A high-resolution depositional model of the tidally-influenced Middle Jurassic Curtis Formation, Humbug Flats, Utah, USA

Algirdas Rimkus
A high-resolution depositional model of the tidally-influenced Middle Jurassic Curtis Formation, Humbug Flats, Utah, USA

Algirdas Rinkus

Master Thesis in Geosciences
Discipline: Petroleum Geology and Geophysics
Department of Geosciences
Faculty of Mathematics and Natural Sciences
University of Oslo
01-06-2016
© Algirdas Rimkus, 2016

Supervisors: Ivar Midtkandal, Anja Sundal and Alvar Braathen

This work is published digitally through DUO – Digitale Utgivelser ved UiO

http://www.duo.uio.no

It is also catalogued in BIBSYS (http://www.bibsys.no/english)

All rights reserved. No part of this publication may be reproduced or transmitted, in any form or by any means, without permission.
Acknowledgements

This study was carried out at the University of Oslo as a part of the COPASS project. Firstly, I would like to thank my supervisors Ivar Midtkandal, Anja Sundal and Alvar Braathen for the opportunity to work on this thesis and for scientific guidance and inspiration that they have provided me with throughout the year.

I would like to express my great appreciation to everyone working at the Department of Geosciences, especially to Valentin Zuchuat for his constructive feedback and invaluable discussions that we had and also to Berit Løken Berg for her assistance with sample analysis at the SEM laboratory.

My sincere thanks goes to the Lidar team led by Jan Tveranger at the University of Bergen for providing the data, software and technical support for this thesis.

I would also like to thank the Norwegian Petroleum Society for inviting me to present my findings in the Reservoir Characterization conference in Stavanger, December 2015.

I am particularly grateful to all of my family who supported my during my studies in Oslo.

Finally, I would like to thank the student community at the Department of Geosciences, notably to Arve Sleveland, Ragni Osvik Gurrik and Fredrik Wesenlund for their assistance during fieldwork and subsequent discussions.

June 2016

Algirdas Rimkus
Abstract

An investigation of the depositional architecture of the Curtis Formation and an evaluation of how the observed facies distribution affects overall reservoir quality is conducted. This tidally influenced marginal marine succession is well exposed in southeastern Utah (Humbug Flats, northern San Rafael Swell), and provides a high-resolution analogue to subsurface reservoirs. In order to determine the distribution of reservoir-grade sandstone bodies and characterize their heterogeneities, traditional sedimentological field methods were applied and LIDAR-scan data were collected. Mineralogical and reservoir quality parameters were evaluated from thin sections and were used to constrain the model.

The Middle Jurassic (Callovian) Curtis and Summerville formations represent a complex set of vertical and lateral facies transitions from tidal shallow marine to supratidal sabkha deposits, respectively. The Curtis Formation developed in a transgressive to regressive, low-gradient epicontinental setting where sandstone body stacking patterns were determined by changes in accommodation and sedimentary supply. Determining reservoir quality in tidal sediments is extremely challenging due to inherently complex and heterogeneous sand distribution.

Sub-seismic scale reservoir heterogeneities are the main focus in this study. Sedimentological characterization is used for classification of significant structures and layers, which form potential baffles to fluid flow within genetically related units. Excellent outcrop quality allowed lateral correlation between log sites, supplemented by conventional photographs and LIDAR imagery. The lower succession, interpreted as subtidal shelf deposits, contains channelized sandstone and conglomerate bodies in a heterolithic matrix. Even though the conglomerates have excellent reservoir quality, their connectivity is limited. A cleaning upwards trend towards the middle part corresponds with a transition to a subtidal to lowermost intertidal environment where wave and tide energy was at its highest, which in turn represents improved reservoir quality with laterally extensive, relatively homogeneous sandstones. The uppermost part displays a dirtying-upwards trend with increasingly heterolithic strata.

In general, the reservoir quality of the Curtis Formation shows a general water depth-related trend: sand-to-mud ratio is low during the transgressive phase, becomes highest during the early highstand and decreases again during the regressive phase. Lateral connectivity is generally high, whereas siltstone interlayers provide frequent vertical flow baffles. Locally, mud-drapes and shifts in depositional transport directions cause variation in directional permeability. This depositional model may serve as an inter-well scale analogue with respect to reservoir property distributions in tidally deposited heterogeneous reservoir rocks.
# Table of Contents

1. **INTRODUCTION** ................................................................................................................................. 1  
2. **REGIONAL GEOLOGY** .............................................................................................................................. 2  
   2.1 TECTONIC SETTING ............................................................................................................................... 2  
   2.2 PALEOLATITUDE AND PALEOClimATE ............................................................................................... 4  
   2.3 STRATIGRAPHY AND PALEOGEOGRAPHY .................................................................................... 4  
   2.3.1 Lower Jurassic series ....................................................................................................................... 7  
   2.3.2 Middle Jurassic series ..................................................................................................................... 7  
   2.3.3 Upper Jurassic series ....................................................................................................................... 15  
3. **METHODS AND APPROACH** .................................................................................................................. 16  
   3.1 STUDY AREA ...................................................................................................................................... 16  
   3.2 SEDIMENTARY LOGGING ..................................................................................................................... 18  
   3.3 SAMPLING ....................................................................................................................................... 19  
   3.4 LIDAR DATA ..................................................................................................................................... 20  
   3.5 CHARACTERIZATION OF THE J-3 UNCONFORMITY .................................................................... 21  
   3.6 PETROGRAPHIC ANALYSIS ............................................................................................................. 22  
4. **RESULTS** ............................................................................................................................................ 24  
   4.1 FACIES DESCRIPTION ......................................................................................................................... 24  
   4.1.1 Facies A: Horizontal laminated sand-silt ....................................................................................... 24  
   4.1.2 Facies B: Ripple and plane laminated sandstone and siltstone .................................................... 25  
   4.1.3 Facies C: Horizontal and low-angle bedded fine grained sandstone ........................................... 26  
   4.1.4 Facies D: Trough-cross bedded sandstone .................................................................................... 30  
   4.1.5 Facies E: Flaser-bedded sandstone ................................................................................................. 33  
   4.1.6 Facies F: Heterolithic mudstone and sandstone with wavy bedding ........................................... 35
1. Introduction

4.1.7 Facies G: Heterolithic mudstone and sandstone with lenticular bedding ............... 36
4.1.8 Facies H: Cross-stratified gravely sandstone .................................................. 38
4.1.9 Facies I: IHS conglomerate .............................................................................. 39
4.1.10 Facies J: Wavy to low angle cross-stratified red sandstone ............................. 41
4.1.11 Facies K: Wavy laminated dark red-brown siltstone-mudstone ....................... 42
4.1.12 Facies L: Dark brown mudstone and sandstone (Summerville Fm.) ................. 43

4.2 FACIES ASSOCIATIONS ................................................................................... 45
4.2.1 Facies association 1: Subtidal shelf deposits below fair weather wave base ......... 46
4.2.2 Facies association 2: Subtidal channel infill ....................................................... 47
4.2.3 Facies Association 3: Subtidal shelf at or above fair weather wave base .......... 51
4.2.4 Facies Association 4: Sand flat deposits: tidal bars and dune fields ................. 52
4.2.5 Facies association 5: Mixed and mud flats ......................................................... 53
4.2.6 Facies association 6: Upper intertidal to supratidal wet dune system ............... 54
4.2.7 Facies association 7: Supratidal mudflat ............................................................. 55

4.3 LOG CORRELATION ......................................................................................... 57
4.3.1 Sequence Boundary: the J-3 unconformity ......................................................... 57
4.3.2 Correlation of the lower Curtis Formation ......................................................... 60
4.3.3 Correlation of the upper Curtis Formation ......................................................... 64
4.3.4 Correlation panel ............................................................................................. 65

