southeast at the Early Morning Mine section to 6 m (Figure 3.5).

At the Summit section in the northwest this unit is exclusively trough cross-stratified sandstone that can be correlated for 4.3 km towards the southeast (Figure 2.1.10). The Ranchers Cabin section is mainly made up of trough cross-stratified sandstones and a single bed of bioturbated sandstone at the top (Figure 2.1.10). The overall thickness of the unit at this section is 16 m. The lower half of the unit is correlatable across the entire study area. The upper portion pinches out in the northwest at the Summit section and in the southeast at the Hamm Canyon section (Figure 2.1.10). At the Hamm Canyon section this unit thins to 14 m in overall thickness and is composed of trough cross-stratified sandstone and bioturbated sandstone (Figure 2.1.10). Both bed of cross-stratified sandstone pinch out towards the southeast while the bioturbated bed can be correlated for approximately 8 km towards the northwest and 7.5 km towards the southeast (Figure2.1.10).

The Cougars Den section is located 3.5 km south of the Hamm Canyon section where the unit thins to 9 m (Figure 3.5). Facies composition is mainly trough cross-stratified sandstone with lesser amounts of wind-rippled sandstone and bioturbated sandstone, which pinch-out in both directions (Figure2.1.10). The Log Ridge Mine section located 4.2 km away from the Cougars Den is 7 m thick (Figure 3.5). Facies in this unit at the Log Ridge Mine section are limited to structureless sandstone at the base, wind-rippled sandstone and wave-rippled sandstone at the top (Figure 2.1.10). The bottom two thirds of this unit pinches out towards the northwest and is correlable towards the south while the bed of wave-rippled sandstone pinches out in both directions (Figure 2.1.10). At the southeast end of the study area 4.9 km away from the Log Ridge Mine section is the Early Morning Mine section where this unit is 6 m Thick (Figure 3.5). Here the facies are wind-rippled sandstone and bioturbated sandstone that pinch-out towards the northwest (Figure 2.1.10).

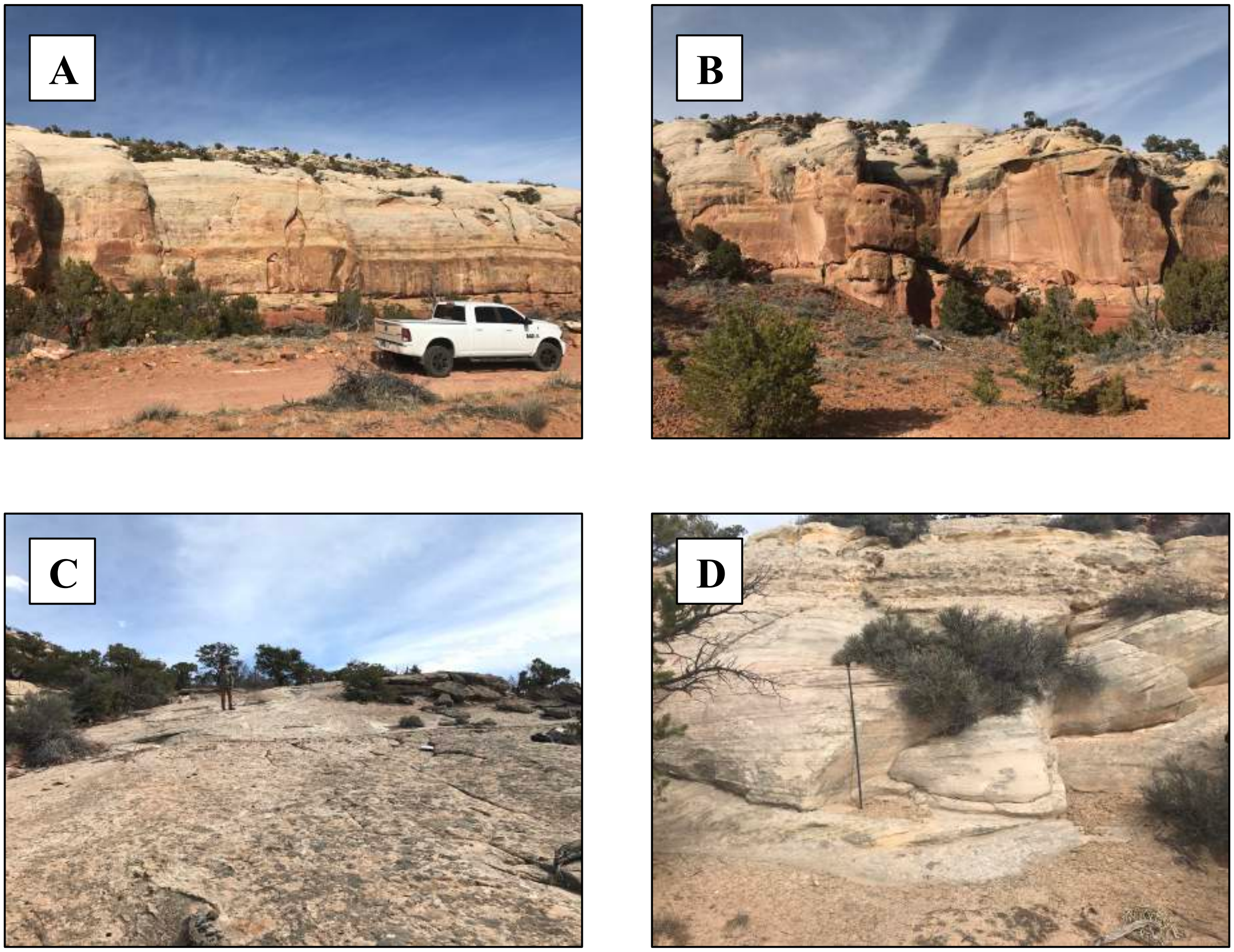


Figure 3.3 A) Photo taken cliff face southeast of the Ranchers Cabin section. **B)** Cliff face found within Hamm Canyon (Figure 1.1). **C)** Cross-bedded sandstone found within the cross-bedded unit at the Summit section. **D)** Close up view of interbedded trough cross-stratified sandstone and bioturbated sandstone from the Hamm Canyon section

3.4 Horizontally Bedded Unit

The Horizontally Bedded unit is the top most stratigraphic unit of the Entrada Formation at Gypsum Valley (Figure 3.5) and the upper unit of the Slick Rock Member (Figure 1.3). This unit is identical to the Horizontally Bedded Unit recognized by Shawe et al. (1968) in both its stratigraphic position and lithofacies composition. It can be described as a red to tan colored fine to medium grain sandstone that is 9 m thick in the southeast at the Early Morning Mine sections and thins to 6 m in the northwest at the Summit section (Figure 3.5). Exposures are most commonly eroded back to form smooth sloping surfaces (Figure 3.4).

At the Summit section in the northwest the unit thickness is 6 m and mainly composed of structureless sandstone capped by a bed of current-rippled sandstone. These beds are laterally continuous and can be trace 4.3 km toward the southeast to the Rancher Cabin section (Figure 2.1.10). The Ranchers Cabin section contains the same facies as the Summit section and is 8 m thick (Figure 3.5). These beds can be traced 4.4 km southeast to the Hamm Canyon section where the unit is 6 m thick (Figure 3.5). At the Hamm Canyon Section facies are identical to the facies found in the Summit and Ranchers Cabin sections with the exception of a single occurrence of trough cross-stratified sandstone (Figure 2.1.10).

The Horizontally Bedded Unit is mostly covered by modern soil and alluvium at the Cougars Den section, which resulted in a projection of facies across the section (Figure 2.1.10). Unit thickness at this section is estimated to be approximately 9 m (Figure 3.5). At the Log Ridge Mine section 4.2 km away the unit thickens to 11 m and is made of mostly structureless sandstone that pinches out at the Early Morning Mine section and capped by bioturbated sandstone that is projected to pinch-out at the Cougars Den section (Figure 2.1.10). At the Early Morning Mine in the southeast unit thickness is 9 m (Figure 3.5) and composed of interbedded wind-rippled sandstone, bioturbated sandstone and current-rippled sandstone that pinch-out in the northwest at the Log Ridge Mine (Figure 2.1.10).

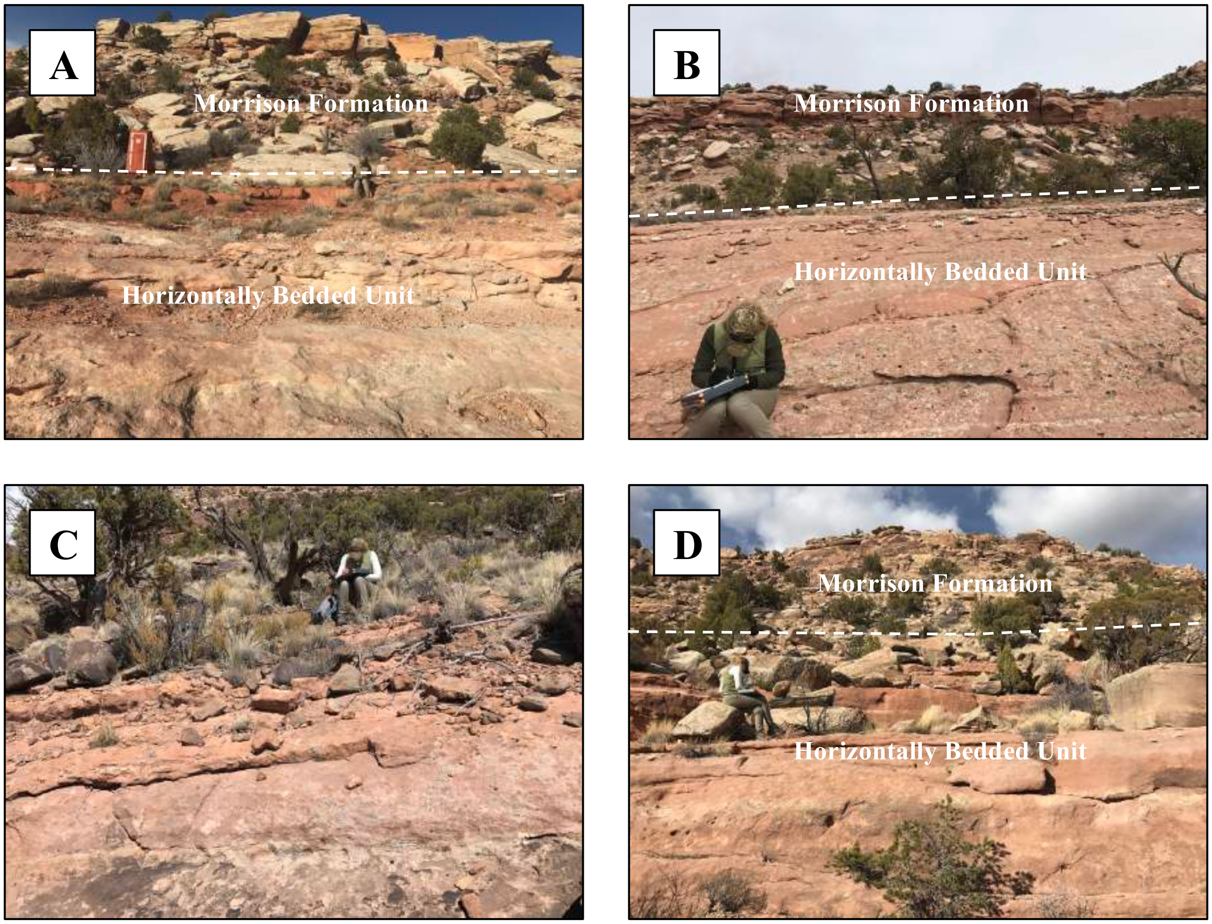


Figure 3.4 A) Photo upper contact of the Horizontally Bedded Unit taken at the Ranchers Cabin section. **B)** Eroded back exposures from the Hamm Canyon section. **C)** Close up view of Horizontally Bedded Unit from the Cougars Den section. **D)** Upper contact with the Morrison Formation at the Log Ridge Mine section.