4.4 GEOLOGICAL DEVELOPMENT ......................................................................... 67
4.4.1 Stage 1: Entrada erg ......................................................................................... 69
4.4.2 Stage 2: Incision of Entrada Sandstone .............................................................. 69
4.4.3 Stage 3: Flooding and first passive infill ............................................................. 73
4.4.4 Stage 4: Development of S1, formation of FA2 sand body ............................... 74
4.4.5 Stage 5: Flooding and second passive infill.................................76
4.4.6 Stage 6: Prograding tidal flats: formation of FA4 sandstone unit...........77
4.4.7 Stage 7: Prograding tidal flats: formation of rippled silty facies............80
4.4.8 Stage 8: Intertidal to supratidal deposition: transition to Summerville.......81

5. DISCUSSION .........................................................................................84

5.1 Driving mechanisms behind the geological development .......................84

5.2 Implications for reservoir quality .......................................................92

6. CONCLUSIONS AND CLOSING REMARKS ........................................98

LIST OF REFERENCES .............................................................................100

APPENDIX A: SEDIMENTARY LOGS .......................................................106

APPENDIX B: THIN SECTION ANALYSIS .................................................140

APPENDIX C: LIST OF FACIES AND FACIES ASSOCIATIONS .................145
1. Introduction

Marginal-marine deposits, especially those that are tidally-influenced, present many challenges both for sedimentologists and reservoir geologists. Due to high heterogeneity of such successions, both lateral and vertical lithology changes occur at a very small scale, which is further complicated by the sensitivity of such systems to relative sea level changes due to the fact that they are found in low-gradient tidal flats and shelf settings.

Tidally-influenced shallow marine seabed structures are formed by processes which include, but are not limited to the development of subtidal to intertidal dune fields, tidal bars, barrier islands, ebb and flood deltas, concentration of tidal currents in subtidal channels and also reworking of older sediment caused by tide wave and storm action. The correct interpretation of such depositional environments therefore greatly depends on high resolution documentation of such indicative structures, attributed to the aforementioned heterogeneity.

In this study, the aforementioned features are targeted in the Middle Jurassic Curtis Formation of the Colorado Plateau. This formation is known to be tidally influenced from previous research; however no high-resolution depositional models have been suggested for the development.

The primary aim of this study is to investigate the high-resolution sedimentological characteristics of the Curtis Formation to discuss what factors influenced the recorded sedimentary architecture. The spatial and temporal distribution of sedimentary sub-environments in shallow, tidally influenced basins is challenging at all scales; therefore a <5 km scale approach used in this study, which highlights how correlation across any distance must be performed with caution. The scale selected is targeted to be fine enough to capture the small details of a complex marginal marine succession, yet at the same time large enough to grasp sub-regional to regional trends in nearshore conditions.

The secondary aim of this study is to evaluate the suitability of the Curtis Formation as a reservoir analogue for tidal deposits. This is accomplished by investigating the lateral distribution and interconnectivity of sandstone bodies and identifying geological heterogeneities at an inter-well resolution, which would be poorly constrained in field or regional scale studies.
2. Regional geology

Beautifully exposed in Central-Southern Utah (the San Rafael Swell, Zion, Canyonlands and Arches National Parks), the Jurassic beds not only are the building blocks of the American landscape, but also are important hydrocarbon and CO2 reservoirs. In this chapter, the tectonic setting, paleolatitude and paleoclimate that were present during the Jurassic in the Colorado Plateau will be overviewed. Priority is given to stratigraphy and paleogeography of the Entrada, Curtis and Summerville formations which are the objects of this study.

Paleogeography and tectonics had a profound influence on depositional environments in the Jurassic period. The combination of equatorial latitudes and the development of a volcanic arc resulted in a distinct arid continental setting in the area during the Jurassic. This is currently exposed in well-known cliff-forming rocks of the Colorado plateau. Peterson (1994) considers tectonic movements the primary force behind relative sea level changes during this period, which is reflected as slight angular disconformances at major unconformities. Eustasy could have also had influence on the configuration of the basin; however, it is very hard to correlate with other study areas because of high structural activity in the Western Interior during the Jurassic.

2.1 Tectonic setting

As overviewed by Kocurek and Dott (1983), in the Jurassic period, the tectonic setting of the western margin of the North American plate was comparable to the Andean-type, with a magmatic arc in the western United States coming into existence in the Triassic (Peterson, 1994). Due to the subduction of the Farallon plate commencing in Early Triassic, a retro-arc type of foreland basin was created and filled in by sediment which were pinching out eastward away from the magmatic arc. The magmatic arc reached its maximum development in the Cretaceous (Peterson, 1994).

For much of the Jurassic, the region was located to the south of an interior seaway called the Sundance (Logan) Seaway. The southern shoreline of this seaway transgressed and regressed in and out of the Western Interior, as the seaway intermittently expanded or contracted (Brenner and Peterson, 1994, Peterson, 1994). During Middle to Late Jurassic time, the region was affected by the earliest stage of the Cordilleran thrust belt formation (Figure 1A).
encompassing orogenic thrust-loading and regional dynamic subsidence driven by subduction of the Farallon plate (DeCelles, 2004). On the margins of the Jurassic basin, positive topographic features were also present: Ancestral Rockies in the east, formed in Pennsylvanian time, Elko Highlands to the west, formed during the Jurassic and also the Mogollon Slope to the south that was present during the Triassic to Jurassic (Lawton, 1994).

As noted by Lawton (1994), the thick marine deposits of Middle Jurassic age are overlain by tidal and marine deposits of Callovian, which, in central Utah, thicken and coarsen from the east in the Colorado Plateau to the westernmost exposures within thrust belt, from mudstone, siltstone, and sandstone to siltstone, sandstone, and local chert pebble conglomerate respectively. Such thickening and coarsening trend indicates two distinct features: the development of the Idaho Trough with high sediment accommodation and also the volcanic arc-derived sediment source, both located towards the west. The paleogeographic distribution of these facies during the Callovian-Oxfordian is illustrated in Figure 1B.

**Figure 1 A:** Approximate position of thrust front through time (Allen et al. 2000); **B:** Paleogeography of western U.S. in late Middle Jurassic to early Late Jurassic time (Callovian-Oxfordian) according to Lawton (1994), coincident with maximum extent of marine deposits of Sundance Formation (Wyoming), upper part of San Rafael Group (Utah, Arizona), and Swift Formation (Montana). Facies distribution after Brenner (1983).

As it was outlined by DeCelles and Currie (1996), Middle Jurassic to Eocene sedimentary rocks in the region can be described as a succession that accumulated in a migrating foreland basin system, progressively stacking backbulge, forebulge, foredeep and wedge-top deposits.
on top of each other. Migration of the thrust front through time is illustrated in Figure 1A. In foreland basins, stratigraphic gaps develop due to the migration of the forebulge, which was interpreted by the authors as the unconformity overlying the Morrison formation.

2.2 Paleolatitude and paleoclimate

According to Kocurek and Dott (1983), during the Jurassic, the Colorado plateau drifted north, occupying latitudes between 5° and 25° north, equivalent to the modern intertropical zone and the trade wind belt. In combination with a volcanic arc to the west, the latitudinal position in the intertropical zone resulted in a characteristic arid climatic setting: wind patterns were modified along the volcanic arc, transporting sands generally southwards in the continental desert. This is evident from the thick eolian deposits present in the Lower and Middle Jurassic successions; however they were also affected by periods of increased humidity and intermittent marine incursions. These developments are described individually in more detail for each stratigraphic unit in Section 2.3.