Chapter 4: Stratal Package Distribution and Descriptions

4.1 Stratal Package Distribution

Within the Entrada Formation at Gypsum Valley, a series of alternating wedge geometries were identified during lithofacies correlation (Figure 4.1). Ten wedges were recognized that pinch out towards the northwest and southeast along the diapir margin. There are more wedges (9) that pinch out toward the southeast, compared to 4 that pinch out to the northwest (Figure 4.1). Internally wedges are composed of varying facies that generally have drying upward facies assemblages. Wedge thickness ranges from a few meters up to tens of meters (Figure 4.1).

4.2 Stratal Package Descriptions

The first three stratal packages comprise the Tidal Unit (Figure 3.1, 4.1). Stratal Package Boundary 1 forms the base of the Entrada Formation. It is a prominent angular unconformity with underlying strata. In the northwest part of the outcrop belt, it rests on the Navajo and Kayenta Formations, with a 10 to 20 degree angular discordance (Figure 1.3). To the south, it rests on Kayenta and Wingate Formations with 30-degree angular discordance. In the southeast end of Gypsum Valley, the Entrada Formation onlaps and pinches out against eroded Permian Cutler and Honaker Trail Formations, with a prominent erosional lag breccia of chert clasts.

Stratal Package 1 forms the base of the Entrada Formation in the Summit section in the northwest end of the study area. It pinches out approximately 4.3 km to the southeast, between the Summit and the Ranchers Cabin section. In the Summit section, it is 8 m thick and pinches out to the southeast and forms the bottom half of the basal Tidal Unit. The base of stratal package 1 is composed of structureless sandstone and interbedded recessive siltstones, which has been interpreted as tidal facies (Figure 4.1). Directly above is a thin bed of wave rippled and laminated sandstone that has the same thickness variability as the beds below. This bed of wave rippled sandstone and laminated sandstone is representative of a wet interdune facies. Capping stratal package 1 is a thin bed of small eolian dune facies that mark the boundary with sequence 3. Stratal package 1 reappears in the southeast at the Hamm Canyon, Cougars Den, Log Ridge Mine and Early Morning Mine sections. Similar to the Summit section, it composes the basal portion of each section (Figure 4.1).

Stratal package boundary 2 separates stratal package 1 from stratal package 2. Stratal package boundary 2 makes up the base of the Ranchers Cabin section and base of stratal package 2 where it merges with stratal package boundary 1 (Figure 4.1). It crops out in the middle of the Basal Tidal Unit and merges into the underlying s stratal package boundary where stratal package 1 pinches out (Figure 4.1). It is characterized by an abrupt change from small eolian dune facies to bioturbated sandstone facies. Although a transgression could produce the same results, a stratal package boundary is preferred, because the mottled sandstones overlie wave rippled sandstones in Hamm Canyon, but form the base of the Entrada Formation in the Ranchers Cabin section (Figure 4.1).

Stratal package 2 makes up part of the Basal Tidal Unit throughout the study area (Figure 4.1). It is mainly composed of wave rippled sandstone facies and bioturbated sandstone facies that onlap towards the southeast onto stratal package boundary 2. This package is defined by a wedge geometry that is approximately 5 m thick at the Hamm Canyon section and pinches out towards the southeast at the Cougars Den section (Figure 4.1).

Stratal package boundary 3 separates stratal package 2 from package 3. Stratal package boundary 3 merges with stratal package boundary 2 in the southeast at the Early Morning Mine section where small eolian dune facies and wave rippled sandstone facies transition into wind-rippled facies. This stratal package boundary also defines the lateral extent of the base of stratal package 3 (Figure 4.1).

Although the three stratal packages vary in thickness, the Basal Tidal Unit is the same thickness across the study area. This is best explained by truncation of the underlying packages along stratal package boundary 3 or stratal package boundary 4. Stratal package boundary 4 separates stratal package 3 from stratal package 4 and merges with stratal package boundary 5 at the Ranchers Cabin section. This boundary also marks the base and lateral extent of stratal package 4 across the study area.

Stratal package 4 is isolated to the northwest portion of the study area at the Summit section where is makes up the bottom half of the Wet Inter-dune Unit. It is composed of interbedded wave-rippled sandstone facies and large eolian dune facies that onlap and pinch out onto stratal package boundary 4 (Figure 4.1).

Stratal package boundary 5 extends for approximately 12 km and separates package 5 from packages 3 and 4 found below. It merges with stratal package boundary 6 at the Cougars Den section where large eolian dune facies abruptly transition to small eolian dune facies. This stratal package boundary also marks the base and lateral extent of stratal package 5 across the northern half of the study area (Figure 4.1).

Stratal package 5 makes up a majority of the Wet Inter-dune Unit in the 3 northern most sections. At the Summit section it is approximately 9 m thick and pinches out towards the southeast at the Cougars Den section where stratal package boundary 5 merges with stratal package boundary 6. This package is composed of individual beds that tend to onlap onto one another towards the southeast end of the study area (Figure 4.1).

Stratal package boundary 6 separates stratal package 6 from packages 3 and 5 found below. This boundary marks the base and lateral extent of stratal package 6 and truncates stratal package 5. It also merges with stratal package boundary 7 at the Early Morning Mine where interbedded wind-rippled facies and small eolian dune facies transition into wave-rippled facies (Figure 4.1).

Stratal package 6 spans across 5 of the 6 measured sections in the study area. It makes up the base of the Cross-Bedded Unit in the Summit section and Ranchers Cabin section. Within the Hamm Canyon, Cougars Den and Log Ridge Mine sections, this package makes up the upper half of the Wet Inter-dune Unit. At the Summit section, this package is approximately 8 m thick and is truncated by stratal package boundary 7 at the Early Morning Mine section found in the southeast (Figure 4.1).

Stratal package boundary 7 spans across the entirety of the study area and merges with stratal package boundary 6 at the Early Morning Mine section. It separates stratal package 7 from packages 3 and 6 found below. This stratal package boundary is marked by large eolian dune facies in the northwest and by wave rippled facies in the southeast. The Hamm Canyon section marks the base of the Cross-Bedded Unit (Figure 4.1).

Stratal package 7 spans across the entirety of the study area and has an average thickness of approximately 10 m. This package is primarily composed of the Cross-Bedded Unit through out and a portion of the underlying Wet Inter-dune Unit in the southeast. The 3 northwest sections are defined by large eolian dune facies that inter-tongue with small eolian dune facies and bioturbated facies in the southeast. Stratal package 7 can be split into two domains, a northern domain and a southern domain. The northern domain is exclusively large eolian dune facies while the southern domain is composed of varied facies that are made up of smaller bed forms (Figure 4.1).

Stratal package boundary 8 extends across the entire study area and marks the top of the Cross-Bedded Unit in the Summit section, Log Ridge Mine and Early Morning Mine sections. In the southeast at the Early Morning Mine section, it merges with stratal package boundary 10 where wave-rippled facies transition to wind-rippled facies. At both the Summit section and the Log Ridge Mine section, stratal package boundary 8 merges with stratal package boundary 9 where bioturbated facies onlap (Figure 4.1).

Stratal package 8 is composed of the upper portion of the Cross-Bedded Unit in the following sections, Ranchers Cabin, Hamm Canyon and Cougars Den. It has a lenticular geometry produced by truncation at both the Summit section in the north and the Log Ridge Mine in the south. This package is capped by a bed large eolian dune facies that are 3 m thick and truncated at both ends. All beds within this package have identical geometries and truncation patterns (Figure 4.1).

Stratal package boundary 9 marks the top of stratal package 9 and merges with stratal package boundary 10 at the Summit section and the Log Ridge Mine section. This boundary also marks the base of the Horizontally Bedded Unit and the top of the Cross-Bedded Unit in the following sections, Ranchers Cabin, Hamm Canyon and Cougars Den (Figure 4.1).

Stratal package 9 makes up a majority of the Horizontally Bedded Unit in the following sections: The Summit, Ranchers Cabin, Hamm Canyon, Cougars Den and Log Ridge Mine. At the Summit section in the northwest, this stratal package is approximately 5 m thick; in the southeast at the Log Ridge Mine, it is approximately 9 m thick. Stratal package 9 is then truncated 4.9 m away from the Log Ridge Mine towards the southeast at the Early Morning Mine. It is primarily composed of structureless sandstone facies with the exception of an individual bed of small eolian dune facies found at the Hamm Canyon section (Figure 4.1).

Stratal package boundary 10 is located a few meters from the top of the Entrada Formation and spans the entirety of the study area. Stratal package boundary 10 merges with stratal package boundary 8 at the Early Morning Mine section in the southeast where structureless sandstone facies transition to wind rippled facies (Figure 4.1).

Stratal package 10 makes up the top of the Horizontally Bedded Unit and the upper most portion of the Entrada Formation. This package can be spilt into two domains, a northern domain and a southern domain. The northern domain includes the Summit, Ranchers Cabin and Hamm Canyon sections, which are exclusively made up of current rippled sandstone facies that are on average 1 m thick. The southern domain includes the Cougars Den, Log Ridge Mine and Early Morning Mine sections and is dominated by interbedded bioturbated sandstone facies and wind-rippled facies. In this southern domain, the stratal package is thickest at the Early Morning Mine, approximately 9 m thick, and thins dramatically towards the northwest (Figure 4.1).

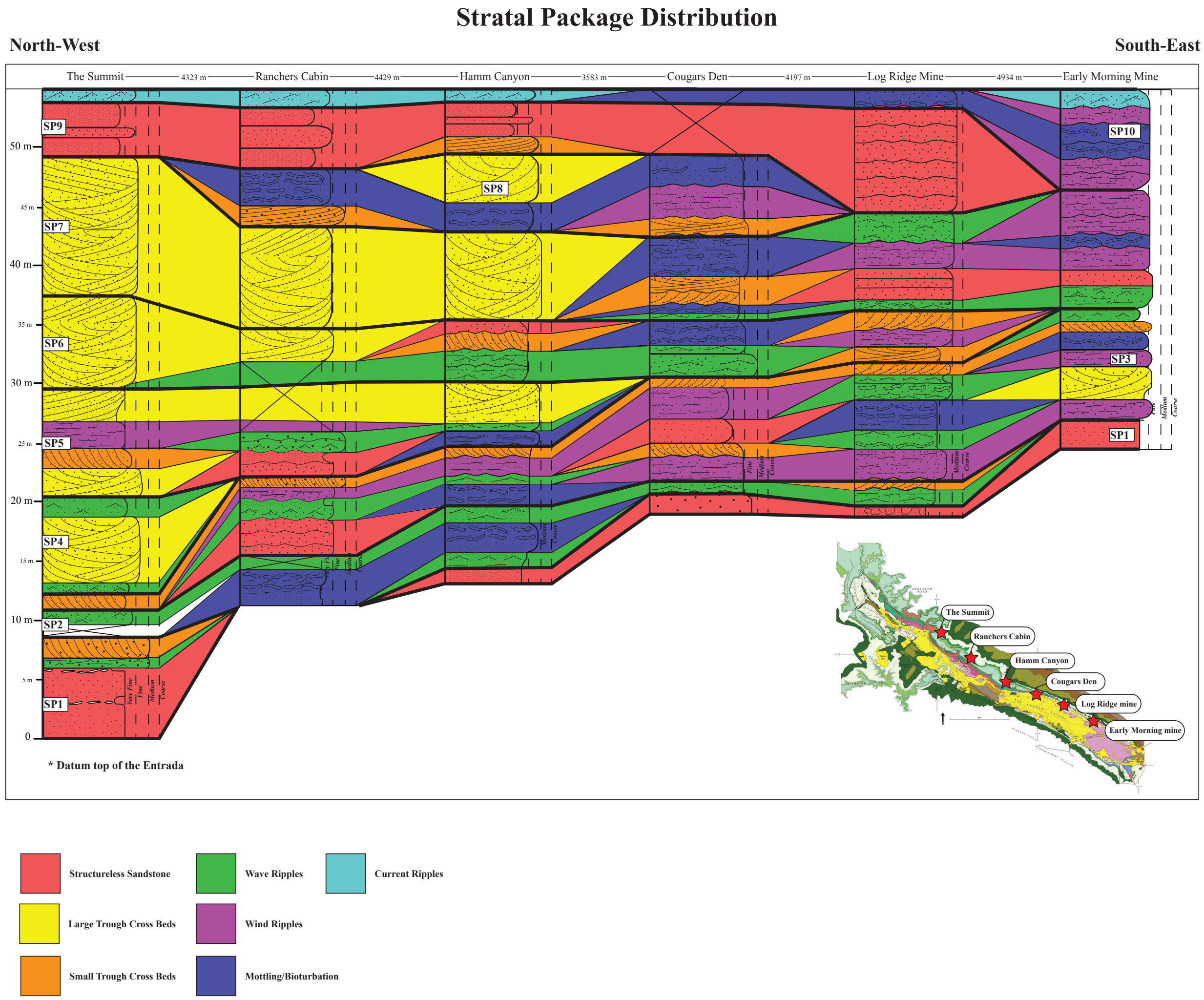


Figure 4.1 Stratigraphic cross-section illustrating lithofacies distribution and stratal package architecture.

Chapter 5: Discussion

5.1 Stratigraphy & Stratal Package Architecture

Gypsum Valley can be divided into two geomorphic regions; Little Gypsum Valley in the north, and Big Gypsum Valley in the south (Fig. 1.1). Little Gypsum Valley represents a collapsed portion of the Gypsum Valley salt wall that formed an extensive salt shoulder (Cater, 1970, Ronson, 2018). At the salt shoulder the Entrada Formation is folded inboard of the diapir and collapsed blocks of the Morrison Formation come into contact with Paradox Salt. Big Gypsum Valley represents a portion of the salt wall that formed a paleotopographic high where sediments are thinned and rotated onto the diapir (Figure 5.1). An exposure of the Entrada Formation, perpendicular to the diapir margin at Hamm Canyon displays the remnants of a wedge stratal package (Figure 5.2). Four stratigraphic units were identified during stratigraphic correlation. Overall formation thickness ranges from 54 m at the Summit section to 23 m at Early Morning Mine section. Lateral thickness and facies composition within each unit vary across the study area. While these units are excellent for mapping the Entrada, in the study area the internal stratigraphy is much more complex.

Before understanding the internal complexity and distribution of lithofacies, the topographic relationship of the units must be considered. Figure 5.3 represents a model for the two major settings for the Entrada Formation. The Entrada formed during a transgression and regression of the Zuni-Sundance Sea (Crabaugh and Kocurek 1993). In the Gypsum Valley area, deposition occurred in an upper, low-energy tidal flat that contained scattered eolian dunes (Figure 5.3 A). The dunes were rarely preserved until with the regression of the sea they became more abundant. They are preserved in the Basal Tidal Unit in SP 1 and 3. Because the dunes are topographically higher, they were preferentially eroded when stratal package boundaries formed.

Overlying the tidal facies, the wet inter-dune deposits were conversely topographically low, and less vulnerable to erosion. Figure 5.3 B illustrates how variable amounts of erosion in these environments could create upward drying sequences that exhibit facies changes along strike (Figure 4.1). The base of these packages is generally composed of wet facies such as wave rippled sandstone and bioturbated sandstone that would later be buried by prograding dunes. Rotation of these strata is interpreted to have been caused by diapiric rise followed by erosion of the dune facies resulted in this uneven distribution of facies.

The upper part of the Wet Inter-Dune Unit and the Cross-Bedded Unit present a contradiction, where the eolian dune facies are thicker, but are composed of the topographically higher dune facies (Figure 3.0 & Figure 4.1). This indicates more rapid deposition in Little Gypsum Valley, with accumulation of a persistent dune field that lasted through deposition of the Cross-Bedded Unit. These dunes are present throughout the region (Shawe et al., 1982) and their absence around Big Gypsum Valley indicates there was some obstacle to sand transport or accumulation. This obstacle may have been the diapir, which could have formed a windbreak, or possibly enhanced erosion, leading to the persistence of inter-dune environments (Figure 2.2.2). The change to the upper Horizontally-Bedded Unit marks a transgression that caused a return of the wet inter-dune environment. This transgression is well known across the Entrada dune field (Crabaugh and Kocurek, 1993), and thickens to the southeast (Figure 3.0). This may mark a subsidence of Big Gypsum Valley, or may represent burial of the topographically high dune field. If this change in thickness is similar to the topographic expression of the dune field, the field must have lain 23 m above the adjacent flats.

The thickness of the Entrada Formation at Big Gypsum Valley is substantially thinner than what is recognized regionally and in the northwest part of the study area. This difference in thickness is the result of localized thinning onto the Gypsum Valley diapir, an area with topographic relief produced by passive diapirism. The uneven thickness distribution of the Entrada can be explained by the differential rise of the Gypsum Valley salt wall where diapiric rise in the southeast (Big Gypsum Valley) out paced sediment accumulation in the northwest (Little Gypsum Valley). The rising salt, combined with minibasin subsidence probably created topographic highs as is indicated by the onlap of strata onto older strata. Temporary lowering of base level cut unconformities across sediments drape-folded against the diapir margin.

The Basal Tidal Unit maintains a relatively uniform thickness across the study area and appears to be unaffected by diapirism (Figure 3.5). However, analysis of 3 stratal packages found within suggest otherwise (Figure 4.1). In the northwest at the Summit section, the unit is bisected by stratal package boundary 2, which marks the first stage of diapiric rise during deposition of the Entrada. Stratal package 1 onlaps onto stratal package 1 at the Ranchers Cabin and thinned across the rest of the study area by diapiric rise in the southeast that was accompanied by erosion (Figure 4.1). Within package 1, the facies assemblage represents an upward drying succession developed by a small scale progradation (Figure 4.1).

Onlapping of stratal package 2 onto stratal package boundary 2 at the Cougars Den section can be explained by continued diapiric rise that out paced deposition rates of the Entrada (Figure 4.1). This sequence mostly composed of tidal facies throughout the sections this was accomplished by aggradation at the time of deposition. Stratal package 3 thins in the northwest and is partially truncated at the Summit section. This geometry suggests a shift in diapiric rise coupled with extensive erosion that leveled off the Basal Tidal Unit (Figure 4.1). Within package 3, the facies assemblage represents a rapid drying of facies,likely caused by a progradation of the Entrada Erg (Figure 5.3).

The Wet Inter-Dune Unit thickness distribution is interpreted to be the result of a reversal in diapiric rise from the northwest back to the southeast (Figure 4.1). This unit is made up of stratal package 4, a majority of package 5 and half of package 6. Stratal package 4 onlaps onto stratal package boundary 4 and is truncated at the Hamm Canyon section as a result of rapid diapiric rise and erosion in the southeast. This sequence contains interbedded trough cross stratified sandstone and wave-rippled sandstone meaning cyclic deposition of eolian dune faces and wet intern dune facies (Figure 5.3).

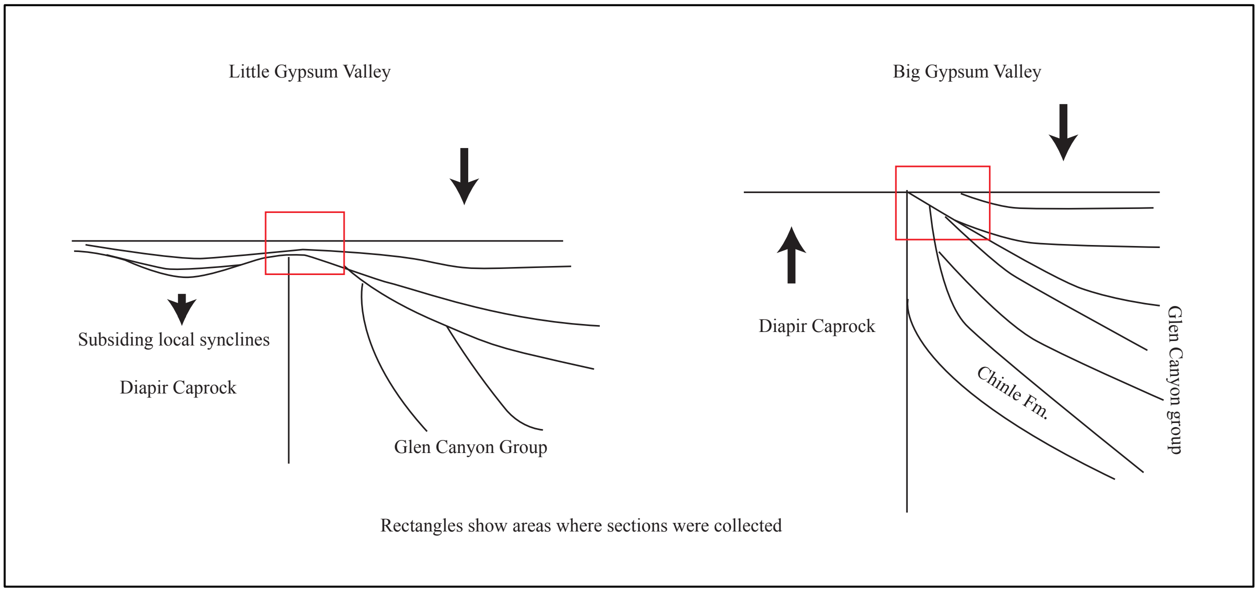
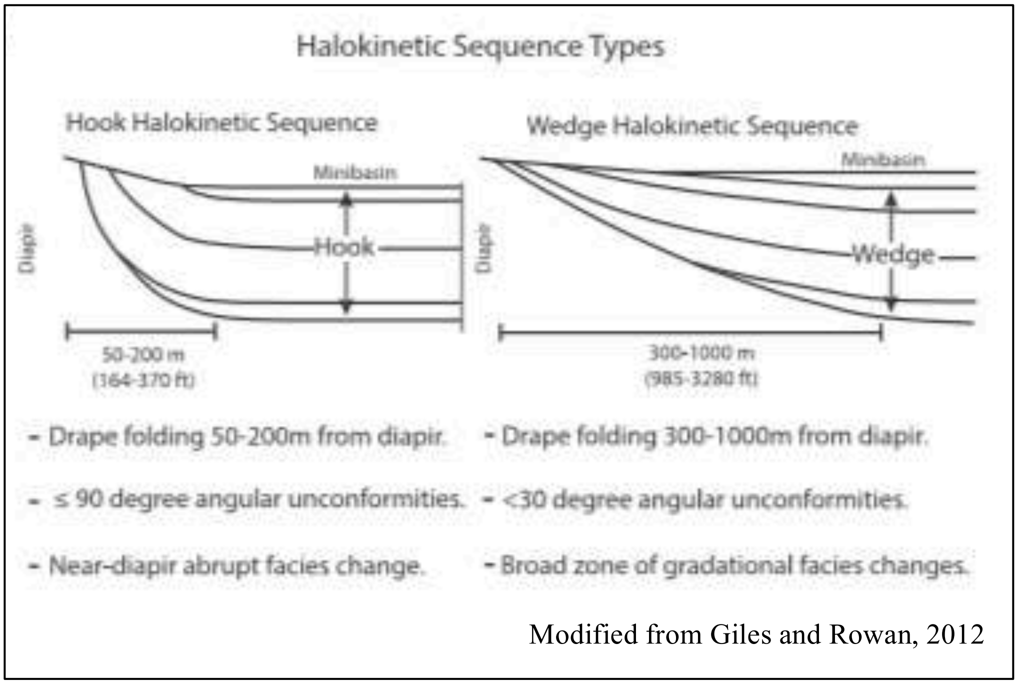