According to Peterson (1994), several tectonic factors lead to a dry climate in the Western Interior during the Jurassic. The area was downwind from the magmatic arc, causing a rain shadow from the west. The supercontinent Pangea gradually started breaking apart in the Early Jurassic, which could have resulted in in a gradual breakdown of monsoonal circulation prevalent during the Triassic. Also, the continent was moving northwards from 18° north to 30-35° north during the Jurassic, which would have brought the southern part of the basin into the driest latitudinal zone.

2.3 Stratigraphy and paleogeography

The Jurassic sedimentary succession in Central Utah displays a variety of continental, marine and hypersaline deposits, which include both siliciclastic and carbonate sediment. The succession is primarily dominated by eolian strata, which are some of the best documented desert sediments in the Earth’s stratigraphic record (Allen et al., 2000). The distribution and correlation of Jurassic stratigraphic units in the Colorado Plateau is displayed in Figure 2. Directly affected by the formation of a volcanic arc and early development of a foreland basin, the Jurassic sedimentary record includes deposits unique in both their depositional characteristics (especially their thickness and lateral extent) and their
exposure in outcrops today. The latter enables the succession to be researched in great detail, however for some formations, published data is still limited. In this section, each sedimentary succession between major unconformities and its respective geological development will be described individually, with the primary focus being on the Entrada, Curtis and Summerville formations which are the subject of this thesis; however, general knowledge of the surrounding formations is still of major importance when stratigraphic relationships, dating of formations and the geological development of the area are considered. The unconformities in the Jurassic succession are denoted stratigraphically upwards as J-0 to J-5. As it will be evident from the described stratigraphic units, depositional environments varied substantially over 55 million years. However, even more change is evident when individual strata are analysed, showing how sensitive and complex these continental and marginal marine environments are.

Figure 2: Correlation chart for Jurassic stratigraphic units in the southern part of the Western Interior basin including reference columns for Wyoming units and depositional cycles of Brenner and Peterson (1994) in the northern part of the Western Interior for comparison. Transgressive-regressive cycles and unconformities also indicated (Peterson, 1994).
During the Middle Jurassic a marine seaway came into existence in large parts of Utah due to the formation of a foreland basin, which at different stages was called the Carmel Seaway, the Curtis Seaway and eventually in the Cretaceous, the Western Interior Seaway. In the study area, marine cycles of this seaway were recorded in the stratigraphy as intermittent floodings by transgressions of shallow seas from the north. While Early Jurassic was dominated by solely by continental sedimentation, in the Middle Jurassic, there were 5 distinct transgressive-regressive cycles, during which a seaway that covered primarily Idaho and Wyoming expanded and contracted, moving the shoreline across the northern parts of the region. During the Late Jurassic, there were two marine transgressions, which were followed by deposition of continental beds of the Morrison formation (Peterson, 1994).

Research in the study area started in the beginning of the 20th century, when the geology of the Green River Desert was described by Emery (1918). A paragraph in the publication says:

The thin-bedded upper part of the Navajo contrasts strongly with the massive lower part just described. The beds are sandstone and sandy shale and are for the most part brick-red in colour, but near the middle of the series is a conspicuous zone of light-colored beds which though of similar lithology to the associated beds, differ in that they are light greenish in color. With them are associated irregular bunches of quartz which weather into small rounded red balls or lozenges resembling in appearance red rubber bath sponges. These “sponges” may be seen in profusion along the Hanksville road two miles or so south of San Rafael bridge. The very top of the upper Navajo sandstone is characterized by a 90-foot cliff of sandy shale interbedded with dirty gypsum. There is about 15 feet of almost solid gypsum just below the McElmo, which is thought to unconformably overlie the Navajo.

This is one of the oldest published descriptions of the Uppermost Entrada, Curtis and Summerville formations and the J-3 unconformity, even though neither of the formations was distinguished from the Navajo, but their lithological characteristics, which are now well-researched, make them easily identifiable in the text. Moreover, investigation of geological maps covering the area next to the aforementioned San Rafael bridge shows that Triassic beds are exposed. In this chapter, lithological characteristics will be overviewed in this chapter based on the most recent research available.
2.3.1 Lower Jurassic series

The Lower Jurassic series comprises Wingate, Kayenta and Navajo formations of continental origin, which also make up the Glen Canyon group. Bound at the base by the J-0 unconformity, the Wingate sandstone consists of eolian cross-stratified sandstone with some occurrences of irregularly bedded, silty sandstone of sabkha origin. This is followed by the Kayenta sandstone of fluvial origin, interbedded with minor amounts of red overbank mudstone. The Navajo formation comprises large-scale eolian cross-bedded sandstones and some lenses of limestone, which are interpreted to have been deposited in small lakes found in the Navajo desert (Peterson, 1994).

2.3.2 Middle Jurassic series

The first marine transgression (TR-1 cycle) of the Western Interior Seaway is only recorded to the north in Wyoming as the Gypsum Spring Formation of Aalenian-early Bajocian age (Figure 2). The Temple Cap Sandstone of eolian origin is considered to be its correlative in Southwest Utah. Both units are bound by the J-1 and J-2 unconformities at the base and top respectively.

In the San Rafael Swell (SRS), the oldest rock of Middle Jurassic age is the Page eolian sandstone, deposited on top of the J-2 unconformity. According to Peterson (1994), the J-2 unconformity was formed after a westward tilting of the Plateau block. The correlative of the Page sandstone towards the southwest and northeast is the lowermost part of the Carmel formation, meaning that the Page Sandstone was deposited in a laterally constricted area.

The Carmel Formation is extensive in the Colorado Plateau and consists mostly of limestone, gypsum, mudstone and silty sandstone. It is the expression of the second and third marine transgressive-regressive cycles (TR-2 and TR-3) in the Western Interior Basin. It has been interpreted as a normal marine carbonate deposit, except for the uppermost part of Carmel, which belongs to the regressive part of TR-3 cycle and includes gypsum and other evaporites of restricted marine origin (Peterson, 1994). Based on the fossil assemblage found in the lowermost limestone unit, it was dated to be of late Bajocian age (Imlay, 1980).
Regional geology

**Entrada Formation**

During Early to Middle Callovian times, the Western Interior was covered by the laterally extensive Entrada erg, resulting in a distinct succession of continental deposits.

**Lithology and depositional environments**

The Entrada Sandstone deposits are mainly cross-bedded eolian dune sandstones, commonly interbedded with irregular red sandstone and silty sandstone, considered to be sabkha deposits.

In East-Central Utah, the Entrada Sandstone is commonly subdivided into three distinct members (Wright et al., 1962). Starting from the oldest, Dewey Bridge Member comprises reddish-brown siltstones, sandy siltstones and silty sandstones. The Dewey Bridge Member is overlain by the Slickrock Member, which is composed of yellow to light brown very fine- to fine-grained sandstones. The uppermost Moab Member consists predominantly of white sandstone with very thick sets of sweeping crossbeds. This member pinches out in all directions away from its thickest section south of the city of Moab.

According to (Peterson, 1994), the Entrada Sandstone grades laterally to the northwest of the Kaiparowits basin and Henry basin, and also east of the San Rafael Swell into a flat-bedded red silty sandstone known as the earthy facies, where individual aforementioned members are not recognized. As type locality of Gilluly and Reeside (1928) is where this laterally limited lithology is present, it is therefore considered not representative of the whole succession in the Colorado Plateau.

The development of the Entrada erg was researched in detail by (Kocurek, 1981). According to the author, the progradation of Entrada dunes over the Carmel mudflats created a distinctly conformable bounding surface, which is dominated by load features and contorted bedding: rolled pillows and dikes of Entrada sandstone into the Carmel and upwards swells of Carmel into the Entrada. Moreover, the lower two meters consist of both eolian and marine structures, which indicate that the early erg deposits were reworked by the retreating Carmel Sea to some extent.