Figure 5.1 Explanation of the two regions found at Gypsum Valley. Little Gypsum Valley (Left) illustrates the extensive salt shoulder. Big Gypsum Valley (Right) illustrates diapir flanking sediments geometries.



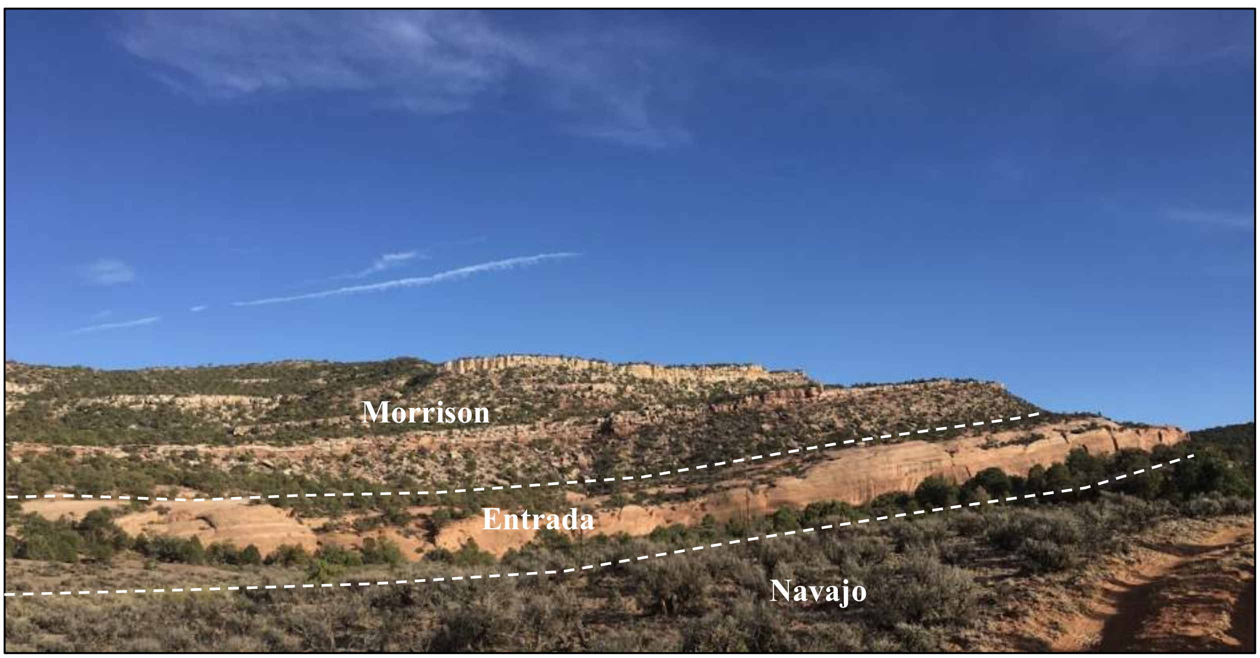


Figure 5.2 Outcrop photo taken on the southern end of Hamm Canyon showing the wedge geometry of the Entrada Sandstone along the flank of the Gypsum Valley salt wall.

Stratal package 5 onlaps onto stratal package boundary 5 and is truncated at the Cougars Den section. The lateral extent of package 5 can be explained by a decrease in diapiric rise and a relative increase in sediment supply (Figure 4.1). Package 5 is capped by eolian dune facies that represent the upwards drying of facies as a result of progradation (Figure 4.1). Stratal package 6 onlaps and is truncated at the Early Morning Mine section. Package 6 facies composition also contains drying upward facies succession representing another progradational sequence. This series of startal packages represent a gradual decrease in diapiric rise rates as the Wet Inter-Dune Unit was deposited (Figure 4.1). The transition from the Wet Inter-Dune Unit to the Cross-Bedded Unit marks an upward drying within SP 6, where topographically higher dunes bury the water table defined wet inter-dunes in the lower part of the unit.

The Cross-Bedded Unit has a similar thickness trend of thinning towards the southeast similar to the Wet Inter-Dune Unit previously mentioned (Figure 3.5). This trend is the result of continued diapiric rise in the southwest and a steady increase in sediment supply (Figure 4.1). Stratal package 7 makes up a majority of this unit and spans across the entire study area (Figure 4.1). There is a facies change between the Hamm Canyon section and Cougars Den section where large trough cross-stratified sandstones abruptly transition to bioturbated sandstones (Figure 4.1). This abrupt change in facies is possibly the result of rotation and erosion during diapiric rise of the salt wall. It also marks another the upwards drying of facies resulting from progradation of the Entrada Erg and may indicate a topographic difference between the northwestern and southeastern parts of the study area. The topographically lower area in the southeast collected topographically low interdune strata, whereas the topographically higher dunes were deposited to the northwest. The lateral extent of package 7 suggests that sedimentation outpaced diapiric rise of the salt wall allowing accumulation of this relatively thick stratal package (Figure 4.1).

Stratal package 8 marks the top of the Wet Inter-Dune Unit at the Ranchers Cabin, Hamm Canyon and Cougars Den sections (Figure 4.1). This package is truncated in the northwest and the southeast. This geometry indicates filling of a local topographic low along the deforming diapir (Figure 4.1). Because these three stratigraphic sections are located the farthest from the diapir, this package may expose in a window of strata that thicken to the northwest into the Dry Creek minibasin and are truncated below the other sections. Internally, this sequence is composed of another drying upward facies assemblage marked by large eolian dune facies representative of progradation.

At Gypsum Valley, the Horizontally Bedded Unit caps the Entrada sandstone and thins towards the northwest (Figure 3.5). The unit is overall much thicker in the study area than in the outcrops to the south and west studied by Shawe et al. (1968). This thickness distribution can be explained by either the filling of the differential topography illustrated in stratal package 7, or reduced diapiric rise in the southeast compared to the northwest and accompanying thinning and rotation of the sequence (Figure 4.1). Internal facies composition of this unit represents an aggredational sequence set. This can be explained by a hiatus in diapiric movement during active deposition of the package.

Stratal package 9 truncated on both ends (Figure 4.1) and is made up of an upward drying sequence (Figure 5.3). This relationship can be explained by subsidence centered at the Hamm Canyon section along with rotation and erosion at the northwest at southeast ends (Figure 4.1). Stratal package 10 has a similar thickness distribution as the sequence below, however it is much thinner (Figure 3.5).

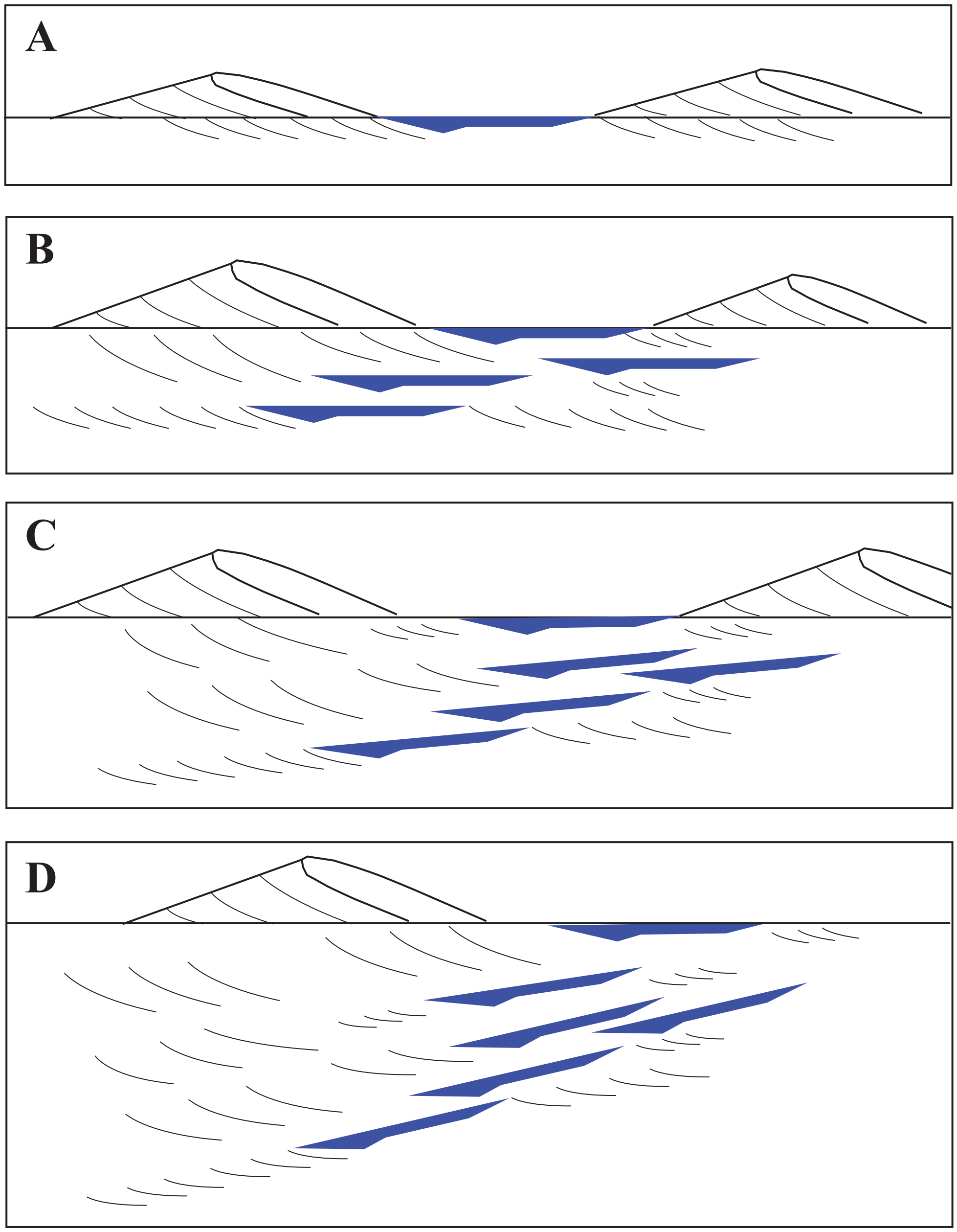


Figure 5.3 A) Schematic illustration of initial deposition of wet inter-dune and large eolian dune deposits. **B)** Continued deposition of wet inter-dune and large eolian dune resulting in an increase in thickness. **C)** Continued deposition coupled with rotation caused by halokinesis resulting in the topographically higher dunes being eroded to form a wedge geometry. **D)** After further deposition, rotation and erosion a overall wedge geometry is formed and dune deposits are preserved in the northwest while wet inter-dune deposits accumulate in the southeast.