More recent work by Hicks et al. (2010) and Hicks (2011) has shown a variety of tidal structures in distinct beds of the Entrada Sandstone. A variety of facies were interpreted to have been deposited in an erg-margin covered by algal mats, supratidal sabkha ponds.
replenished by storm events, intertidal channel and flat, subtidal ooid-bearing shoal and breaker bar environments and also storm-bed deposits. Due to this interbedding of eolian and sabkha beds, the succession is often termed a “wet dune system” (Peterson, 1994). The description of Hicks (2011) shows a much more complicated conceptual model than a simple erg dominated solely by eolian processes. Due to proximity to a marine environment, lateral facies changes appear and the system becomes extremely sensitive to fluctuations of the base level. This is supported by the interpretation of the middle Entrada member, which is thought to be a southeastward extending tongue of tidal flat and coastal sabkha deposits that formed during a transgression of the basin from the north (Peterson, 1994). This transgressive-regressive cycle has resulted in a distinct member being deposited, however, smaller scale trends can also be identified locally. The sands were sourced from eolian and wadi reworking of older eolian deposits, as well as the craton to the east and remnants of Ancestral Rockies (Kocurek and Dott, 1983).

**Age and paleogeography**

Due to the fossil-lacking continental origin of the Entrada Sandstone, its age is determined only by evaluating the timing of its bounding formations, the underlying Carmel Formation, dated by both paleontological and geochemical means, and the overlying Curtis Formation, with its dating described in the following section. This timeframe limits the deposition of the Entrada Sandstone to the Early Callovian.

As the Carmel Sea retreated during the Callovian, it resulted in a northwestwards progradation of the Entrada Erg, eventually occupying large parts of the Colorado Plateau (Kocurek, 1981). The paleogeographic situation during Middle Callovian is shown in Figure 3, where the areal extent of the Entrada erg and the maximum extent of the marginal marine influence are outlined. As it can be seen, the study area during this time was covered by sabkhas and tidal flats. It also must be noted that in the figure current latitudes are shown, whereas during the Callovian, the area was situated below 20° north (Anderson and Lucas, 1994).

Deposition of the Entrada Sandstone was followed by the transgressive-regressive TR-5 cycle, during which Curtis and Summerville formations were deposited.
Figure 3: Paleogeography of the southern part of the Western Interior basin during middle Callovian time (late Middle Jurassic) and deposition of the lower beds of the Entrada Sandstone and related beds (Peterson, 1994).

**Curtis Formation**

Gilluly and Reeside (1928) released one of the earliest publications where the Curtis Formation was properly defined. It was named after its excellent exposure at Curtis Point in the north-eastern San Rafael Swell. It was described as a series of greenish-grey glauconitic conglomerates, sandstones, and shales containing Upper Jurassic fossils. The formation was identified by its typical green-grey colour on fresh fracture, which eventually turns brown due to subaerial exposure. The total thickness at its type locality is 193 feet (58.82 m), while at the Summerville point at the northern end of the San Rafael swell it increases to 252 feet (78.81 m). At the base of the formation, an erosional unconformity with irregularities up to 50 feet (15.24 m) in height was reported. The conglomeratic facies were described as becoming less prominent towards the south, with the whole formation thinning in the same direction; whereas to the east, the mud content was noted to be increasing. Due to its limited lateral extent, it was interpreted to represent a restricted marine phase of the Jurassic. Based on the fossils collected and coarse-grained sedimentary structures found, it was interpreted as a shallow marine deposit.
Lower boundary

A survey by Pipiringos and O'Sullivan (1978) dealt with the nature and extent of unconformities in the Triassic and Jurassic rocks of Utah. The J-3 unconformity, found at the base of the Curtis formation, was reported to be rich in black and white chert pebbles at the contact or in close proximity above it, with the diameter of the clasts displaying a northeastwards-decreasing trend of grain size which corresponded to the orientation of cross-beds in the formation, both outlining the general direction of sediment transport during the time of deposition. The coarse-grained clasts were identified as sourced from the west of the San Rafael Swell. The extent of the unconformity was described as laterally confined to Utah, northern Arizona, and possibly westernmost Colorado. Unfortunately, the topographic relief was not systematically investigated in the study; however, preliminary examination indicated a relief of 14 m over a distance of 3 km in the northeastern San Rafael Swell. According to the study, the unconformity was bound by beds of Callovian age, which lasted about 2 m.y., therefore the duration of uplift and erosion of the Entrada Sandstone was estimated to be less than 1 m.y. long.

The J-3 unconformity has been described as a transgressive erosional surface fading out eastwards towards Moab (Peterson, 1994), which was created as a result of marine destruction of eolian sand seas (Eschner and Kocurek, 1986). In the latter study, paleotopographic highs of up to 7 m were identified. According to the authors, such features were created when Entrada coastal dune fields were flooded during a transgression. Poor correlation of the unconformity to global sea level curves has also linked it solely to tectonic processes (Peterson, 1994).

Age

Paleontological work involving dating of the formation includes multiple publications by R. W. Imlay, primarily, the extensive description of Jurassic paleobiogeography of the conterminous United States (Imlay, 1980). In this study, Curtis formation in the San Rafael Swell was determined to be equivalent to the Curtis Member of the Stump formation in northern Utah, based on the fact that they both lie unconformably on top of the Entrada Formation. They are also both considered to be identical with the Pine Butte Member of the Sundance Formation in Wyoming based on lithological similarity. This identification meant that the Curtis Formation of the San Rafael Swell must be older than Early Oxfordian,
because the equivalent beds in Wyoming disconformably underlie the Lower Oxfordian Redwater members of the Sundance and Stump formations, the age of which was based on the late Callovian – early Oxfordian ammonite *Scarburchiceras bighornense*, identified within the unit in northeastern Utah (Imlay, 1982). However, as the study indicates, the source of the ammonite raised some questions regarding its origin in the field.

According to recently published biostratigraphic data by (Wilcox and Currie, 2008, Wilcox, 2007), in the San Rafael Swell, the lower 50 ft. of the Curtis Formation contains both Early Oxfordian dinoflagellate cysts and the previously mentioned Late Callovian – early Oxfordian ammonite. Moreover, in the Uinta Mountains region, the Curtis and Redwater members of the Stump Formation are also found to be of Early Oxfordian age. The discoveries change the time designation of the Curtis and Summerville formations from the late middle Callovian to Oxfordian. Also, these findings also support the time-equivalence of the Curtis and Stump formations. However, in this study, the official time designation of Middle Jurassic utilized by the USGS will be used (USGS, 2015).

*Lithology and depositional environments*

As reported by Caputo and Pryor (1991), the tide- and wave-influenced shallow marine Curtis Formation makes up a part of a transgressive-regressive succession. In the outcrops examined by the authors, the base of Curtis begins with mudstone-sandstone facies, interpreted to be subtidal nearshore shelf deposits. In this facies, gravelly sandstone bodies are found, which have been described as coarse-grained sand waves. The sediment for these palimpsest bodies were derived from pre-Curtis alluvial drainage and consequently mixed with Curtis sediment and reorganized by marine currents into gravel waves. Siltstone laminations and ripple intrasets in the sandstone bodies were interpreted as sub-threshold current velocity structures. Peterson (1994) has identified the source of coarse clastic material in the basal beds of the Curtis Formation as the first influx of sediment derived from newly elevated highlands to the west. Continuing the description of the Curtis-Summerville succession described by Caputo and Pryor (1991), the mudstone-sandstone facies are in turn overlain by sand-rich shallow marine deposits (composite sandstone facies) in the middle part of the succession. Finally, in the upper part of the Curtis Formation, rippled silty facies emerge, interpreted as tidal sand flats, which eventually conformably grade to the Summerville Formation.
**Paleogeography**

As it was described by Kocurek and Dott (1983), the transgression of the Curtis sea (TR-5 of Peterson (1994)) established marine conditions in the region, while the Entrada erg retreated southwards at the same time, still containing very large dunes regardless. However, as it was later interpreted by Anderson and Lucas (1994), the sediment source for the Entrada erg was inundated by the Curtis transgression as a result essentially interrupting sand transport, possibly also due to modification of trade winds by the marine water body. The distribution of facies during the deposition of the Curtis Formation is illustrated in Figure 4.