5.2 Post-Deposition Deformation

Passive diapirism continued after the deposition of the Entrada Formation and can be seen when plotting measured sections on a 1:100 scale cross section (Figure 5.1), where two distinct structural domains are recognized. Towards the northwest is the northern domain which is home to base elevations that exceed 1930 m. In the southeast lies the southern domain, where base elevations fall below 1920 m. In general, both domains dip away from each other to form an asymmetrical anticline (Figure 5.1). The crest of this structure is located at the Hamm Canyon section found on the edge of the northern domain.

These relationships can be explained by continued deformation after deposition of the Entrada Formation. The resultant geometry suggests the Entrada and other strata were buried by parts of the diapir. The remaining active diapir was smaller and more circular in outline. Ronson (2018) documented burial of the northern part of the diapir and accompanying syndepositional subsidence. There has been little post depositional subsidence in this area, and the Entrada only dips at 3-6 degrees into the Dry Creek minibasin (Figure 1.1). Along the margins of Big Gypsum Valley, the Entrada Formation onlaps onto underlying strata and is rotated to a 15-degree angle. The onlap is most pronounced along the Megaflap, where it pinches out entirely and is overlapped by the Jurassic Summerville Formation strata. The Summerville and overlying Morrison dip at 10-degree angle, indicating subsidence of the adjacent minibasins, and possible continued diapiric rise at the southeastern end of the transect through the Entrada. This same relationship can be observed in scattered windows through the overlying Morrison strata (Figure 1.1).

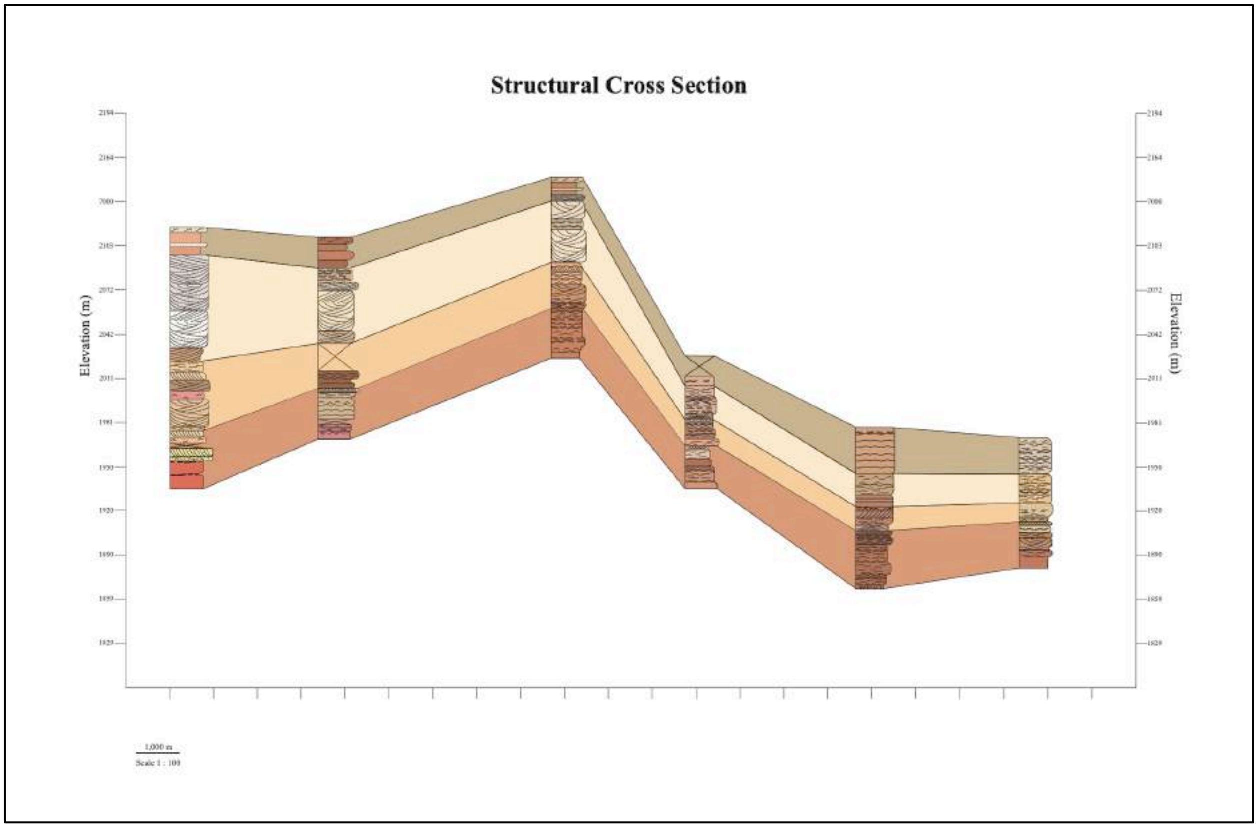


Figure 5.4 Structural cross-section across the study area at 1:100 scale.

Chapter 6: Conclusion

The deposition of the Jurassic Entrada Formation at Gypsum Valley was affected by the differential rise of the Gypsum Valley salt wall. A total of 11 lithofacies were identified and grouped into facies associations that included the following. Facies Association 1: tidal deposits, which are composed of structureless sandstone, wave-rippled sandstone, flaser bedded sandstone and bioturbated sandstone. Facies Association 2: wet inter-dune deposits, which included wave-rippled sandstone, large trough cross-stratified sandstone, small trough cross-stratified sandstone, wind-rippled sandstone and structureless sandstone. Facies Association 3: large eolian dunes, which are composed of large trough cross-stratified sandstone. Facies Association 4: small eolian dunes that were exclusively composed of small trough cross-stratified sandstone. Finally, Facies Association 5: scoured eolian deposits, which are composed of structureless sandstone. Lithofacies are unevenly distributed across the study area. Large eolian dunes along with other dry eolian facies are more concentrated in the northwest. Towards the south, facies such as tidal and wet inter-dune deposits are more prevalent. This uneven distribution is the result of a topographic difference where the northwest sections were deposited on a slight topographic high, probably due to diapiric rise coupled with rotation and erosion of strata in flanking positions.

At Gypsum Valley, the Entrada Formation can be broken up into 4 stratigraphic units similar to those documented by Shawe et al. (1968). The units are named based on general facies assemblages and not a single facies. These units include the following (in ascending order), Basal Tidal Unit, Wet Inter-Dune Unit, Cross-Bedded Unit and the Horizontally Bedded unit. The Basal Tidal Unit is mainly composed of tidal facies and has a uniform thickness across the study area. The contact with the unit above is sharp and marked by a laterally continuous bed of small eolian dunes. The Wet Inter-Dune Unit has an uneven thickness distribution that is the result of diapiric rise in the southeast coupled with rotation and erosion of diapir flanking sediments. This produced a southeast thinning trend of the Wet Inter-Dune Unit. The Cross Bedded Unit is primarily made up of both large and small eolian dune deposits that display southeastward thinning trend. This trend is the result of the same processes that affected the Wet Inter-Dune Unit found below. The Horizontally Bedded Unit whose facies composition is dominantly structureless sandstones makes up the top of the Entrada. Its thickness trend is different than the other units in that it thins towards the northwest. The unit is thicker than regionally, and may reflect a topographic low, or inhanced subsidence in the study area. The southeast-thickening trend can also be explained by broad subsidence in this area near the end of Entrada deposition. An alternative explanation is that there was deeper truncation in the northwest along the angular unconformity with the overlying Summerville Formation strata. A third hypothesis is that the Horizontally Bedded Unit thins against the topographic high of the dune field that formed in the northwest part of the study area.

A total of 10 stratal packages were identified with in the Entrada Sandstone. Stratal packages 1, 2 and 3 are part of the basal tidal unit; collectively they produce a uniform thickness across the study area suggesting erosion near the end of deposition of the tidal unit that beveled the underlying sequences. Stratal packages 1 and 2 show the evidence of diapiric rise concentrated in the southeast based of lateral truncations and facies assemblages. Package 3 is the result of a shift of diapiric rise towards the northwest. Stratal packages 4, 5 along with portions of 6 and 7 make up the Wet Inter-Dune Unit. These packages all pinch-out towards the southeast and display the effects of a progressive shift of diapirism back towards the southeast. Portions of packages 6 and 7 along with packages 8 and 9 make up the Cross-Bedded Unit. This unit represents the continuation of greater diapiric deformation in the southeast and is capped by sequence 8. Between these areas of diapiric rise sediments were rotated and truncated by erosional processes. Packages 9 and 10 make up the Horizontally Bedded Unit, which thins towards the northwest unlike the other stratigraphic units. These packages may define onlap of the underlying dune field, or a more broad subsidence in the Big Gypsum Valley area that allowed greater accumulation of strata.

References

Baars, D. L., and Stevenson, G. M., 1981. Tectonic evolution of the Paradox basin, Utah and Colorado; in, Geology of the Paradox Basin, D. L. Wiegand, ed.: Rocky Mountain Association of Geologists, 1981 Field Conference, p. 23-31

Barbeau, D.L., 2003. A flexural model for the Paradox Basin: implications for the tectonics of the Ancestral Rocky Mountains. Basin Research 15, 97–115

Blakey, Ronald C., and Richard Gubitosa. "Controls of Sandstone Body Geometry and Architecture in the Chinle Formation (Upper Triassic), Colorado Plateau." *Sedimentary Geology*, vol. 38, no. 1–4, Mar. 1984, pp. 51–86.

Cater, F.W., 1970. Geology of the Salt Anticline Region in southwestern Colorado. U.S. Geol. Surv., Prof. Pap., 637: 80 pp.