![Figure 4: Paleogeographic situation in the Western Interior during the deposition of the Curtis Formation and correlative beds. The arrows denote two eolian dune fields, the Romana Sandstone to the southwest of the basing and the Moab Tongue in the southeastern corner of Utah.](image)

**Summerville Formation**

The Summerville Formation was named after its exposure at the Summerville Point in the northern end of the San Rafael Swell, where its type section is located (Gilluly and Reeside, 1928). In the outcrop, the 163 feet (49.68 m) thick succession comprises primarily alternating chocolate-coloured mudstone and laminated sandstone beds with some red mudstone towards the base. The thickness of the formation varies laterally, up to 331 feet (100.89 m) near the Drunk Man’s Point towards the south, however, southwards beyond this

Regional geology

point it starts to thin considerably again. In the type locality of the Curtis Formation, the Summerville Formation is 125 feet (38.1 m) thick (Gilluly and Reeside, 1928). The Summerville Formation has a wider lateral extent than the Curtis: where the latter is not recognizable, the Summerville rests directly on top of the Entrada Sandstone (Gilluly and Reeside, 1928).

Lithology and depositional environments

As it was described by Caputo and Pryor (1991), the Summerville Formation comprises two distinct lithologies: reddish-brown silty facies and gypsiferous facies. According to the author, towards the east and southeast, formation thickness decreases greatly due to basin-edge deposition and erosion along the J-5 unconformity. Rare paleoflow indications suggest a multidirectional flow pattern with mean azimuths to the northeast in the western SRS, the north, east and southeast in the eastern SRS, and to the south in the Green River desert. The distinctive chocolate brown of the formation was interpreted to be related to a high ratio of ferric to ferrous iron, little to no organic material and prolonged exposure to the atmosphere in the upper intertidal to supratidal environment which favoured oxidation at the time of deposition.

Sandstone and siltstone intervals interbedded with mudstone were identified by Caputo and Pryor (1991) as drainage channels which dissected an extensive siliciclastic sabkha or a mudflat. The average paleoflow direction was interpreted to represent a northeast-oriented dip direction of the paleoslope. Meanwhile, the gypsiferous facies represent bodies of standing water, where due to high evaporation rates, precipitation of gypsum took place. Such pools of water were intermittently recharged by storms and spring tides, evaporative pumping and terrestrial run-off.

Age and paleogeography

As the Summerville Formation is generally lacking fossils (Gilluly and Reeside, 1928), its chronostratigraphic position is determined based on the ages of the conformably underlying Curtis Formation and the unconformably overlying Morrison Formation. As it was previously described, the Curtis Formation is of early Oxfordian age, whereas the base of the Morrison Formation is no older than latest Oxfordian in age. Also, according to Wilcox and Currie (2008), even though the Summerville Formation in the San Rafael Swell was not dated in the study, its equivalent units to the north are of early Oxfordian age.
2.3.3 Upper Jurassic series

In the San Rafael Swell, the Upper Jurassic series, which was deposited on the Summerville Formation, separated by the J-5 unconformity, comprises the latest Oxfordian – Tithonian Morrison Formation.

**Morrison formation**

The Morrison formation can be divided into three distinct members: Tidwell, Salt Wash and Brushy Basin, all of which are distinctly heterolithic, and also well-known for being uranium-rich, as well as holding ample dinosaur fossils (Peterson, 1994). Given the fact that Morrison is entirely a continental deposit, its uniform coverage of a large area is surprising (Hintze and Kowallis, 2009). The formation has been interpreted to represent a variety of depositional environments. The Tidwell and Brushy Basin members are composed of varicoloured mudstones and ribbon-type fluvial beds, typical of broad mudflats with rare streams. Meanwhile, the Salt Wash Member has been deposited in a complex fluvial environment with coarse grained clastic deposits being the dominant lithology, set in a muddy floodplain matrix (Tyler and Ethridge, 1983).

The age of the Morrison Formation is well-dated by both isotopic and paleontological methods. Numerous studies have been summarized by Peterson (1994), comprising investigations of argon isotopes, dating of bentonite beds and microfossils. Combination of the methods suggests a latest Oxfordian to Tithonian age of deposition.
3. Methods and approach

Field work of this study took place during from 22nd of May to the 7th of July, 2015. Throughout the period, scouting of the area was performed, sedimentary logs were taken at selected locations, paleocurrent directions were measured whenever it was possible to do so reliably, samples of rocks were acquired and correlation between log sites was established. This was followed by preparation and analysis of the data. Lidar images were acquired separately by a team from the University of Bergen. The approach of each stage is described individually in this chapter.

3.1 Study area

The study area was located in the Humbug flats, Emery County, Utah, USA. The study took place primarily in the Stove Gulch and partly in the Sulphur Canyon (Figure 5), where exposures of uppermost Entrada Sandstone, Curtis Formation and in limited areas, lowermost Summerville Formation were present.

The study area was primarily limited by presence of Curtis Formation exposures and their accessibility. A major normal fault was present in the southern part, with the study area being in the hanging wall of the fault. In the footwall, only the Entrada Sandstone and lowermost Curtis were exposed, however, with the latter being at high elevation and consequently hard to reach, therefore the footwall was not targeted in the study. To the east, the study area was bound by the Price River. To the north and west, a smaller fault and high topography were the controlling factors, resulting in younger strata exposed in the hillsides.

The sinuous, highly exposed nature of the Stove Gulch (Figure 5) provided an excellent opportunity to investigate the J-3 unconformity and the lowermost Curtis Formation in great detail, with outcrops oriented in a variety of directions at very close proximity, allowing having three-dimensional control of the succession. On the contrary, the logging sites that were selected fall in an approximately straight line, representing a 2D profile.
**Figure 5:** Location of the study area in the state of Utah, USA and a map of the study area, with the locations of logging localities and bounding faults outlined. Lidar coverage is highlighted with blue lines. Photo: Google Earth
3.2 Sedimentary logging

For the evaluation of the sedimentary succession and its lateral variation, a total of 10 sedimentary logs were taken in the study area (Table 1, Figure 5). Firstly, a section was logged in a scale of 1:100 in order to investigate the general stratigraphic trend in the study area and to familiarize with the lithology. All other sections were logged in a scale of 1:50. The second section was logged close to the first location, where the exposure was better in the lowermost Curtis Formation and many small-scale features were consequently identified. On the contrary, the second logged succession was not nearly as full as in Location 1. Further on, a section was logged in a locality where a full succession from Top Entrada to Base Summerville was exposed in order to have a log capturing all three formations. Finally, the rest of the logs were made in locations that extended beyond the first three logs and filled in gaps between them.

Due to the fact that uppermost Curtis and Summerville formations were eroded in the majority of the area, one day was dedicated to scouting of the overlying formations with the purpose of getting acquainted with the general development and typical lithology of the overlying Summerville and, to a lesser extent, Morrison formations.