Cattaneo, A., Steel, R.J., 2003. Transgressive deposits: a review of their variability. Earth-Science Reviews 62 (3 – 4), 187 – 228

Chan, M.A., Parry, W.T., and Bowman, J.R., 2000. Diagenetic hematite and manganese oxides and fault- related fluid flow in Jurassic sandstones southeastern Utah: American Association of Petroleum Geology Bulletin , v. 84, p. 1281-1310

Condon, S. M., 1997. Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and southwestern Colorado. U. S. Geological Survey, Professional Paper, 2000-P

Crabaugh, M. and Kocurek, G., 1993. Entrada Sandstone: an example of a wet aeolian system. Geological Society, London, Special Publications, 72(1), pp.103-126

Dickinson, W. R., and G. E. Gehrels. "U-Pb Ages of Detrital Zircons from Permian and Jurassic Eolian Sandstones of the Colorado Plateau, USA: Paleogeographic Implications." *Sedimentary Geology*, vol. 163, no. 1–2, 2003, pp. 29–66.

Doelling, H.H., 1988. Geology of Salt Valley Anticline and Arches National Park, Grand County, Utah. In: Doelling, H.H., Oviatt, C.G., Huntoon, P.W. (Eds.), Salt Deformation in the Paradox Region, Utah Utah Geological and Mineral Survey Bulletin, vol. 122, pp. 1–60.

Elston, D.P., Shoemaker, E.M. and Landis, E.R., 1962. Uncompahgre front and salt anticline region of Paradox Basin, Colorado and Utah. AAPG Bulletin, 46(10), pp.1857-1878

Escosa, F.O., Rowan, M.G., Giles, K.A., Deatrick, K.T., Mast, A.M., Langford, R., Hearon, T.E., IV, and Roca, E., 2018, Lateral terminations of salt walls and megaflaps: An example from Gypsum Valley Diapir, Paradox Basin, Colorado, USA: Basin Research, v. 31, p. 191–212, https://doi .org/10.1111/bre.12316.

Ford, R.L., Gillman, S.L., Wilkins, D.E., Clement, W.P. and Nicoll, K., 2010. Geology and Geomorphology of Coral Pink Sand Dunes State Park, Utah. Geology of Utah's Parks and Monuments, Utah Geological Association Publication 29, pp.379-406

Ge, H., Jackson, M.P. and Vendeville, B.C., 1997. Kinematics and dynamics of salt tectonics driven by progradation. AAPG bulletin, 81(3), pp.398-423

Giles, K.A. and Lawton, T.F., 2002. Halokinetic sequence stratigraphy adjacent to the El Papalote diapir, northeastern Mexico. AAPG bulletin, 86(5), pp.823-840

Giles, Katherine A., and Mark G. Rowan. "Concepts in Halokinetic-Sequence Deformation and Stratigraphy." *Geological Society, London, Special Publications*, vol. 363, no. 1, 2012, pp. 7–31.

Heness, E.A., 2016, Salt Tectonic Controls on Facies and Sequence Stratigraphy of the Triassic Chinle Formation, Gypsum Valley, Colorado [M.S. Thesis] El Paso, University of Texas at El Paso.

Hite, R. J., and W. C. Gere, 1958, Potash Deposits of the Paradox Basin, *in* Guidebook to the Geology of the Paradox Basin, Ninth Annual Field Conference: Salt Lake City, Intermountain Association of Petroleum Geologists, p. 221–225.

Hunter, R.E., 1977. Basic types of stratification in small eolian dunes. Sedimentology, 24(3), pp.361-387

Kluth, C.F. and Coney, P.J., 1981. Plate tectonics of the ancestral Rocky Mountains. Geology, 9(1), pp.10-15

Kocurek, G., 1981. Erg reconstruction: the Entrada sandstone (Jurassic) of northern Utah and Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology, 36(1-2), pp.125-153.

Lancaster, N., 1988. Controls of eolian dune size and spacing. Geology, 16(11), pp.972-975

Langford, R. and Chan, M.A., 1988. Flood surfaces and deflation surfaces within the Cutler Formation and Cedar Mesa Sandstone (Permian), southeastern Utah. Geological Society of America Bulletin, 100(10), pp.1541-1549

Langford, R.P., Gill, T.E. and Jones, S.B., 2016. Transport and mixing of eolian sand from local sources resulting in variations in grain size in a gypsum dune field, White Sands, New Mexico, USA. Sedimentary Geology, 333, pp.184-197

Loope, DAVID B., et al. "Abandonment of the Name Elephant Canyon Formation in Southeastern Utah: Physical and Temporal Implications." *Mountain Geologist;(USA)*, vol. 27, no. 4, 1990.

Matthews, W.J., Hampson, G.J., Trudgill, B.D. and Underhill, J.R., 2007. Controls on fluvio lacustrine reservoir distribution and architecture in passive salt-diapir provinces: Insights from outcrop analogs. AAPG bulletin, 91(10), pp.136

McFarland, J. C., 2016, Structural and stratigraphic development of a salt-diapir shoulder, Gypsum Valley, Colorado, MS Thesis: El Paso, Texas, The University of Texas at El Paso, 93 p.

McKee, Imlay R. W., E. D. "Paleotectonic Maps of the Jurassic System." *US Geol. Survey Misc. Geol. Inv. Map*, vol. 6, 1956, pp. 1–175.

McKee, E.D. and Bigarella, J.J., 1979. Sedimentary structures in dunes. McKee (Ed.), A Study of Global Sand Seas. US Geological Survey Professional Paper, 1052, pp.83-134.

Nio, S. D., and C. S. Yang, 1991. Diagnostic attributes of clastic tidal deposits: A review, in Clastic Tidal Sedimentology, edited by D. G. Smith et al., Mem. Can. Soc. Pet. Geol., 16, 3-27

Nuccio, V. F. & Condon, S. M., 1996. Burial and thermal history of the Paradox Basin, Utah and Colorado, and petroleum potential of the middle Pennsylvanian Paradox Formation. US Geol. Surv. Bull. 76, O1–O41

O'Sullivan, R.B., 1980, Stratigraphic sections of Middle Jurassic San Rafael Group from Wilson Arch to Bluff in southeastern Utah: U.S. Geological Survey Oil and Gas Investigations Chart OC-102

O'Sullivan, R. E. *Correlation of the San Rafael Group and Related Rocks from KaneSprings Utah to Uravan Colorado*. US.S. Geological Survey, 1991.

Otto, E.P. and Picard, M.D., 1976. Petrology of Entrada Sandstone (Jurassic) northeastern Utah. In: Symposium on the Geology of the Cordilleran Hingeline, Rocky Mountain Association of Geologists, 1976 Symposium, pp. 231- 245

O'Sullivan, R.B., 1981. Stratigraphic sections of Middle Jurassic Entrada sandstone and related rocks from Salt Valley to Dewey Bridge in East-Central Utah. U.S. Geol. Surv. Oil and Gas Invest. Chart OC-113.

Peterson, J.A. and Hite, R.J., 1969. Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains. AAPG bulletin, 53(4), pp.884-908.

Phoenix, D.A., 1958. Sandstone cylinders as possible guides to paleomovement of ground water. In New Mexico Geological Society, Guidebook of 9th Field Trip Conference (pp. 194-196).

Pipiringos, G. N. and O'Sullivan, R. B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey Professional Paper 1035, A1–A28 p.

Rasmussen, Donald L. "Namakiers in Triassic and Permian Formations in the Paradox Basin (Usa) with Comparisons to Modern Examples in the Zagros Fold Belt, Iran." *Geology of Utah's Far South*, edited by J.S. MacLean et al., Uah Geological Association, 2014, pp. 689–756.

Rasmussen, D., (2015) Subsurface and surface stratigraphic evidence for surface extrusions of Pennsylvanian Paradox salt beginning in the Early Permian and still happening, Paradox Basin, SE Utah and SW Colorado. RMS-SEPM Lecture Abstract, 2015

Reineck, H.E. and Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11(1-2), pp.99-104

Ronson, R.B., 2017. *Facies changes associated with formation of an extensive salt shoulder by the coastal and eolian Carmael and Entrada Formations, Gypsum Valley, Colorado.* The University of Texas at El Paso, pp. 23-62.

Shawe, D.R., Simmons, G.C. and Archbold, N.L., (1968) Stratigraphy of Slick Rock District and vicinity San Miguel and Dolores Counties, CO: U.S. Geol. Survey Prof. Paper 576-A, A1–A108 p.

Stevenson, G. M., and D. L. Baars. "Paradox--Pull-Apart Basin of Pennsylvanian Age: ABSTRACT." *AAPG Bulletin*, vol. 69, no. 5, 1985, pp. 867–68.

Shoemaker, E.M., Case, J.E., and Elston, D.P., 1958, Salt Anticlines of the Paradox Basin, in Guidebook to the Geology of the Paradox Basin, Ninth Annual Field Conference, Utah Geological Survey, p. 39–59.

Shoemaker, E.M., Case, J.E., and Elston, D.P., 1958, Salt Anticlines of the Paradox Basin, in Guidebook to the Geology of the Paradox Basin, Ninth Annual Field Conference, Utah Geological Survey, p. 39–59.

Stewart, W.D. and Walker, R.G., 1980. Eolian coastal dune deposits and surrounding marine sandstones, Rocky Mountain Supergroup (Lower Pennsylvanian), southeastern British Columbia. Canadian Journal of Earth Sciences, 17(9), pp.1125-1140

Stokes, W.L., and Phoenix, D.A., 1948, Geology of the Egnar - Gypsum Valley Area, San Miguel and Montrose Counties Colorado: U.S. Geological Survey OM-93 Oil and Gas Investigations Map.

Trudgill, B. D., Banbury,N., and J. R. Underhill, 2004. Salt evolution as a control on structural and stratigraphic systems: Northern Paradox foreland basin, SE Utah, U.S.A., in P. J. Post, D. L. Olson, K. T. Lyons, S. L. Palmes, P. F.Harrison, and N.C.Rosen, eds., Salt sediment interactions and hydrocarbon prospectivity: Proceedings of 24th Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference, p. 669–700. 92

Trudgill, B.D., and Paz, M., 2009. Restoration of Mountain Front and Salt Structures in the Northern Paradox Basin, SE Utah, in W.S. Houston, L.L. Wray, and P.G. Moreland, eds., The Paradox Basin Revisited – New Developments in Petroleum Systems and Basin Analysis: RMAG 2009 Special Publication – The Paradox Basin, p. 132-177

Trudgill, B.D., 2010, Evolution of salt structures in the Paradox Basin: Controls on evaporite deposition, salt wall growth and supra-salt stratigraphic architecture: Basin Research, v. 23, p. 208-238

Trudgill, B. D., 2011. Evolution of salt structures in the northern Paradox Basin: Controls on evaporite deposition, salt wall growth and supra-salt stratigraphic architecture: Basin Research, v. 23, p. 208–238

Tsoar, H. and Blumberg, D.G. 2002. Formation of parabolic dunes from barchans and transverse dunes along Israel's Mediterranean coast. Earth Surface Processes and Landforms 27: 1147-1161.