The log localities were chosen according to their accessibility, exposure of uppermost Entrada Sandstone and also the fullest succession of Curtis Formation available. This was most commonly achieved by following a gully down towards the Entrada-Curtis boundary and logging upwards through the stratigraphy to the highest point of elevation nearby. For the best vertical logging accuracy and maximum quality of exposure, sites with steepest scalable walls were sought after, but were not always available due to the slope-forming erosional nature of the Curtis Formation.

Logging was carried out by measuring bed thickness, determining the dominant grain size, identifying depositional and grain size trends, lateral continuity of beds and describing primary and secondary structures. Paleocurrent directions were also measured where reliable measurements could be made. A total of 162 measurements were taken by measuring cross-stratification foreset dip directions, exposed ripples in heterolithic sediment and unidirectional ripples on bedding surfaces.
### Table 1: List of logging localities

<table>
<thead>
<tr>
<th>Log #</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Total thickness logged</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N 39 20.429</td>
<td>W 110 31.360</td>
<td>69.0 m</td>
</tr>
<tr>
<td>2</td>
<td>N 39 20.448</td>
<td>W 110 31.875</td>
<td>31.5 m</td>
</tr>
<tr>
<td>3</td>
<td>N 39 20.506</td>
<td>W 110 33.136</td>
<td>46.25 m</td>
</tr>
<tr>
<td>4</td>
<td>N 39 20.357</td>
<td>W 110 33.073</td>
<td>48.25 m</td>
</tr>
<tr>
<td>5</td>
<td>N 39 20.888</td>
<td>W 110 31.002</td>
<td>43.5 m</td>
</tr>
<tr>
<td>6</td>
<td>N 39 20.389</td>
<td>W 110 31.639</td>
<td>17.0 m</td>
</tr>
<tr>
<td>7</td>
<td>N 39 20.807</td>
<td>W 110 31.394</td>
<td>49.0 m</td>
</tr>
<tr>
<td>8</td>
<td>N 39 20.743</td>
<td>W 110 31.128</td>
<td>31.75 m</td>
</tr>
<tr>
<td>9</td>
<td>N 39 20.677</td>
<td>W 110 31.191</td>
<td>32.0 m</td>
</tr>
<tr>
<td>10</td>
<td>N 39 20.562</td>
<td>W 110 32.055</td>
<td>36.5 m</td>
</tr>
</tbody>
</table>

3.3 Sampling

Samples of rocks were collected in the field with an emphasis on being representative of the preliminary facies that were identified during fieldwork, based on distinctive textures, structures and also stratigraphic level. Unfortunately, samples of some facies were not collected due to high friability caused by high mud content in the sediment. Other facies were distinguished from lithologies that were considered as a single facies during processing of the data and after field work was complete. Poor consolidation of sediment is generally prevalent in both the lowermost and uppermost parts of Curtis Formation and all of the Summerville Formation, where mud-rich sediment prevails; therefore samples are limited to the Entrada Sandstone and the middle part of the Curtis Formation. A total of 11 samples were acquired (Table 2).
Table 2: List of lithological samples acquired

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Stratigraphic level</th>
<th>Lithology</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR270615-1</td>
<td>Log 3:12 m</td>
<td>Trough-cross bedded fine gr. sst</td>
<td>Reservoir characterization</td>
</tr>
<tr>
<td>AR280615-1</td>
<td>Log 4: 7 m</td>
<td>Cross-stratified conglomerate</td>
<td>Res. char.</td>
</tr>
<tr>
<td>AR280615-2</td>
<td>Log 4: 23.7 m</td>
<td>Ripple laminated fine sst.</td>
<td>Res. char.</td>
</tr>
<tr>
<td>AR290615-1</td>
<td>Log 5: 42.5m</td>
<td>TCB sandstone</td>
<td>Res. char.</td>
</tr>
<tr>
<td>AR290615-2</td>
<td>Log 5: 42.8m</td>
<td>TCB fine sst. – higher mud cont.</td>
<td>Res. char. – no thin section – sample too friable</td>
</tr>
<tr>
<td>AR010715-1</td>
<td>Log 6 7.5m</td>
<td>Fine sst. with poorly visible horizontal flasers – cliff forming unit</td>
<td>Res. char.</td>
</tr>
<tr>
<td>AR010715-2</td>
<td>Upper Entrada</td>
<td>Deeper Entrada dune sandstone</td>
<td>Lith. reference</td>
</tr>
<tr>
<td>AR020715-1</td>
<td>Log 7: 13.5m</td>
<td>Horizontal bedded fine sst.</td>
<td>Res. char</td>
</tr>
<tr>
<td>AR030715-1</td>
<td>Log 9: 22.5m</td>
<td>Horizontally bedded silty sst.</td>
<td>Res. char</td>
</tr>
<tr>
<td>AR030715-2</td>
<td>Log 10: 2.4m</td>
<td>Thin-bedded gravelly conglomerate</td>
<td>Res. char</td>
</tr>
<tr>
<td>AR070715-1</td>
<td>Uppermost Entrada</td>
<td>Eolian sst.</td>
<td>Lith. reference</td>
</tr>
</tbody>
</table>

3.4 Lidar data

Thanks to rapidly improving technology, the use of Lidar images has provided researchers with an opportunity to carry out accurate correlations in outcrop images at a variety of scales, limited only by availability of outcrops themselves. A large amount of work has been carried out studying reservoir analogues, especially in the state of Utah, where outcrops of excellent quality have been investigated (Buckley et al., 2010a, Buckley et al., 2010b, Hampson et al., 2012, Moore et al., 2012)

Lidar images of the study area have been acquired by a team from the University of Bergen, with more than 9 km of outcrop images acquired in the study area. The Lidar images slightly expanded the study area and allowed to investigate the J-3 unconformity in the outcrop south of the main study area (Figure 5), which was inaccessible for a close inspection. The images were processed by the team and handed over for interpretation using LIME (Lidar Interpretation and Manipulation Environment) software at the University of Oslo.
The coverage of Lidar scans was limited to the steep canyon walls of the Stove Gulch (Figure 5), where beds of the Entrada Sandstone and lowermost Curtis were exposed. The upper part of the Curtis Formation forms gentle topography; hence it was not present in the Lidar scans. Also, some deep gullies dissecting the canyon walls created uncertainties in the interpretation as individual surfaces could not be traced continuously through these areas.

With the existing limitations, the Lidar data was utilized to constrain the correlation and sandstone body geometries in the lowermost Curtis Formation. It also provided excellent data for the characterization of the J-3 unconformity, methods for which are described in the following chapter.

3.5 Characterization of the J-3 unconformity

The erosional relief of the J-3 unconformity is of major importance, especially when establishing the degree of reworking and erosion at the boundary between Entrada and Curtis.

In the field, a single marker bed, an easily identifiable bleached Entrada sandstone bed, was followed along a cliff wall. Assuming that the marker bed was horizontal at the time of deposition, the resulting erosional relief was determined by measuring from the top of the marker bed to the base of Curtis Formation. In order to ensure the use of the same marker bed, correlation between log sites was carried out. Even though Entrada was not logged more than a few meters in the logs, Top Entrada was always included which allowed positioning of the logs at the correct relative stratigraphic level after the erosional relief was established.

The attempt to establish this relationship with direct measurements in the field was lacking precision due to the cliff-forming nature of the Entrada Sandstone. Most localities with the uppermost several meters of Entrada exposed are very hard to access, preventing accurate logging of the stratigraphy. The introduction of Lidar scans provided great lateral coverage and precise absolute elevation measurements of the surface, both of which were essential to determine elevation changes of the unconformity in the study area.