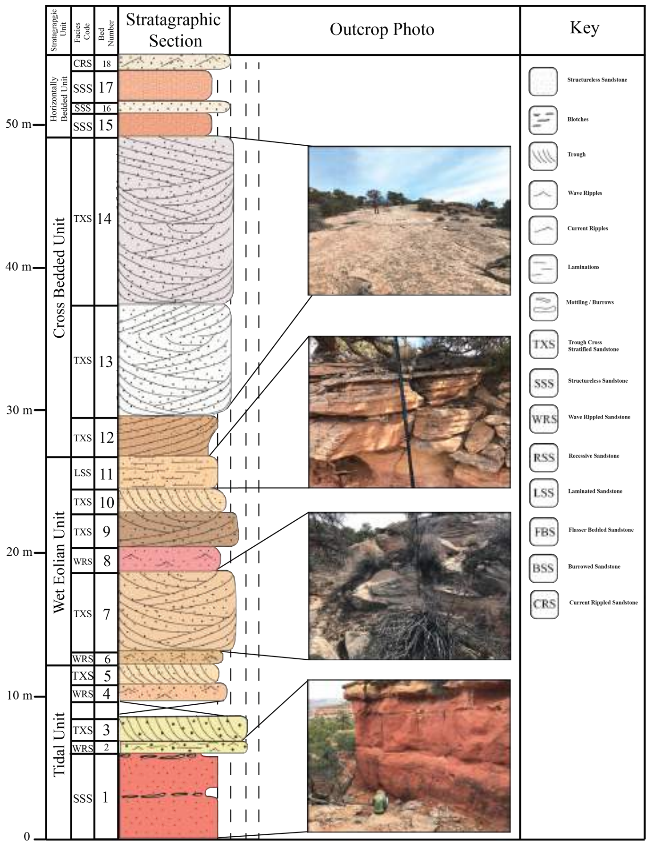
Veiga, G.D., Spalletti, L.A. and Flint, S., 2002. Aeolian/fluvial interactions and high-resolution sequence stratigraphy of a non-marine lowstand wedge: the Avilé Member of the Agrio Formation (Lower Cretaceous), central Neuquén Basin, Argentina. Sedimentology, 49(5), pp.1001-1019.

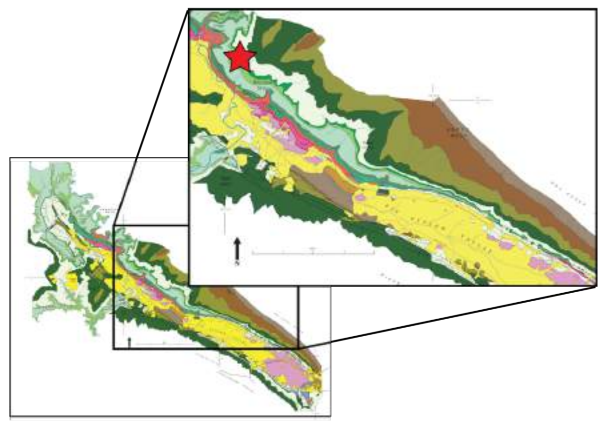
Werner, B.T., 1995. Eolian dunes: computer simulations and attractor interpretation. Geology, 23(12), pp.1107-1110.

Wright, J.C., Shawe, D.R. and Lohman, S.W., 1962. Definition of members of Jurassic Entrada Sandstone in east-central Utah and west-central Colorado. AAPG Bulletin, 46(11), pp.2057-2070.

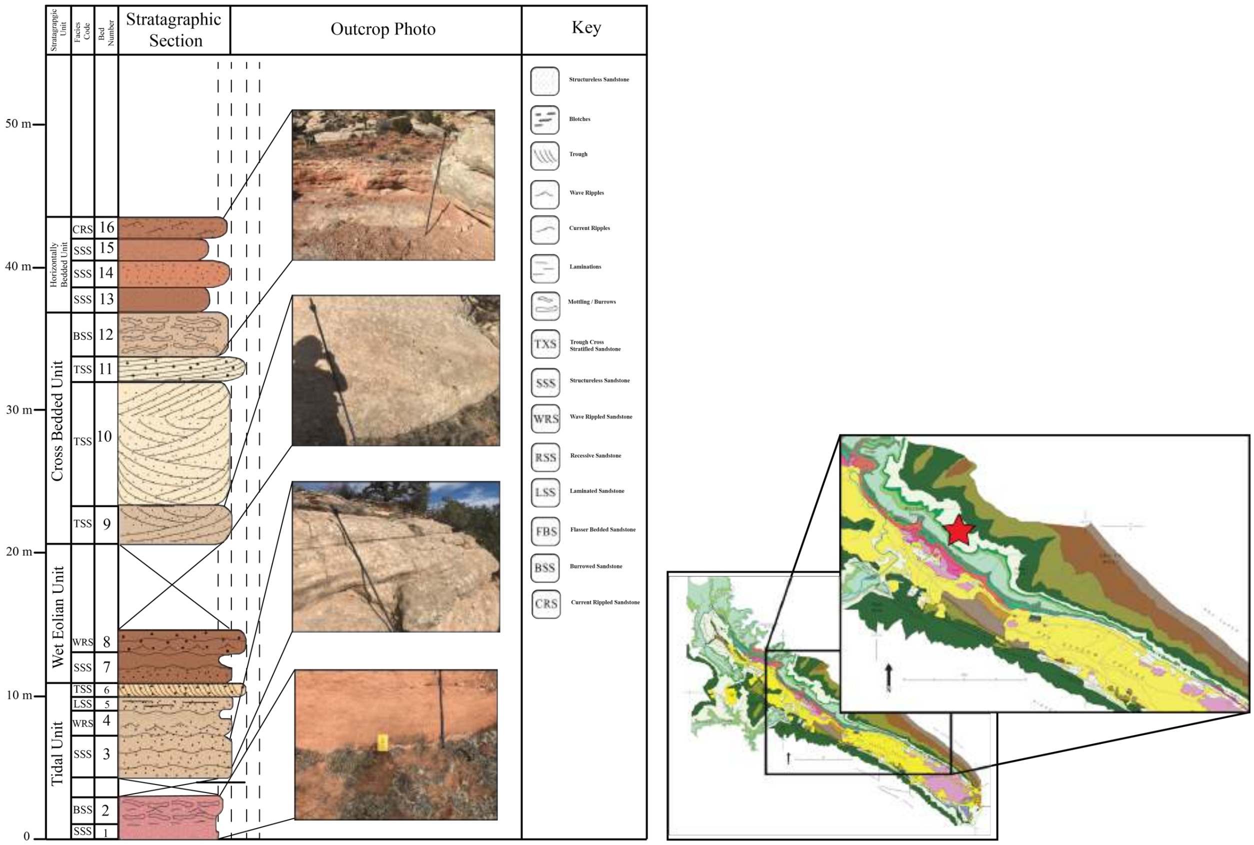
Appendix 1. Stratigraphic sections and section locations.