A reference Entrada Sandstone bed was traced in Lidar images throughout the whole Stove Gulch, except for logs 3, 6, 9 and 10, due to the fact that there was no Lidar coverage, and also except for Log 4, due to faulting in the area, resulting in the reference bed occurring
below the surface. In this case, a different bleached reference bed and its relation to the previous marker bed was utilized.

Logs 1, 2, 5, 7 and 8 were tied in with absolute elevation of Lidar scans, as sedimentary logs could be directly correlated with outcrop images. Logs 3, 4, 6, 9 and 10 were not covered by Lidar scans; therefore they were tied in using coordinates of log tops located at prominent hilltops and by using the absolute elevation of such hilltops acquired from Google Earth. Subtracting the logged thickness of the Curtis Formation from the hilltop elevation gives the absolute elevation of Top Entrada surface in the locality.

The lines interpreted in Lidar and the absolute elevations of top Entrada were consequently imported into Petrel 2015 software (Schlumberger), where a surface visualizing the topography of the unconformity in relation to a horizontal reference bed was created. The isochore interpolation method with default Petrel settings was used to make the surface by using points of the reference bed and top Entrada Sandstone interpreted in LIME software. This gridding method was used because it created a surface which conformed completely to the interpreted points without any smoothing.

### 3.6 Petrographic analysis

Out of the 11 samples acquired, 10 thin sections were made, all of which were analysed under a petrographic microscope. Blue epoxy was used in order to highlight the porosity of the samples. Laboratory work included grain size measurements and mineralogical characterization of thin sections using a petrographic microscope and also investigation of selected samples with a scanning electron microscope. The results for all analysed thin sections are outlined in datasheets provided in Appendix B.

In order to confirm field grain size observations, grain size measurements were carried out by analysing microscopy images of the thin sections and measuring the size of approximately 200 randomly selected grains in a single frame. For these measurements, digital optical microscopy software was used, with the grain size measurements calibrated to a micrometre slide. In these measurements, particles smaller than silt were not measured. Subsequently, the measured grains were categorized according to the scale of (Wentworth, 1922).
In order to determine the mineral content of the samples, a qualitative approach was used, systematically evaluating the grain composition with conventional optical mineralogy techniques. Point counting analysis of the samples was carried out, with a target of 400 points for each section. For a single sample of gravelly medium-grained sandstone (AR030715-2), 200 points of the medium-grained matrix were counted due to the coarse-grained nature of the sediment with a large part of the volume occupied by rock fragments.

Due to time and resource constraints, 5 selected samples were analysed under a Hitachi SU5000 FE-SEM scanning electron microscope (SEM). The analysis targeted the following features of the samples: determining nature and composition of cement, verification of mineralogical analysis, identification of pore-filling clay and clay-rich pellets and mineralogy of accessory minerals.
4. Results

In this chapter, the results acquired after the data was processed are described. Facies were identified based on their lithological characteristics and then were grouped into facies associations that comprise genetically-related sedimentary packages. Afterwards, correlation of such sedimentary packages was established. An interpretation for the geological development of the studied succession is given, which integrates all of the results described.

4.1 Facies description

A total of 12 facies were identified based on their colour, structure, texture and other distinguishable features. A description and a short interpretation of the depositional mechanism are given for each facies.

4.1.1 Facies A: Horizontal laminated sand-silt

**Structure and texture:** Dark brown, very fine sand- and siltstone, found in horizontally laminated (<1 cm thick) beds (Figure 6). Rare ripples are present. The definitive characteristic of the facies is appearance of the sandstone in outcrops as a product of erosion: it is eroded into thin, large sheets of rock which themselves are cemented and therefore fairly rigid. Moreover, the facies can be recognized by its strikingly dark brown surface-weathering colour as opposed to greenish-grey or yellow sandstones in the rest of the Curtis formation. This facies is found exclusively in the uppermost part of Curtis, in the gradually fining-upwards succession, which belongs to the conformable transition into the Summerville Formation. The facies is also always underlain by Facies B. Its lateral extent is poorly constrained due to complete erosion at most of the outcrops, however it is assumed that it is extensive as it is always found in outcrops where the full succession of Curtis is present. Typical thickness of the facies is subjective due to conformable transitions at lower and upper boundaries and also due to erosion of the upper boundary, but approximately it is around 10-15 m thick before red-coloured supratidal sediment appear, for example as in the case of logs 3 and 10. No samples of the facies were acquired due to high friability.

**Interpretation:** The fine grain size, high mud and silt content and horizontal lamination recorded in Facies A suggests it was deposited in a low energy upper intertidal environment. A gradually fining upwards development signifies a transition to a supratidal setting, as tidal
mud flats are typically fining upwards in a prograding shoreline setting (Dalrymple, 2010). Based on the stratigraphic position between relatively coarser grained Facies B and mud-dominated red supratidal sediment above, it fills in the upper intertidal mud flat gap between intertidal mixed flat and supratidal/continental deposits.

4.1.2 Facies B: Ripple and plane laminated sandstone and siltstone

Structure and texture: Facies B consists of dark yellow silty very fine sand. Internally, beds are commonly made up of asymmetrical ripples with apparent opposing directions (Figure 7); however, paleocurrent directions are hard to measure due to poor exposure. Therefore, only two paleocurrent measurements were taken. Facies B is generally found in the uppermost part of Curtis Formation, beneath Facies A, but is also sometimes interbedded with Facies C and D. Lateral extent of the facies is comparable to those of Facies C, in the way that the facies can be traced laterally over many meters. However, as the facies most commonly appears towards the highly eroded upper part of Curtis, the true extent and correlation over the study area can only be based on assumptions.

Thin section analysis: One sample of Facies B was acquired (AR280615-2, Appendix B). Grain size distribution analysis reveals a very fine sand-dominated (70.50 %) composition, with smaller amounts of silt (19.00 %) and fine sand (10.50 %). Mineralogical point-counting analysis identifies the sandstone as subarkose, with a high degree of calcite cementation (18 % of the sample), with only 6.50 % porosity remaining. Glauconitic and chloritic pellets are also present in the sample (3.00 %).

Interpretation: Abundance and preservation of bidirectional ripples indicates a frequent current reversal, potentially created by tidal action. Compared to other facies, a relatively high silt content and lower dominant grain size in the facies signifies poor sorting of the material, attributed to decreased tide and wave energy, effectively limiting transport of mud and clay away from the system. However, when compared to Facies A, the sedimentation rate is somewhat higher, due to the higher thickness and continuity of beds and the amount of ripple lamination preserved. Based on these facts it is interpreted to be deposited in the intertidal zone of a tide-dominated foreshore, or otherwise a mixed flat. It signifies the beginning of a gradual, conformable transition to an upper intertidal setting of Facies A and ultimately the supratidal setting of the Summerville Formation.
4. Results

**Figure 6**: Appearance of Facies A in outcrops: thin beds of sandstone protrude from a scree-covered slope. The typical crumbling into thin sheets of cemented sandstone is seen. Sedimentary log interval taken from Log 3 is for illustration purposes only. Photo: Arve R. N. Sleveland, Smith’s Cabin locality.