The Summit

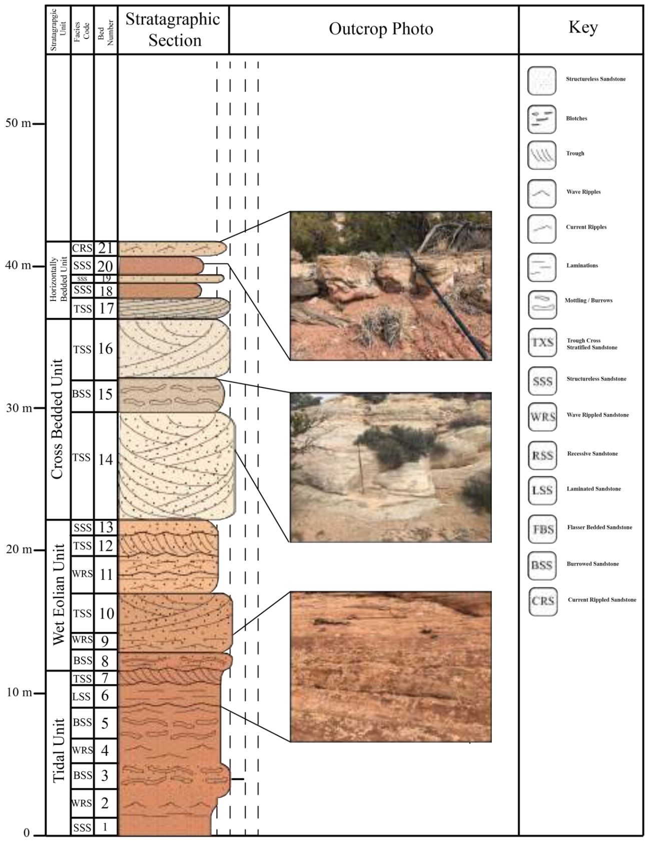


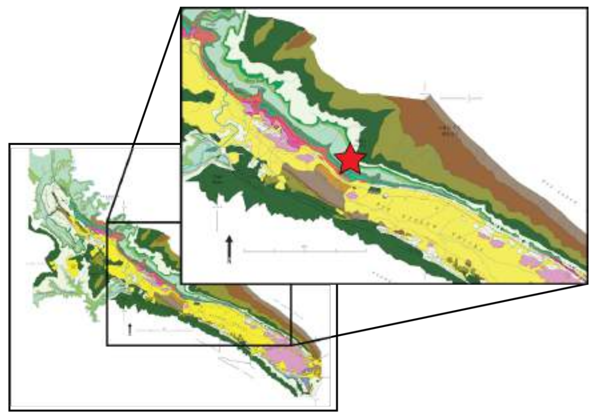


Ranchers Cabin

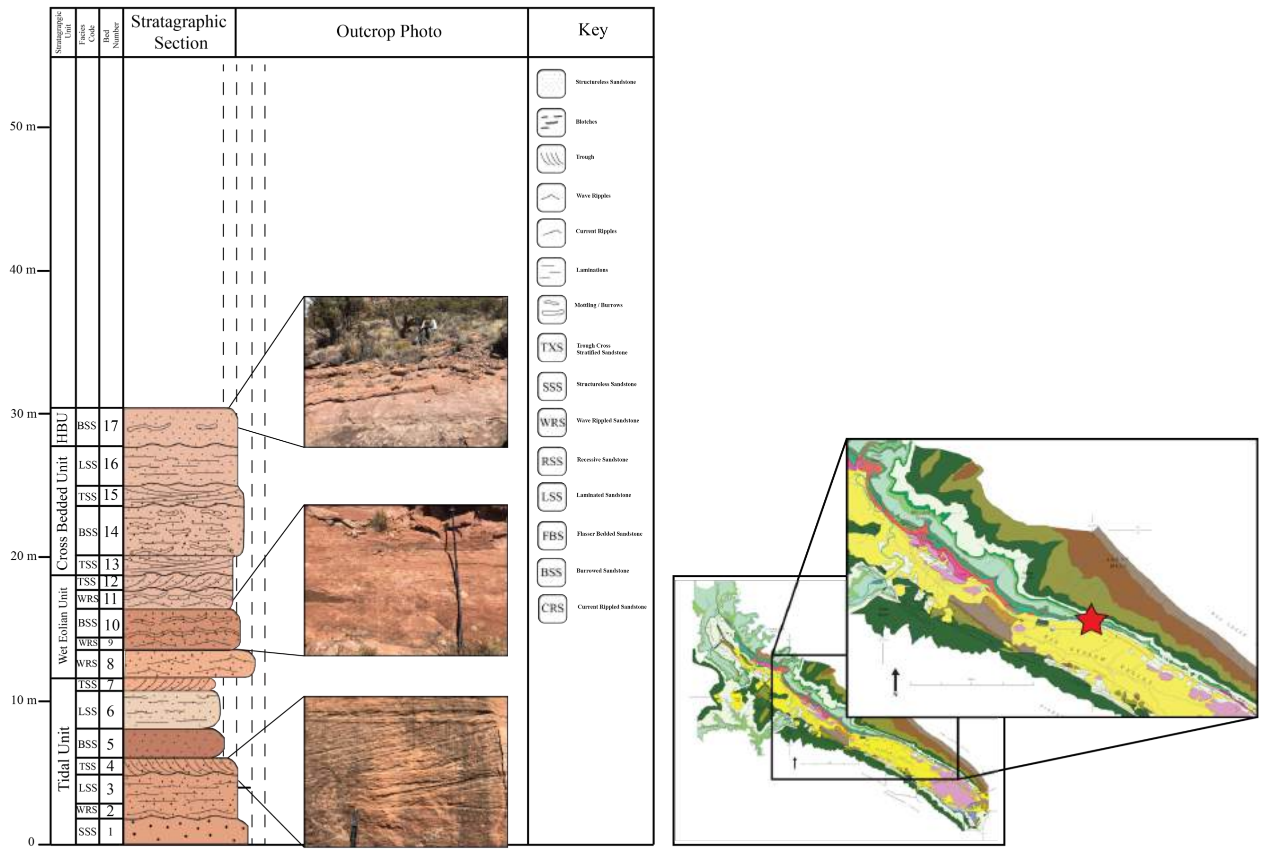


Hamm Canyon


Stratagrapic Unit
Facies Code
Bed Number
Stratagraphic Section
Outcrop Photo
Key
50 m
40 m
30 m
20 m
10 m
0
Horizontally Bedded Unit
Cross Bedded Unit
Wet Eolian Unit
Tidal Unit
CRS 21
SSS 20
SSS 19
SSS 18
TSS 17
TSS 16
BSS 15
TSS 14
SSS 13
TSS 12
WRS 11
TSS 10
WRS 9
BSS 8
TSS 7
LSS 6
BSS 5
WRS 4
BSS 3
WRS 2
SSS 1
Structureless Sandstone
Blotches
Trough
Wave Ripples
Current Ripples
Laminations
Mottling / Burrows
TXS Trough Cross Stratified Sandstone
SSS Structureless Sandstone
WRS Wave Rippled Sandstone
RSS Recessive Sandstone
LSS Laminated Sandstone
FBS Flasser Bedded Sandstone
BSS Burrowed Sandstone
CRS Current Rippled Sandstone

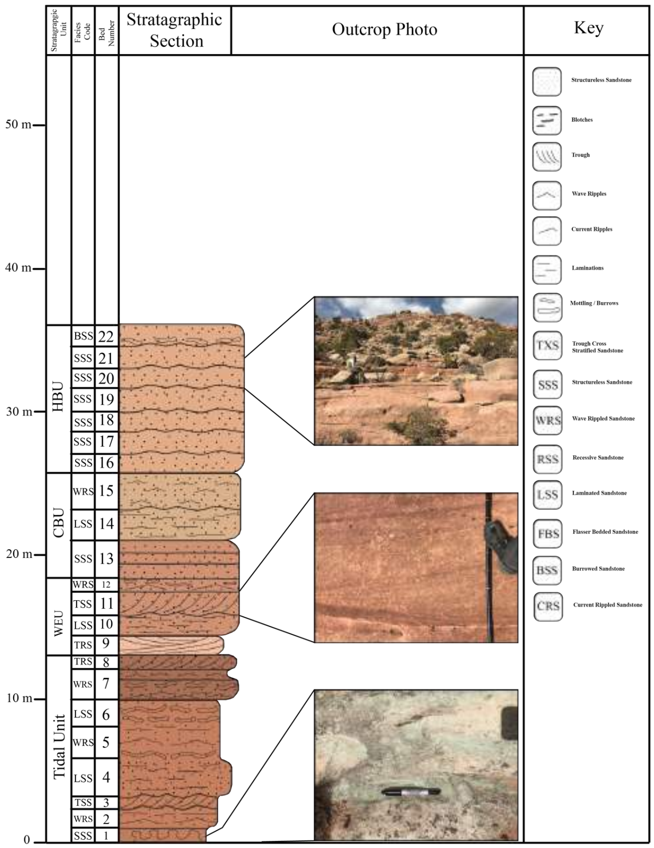


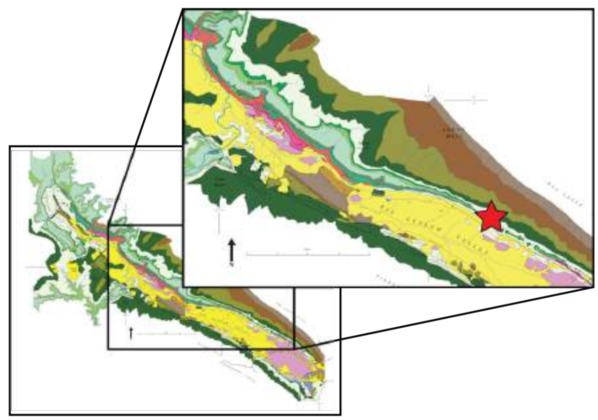
Cougars Den



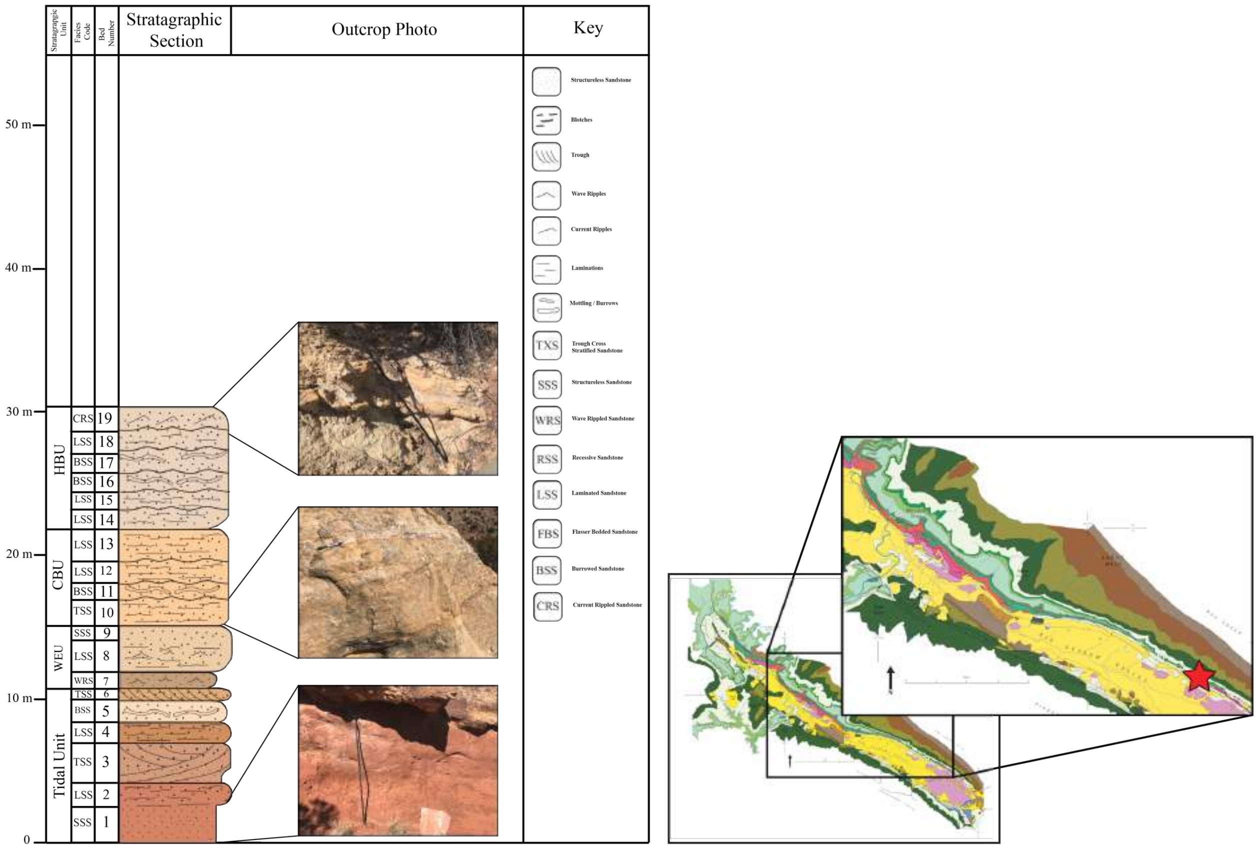
Stratagrapic Unit
Facies Code
Bed Number
Stratagraphic Section
Outcrop Photo
Key
50 m
40 m
30 m
20 m
10 m
0
HBU
Cross Bedded Unit
Wet Eolian Unit
Tidal Unit
BSS 17
LSS 16
TSS 15
BSS 14
TSS 13
TSS 12
WRS 11
BSS 10
WRS 9
WRS 8
TSS 7
LSS 6
BSS 5
TSS 4
LSS 3
WRS 2
SSS 1
Structureless Sandstone
Blotches
Trough
Wave Ripples
Current Ripples
Laminations
Mottling / Burrows
TXS Trough Cross Stratified Sandstone
SSS Structureless Sandstone
WRS Wave Rippled Sandstone
RSS Recessive Sandstone
LSS Laminated Sandstone
FBS Flasser Bedded Sandstone
BSS Burrowed Sandstone
CRS Current Rippled Sandstone

Log Ridge Mine





Early Morning Mine



Curriculum Vita

Rafael A. Delfin was born in El Paso, TX on April 17th, 1995 where he was raised by Rafael M. Delfin and Irma A. Delfin. In 2013 Rafael graduated from Coronado High School and later enrolled at the University of Texas at El Paso. As an undergraduate student Rafael completed an undergraduate thesis and assisted several graduated students in their field based research projects that focused on a variety of geologic settings, gaining him valuable field experience. As an undergraduate Rafael was awarded the W.P Nash Scholarship and D.B memorial scholarships based on his academic standing. In the fall of 2016 he completed his Bachelor's degree one semester early and was name the Outstanding Graduating Senior in Geological Science. In the spring of 2017 he began graduate school at the University of Texas at El Paso as a researcher for the Institute of Tectonic Studies. As a graduate student, he served as the Vice President of the AAPG student chapter and received grants from AAPG Southwest Section, Roswell Geologic Society and the Department of Geological sciences at UTEP. His summers as a graduate student were spent in Houston, TX as a Geologist Intern focusing on major resource plays such as the Marcellus Shale with Southwestern Energy, the Bone Spring Sands with Marathon Oil and most recently, the Lower Spraberry Shale at Chevron. In September of 2019 Rafael accepted a full-time offer from Chevron as an Earth Scientist in the mid-continent business unit.

Contact Information: Rafael A. Delfin

radelfin25@yahoo.com