**Figure 7**: Facies B with typical ripple lamination, as seen in the location of Log 4, 23.75 meters up section.

### 4.1.3 Facies C: Horizontal and low-angle bedded fine grained sandstone

**Structure and texture**: Facies C consists of greenish-grey fine grained sandstone (**Figure 8A**). The defining characteristic of this facies is sharp, extensive, horizontal lower and upper boundaries of individual beds. Internal structures include horizontal lamination, current and wave ripple lamination (**Figure 8B**). Horizontal bed thickness varies in the range of 1-30 cm. Laterally the beds extend over tens of meters in all directions, sometimes pinching out with grain size decreasing in the direction of the pinch-out. As bed thickness can decrease laterally, in a vertical/log section this will most commonly appear as low-angle cross-stratified sandstones. Bed boundaries are either sub-horizontal or contain ripple bedforms. In
some cases, for example in the case of Figure 8C, ripples appear in depressions (swales) of the bedding surface. In the case where ripples and mud draping are abundant, it makes this type of sediment similar to flaser-bedded facies (Figure 12). As a result, an uncertainty in the evaluation of facies appears which mainly depends on the quality of the outcrop. Lower boundary of Facies C is sharp, underlain by Facies E and F. Upwards, bed thickness decreases, finally approaching the characteristics of Facies B. This facies also covers the majority of the study area in map view, as it is exposed in the surface of hill tops.

**Figure 8**: Appearance of Facies C in outcrops and logs. A: Horizontally bedded fine-grained sandstone, as seen in the location of Log 10 approximately 24 m up section; B: Horizontal bedded sandstone in the location of Log 1, 32 m up section. Varying grain size highlights internal ripple structure; C: 3D wave ripples on a bedding surface in the location of Log 1, 46.5 m up section.

**Thin section analysis**: Two samples representative of Facies C were acquired: AR020715-1 and AR030715-1 (Appendix B). The first sample of the facies consists predominantly of fine sand (72.50 %), with smaller amounts of very fine (18.00 %) and medium-grained sand (9.00 %), whereas the second sample shows a slightly finer composition with 62.50 % of fine sand and 32.50 % of very fine sand, the rest (4.50 %) being medium grained sand. The first sample shows much higher quartz content by volume when compared to the second sample which was taken stratigraphically higher and contains a high amount of calcite.
cement. Both samples are completely calcite-cemented, with less than 1 percent of porosity remaining. Pore-filling kaolinite is very common, especially in sample AR020715-1 (Figure 9A). Unlike other facies investigated, Facies C is rich in ooids (11.25 % and 13.25 % in both samples respectively). Glauconitic and chloritic pellets are present in the sample (5.00 %), slightly higher in abundance than in Facies B. The major constituents (i.e. quartz, feldspar, calcite and dolomite) compare well with the bulk mineral composition of the Curtis Formation sandstones determined by XRD analysis in a petrographic study by Kile et al. (2015).

The abundant ooids show a variety of grain core compositions, with dolomite, quartz, feldspar and secondary minerals being present, illustrated by Figure 9B. Some ooid cores appear to have been dissolved and replaced by authigenic dolomite or calcite, suggesting carbonate sources with different composition. The concentric coating of the ooids consists of either a mixture of chlorite and calcite or solely chlorite. Calcite in the ooids appears as either as radial-fibrous or micritized (secondary) crystals (Flugel, 2004). The final observation is substantial overgrowth of quartz over some grains which is not always visible under a regular microscope or with a BSE (Back-Scattered Electron) detector (Figure 9C), due to the fact that well defined dust rims outlining the original grain shape are generally lacking. This however can be alleviated by an Ultra Variable Pressure Detector (UVD), outlining the rounded grains which have subsequently been overgrown by quartz (Figure 9D).
Figure 9: SEM images of Facies C samples. **A:** Pore-filling kaolinite in sample AR020715-1; **B:** Ooids with a variety of grains in the core encased in calcite cement, sample AR030715-1; **C and D:** Quartz grains as seen in sample AR020715-1 with the BSE and UVD detectors respectively. Euhedral shapes of the grains give away the presence of quartz overgrowths. Cementation of the left grain pointed out by the arrow can be seen clearly, whereas no dust rim is present on the right grain.

**Interpretation:** The recorded bed boundaries are interpreted to have been created by erosion and rearrangement of the seabed into ripple bedforms during high water energy events such as storms or spring tides, or also a combination of both. The sharp bed boundaries are consequently draped by thin mud interbeds during slack water, allowing preservation of such surfaces. In some places, bed boundaries are completely horizontal (i.e. no ripples on bedding surfaces), which could be attributed to lack of fine-grained sediment at the bed boundary, preventing the preservation of fine bedform structures, or simply as plane beds created by the upper flow regime. Such coarser grained material deposition would occur at high points of the seabed, as opposed to accumulation of fine material in swales of the seabed.

The lack of internal structures in some beds could be explained by either bioturbation followed by rapid deposition or continuous reworking of sediment in a foreshore environment. Horizontal laminations internally were potentially formed in the swash or breaker bar environment, where the upper plane bed flow regime prevails. This is also
supported by the presence of ooids, commonly formed to be formed in this type of environment as well (Lloyd et al., 1987). The high water energy of the environment is also backed by good sorting of the material, resulting in high post-depositional porosity permeability, which has since been lost. Prior to cementation, the permeable sandstones were also flushed by meteoric waters, which is evident from the highest amount of pore-filling kaolinite observed. The difference in the amount of calcite cement between the two samples shows that the upwards-thinning trend in Facies C most likely corresponds with an increase of biogenic carbonate matrix which has consequently been reprecipitated into the cement.

In conclusion, based on a homogenous fine-grained composition, horizontal bedding surfaces and mineralogical indicators such as ooids and clay-rich pellets, all of which suggest an interplay between wave reworking and tidal influence in a shallow marine environment, the facies is interpreted to represent a subtidal to lower intertidal sand flat setting where wave and tide energy is at its highest.

4.1.4 Facies D: Trough-cross bedded sandstone

**Structure and texture:** Facies D consists of a greenish-grey, very fine to fine grained sandstone (Figure 10), which is distinctly trough cross-bedded, but has a poorly defined internal structure. Ripples/flasers or internal lamination may be seen on rare occasions. Mud draping is also sometimes present between individual beds, which is easily eroded and consequently highlights the bedding of Facies D. Vertical scale of the troughs varies in the range of 5-40 cm, whereas horizontal scale of the structures is in the range of several meters, possibly even more, but then the appearance of the beds becomes similar to Facies C, as the beds become flatter when they are stretched out. The facies is found in the lower to middle part of Curtis Formation, commonly in proximity to Facies C.
Figure 10: Appearance of Facies D in outcrops. A: Trough cross-beded sandstone. Picture is taken at the location of Log 9. Measuring stick is 1 m long; B and C: Trough cross-beded sandstones at the location of Log 3, from two different angles, with sample AR270615-1 pictured.

Thin section analysis: Two samples of the facies (AR270615-1, AR290615-1; Appendix B) were acquired in separate localities. Grain size analysis points to varying degrees of predominantly very fine and fine sand: 58.48 % and 35.27 % for the first sample and 27.50 % and 64.50 % for the second sample respectively, with minor amounts of silt and medium sized grains. Ooids are not present. Glauconitic pellets make up to 3.75% of the samples.

A single sample of the facies was investigated with a scanning electron microscope (AR290615-1). The analysis revealed lesser carbonate cementation (11-14 %) and slightly higher present-day porosity (4.00 %) when compared to Facies C (Figure 11A), potentially resulting in a higher degree of mechanical compaction, visible from BSE images (Figure 11A-C), and also in UVD images (Figure 11D), where earlier fracturing with subsequent cementation of fractures is visible. Iron precipitates were also present in some pores (Figure 11C).
The extent of quartz overgrowths detected by UVD was found to be comparable to that of Facies C (Figure 11C-D).

**Figure 11**: SEM images of the Facies D sample AR290615-1. A: Overview image showing calcite cement (light grey) and retained porosity; B: Iron oxides precipitated in the pores; C and D: Quartz grains as seen with the BSE and UVD detectors respectively, the arrow pointing to a quartz overgrowth between the grains.

**Interpretation**: Based on the observations, such structures made of very fine to fine-grained sand fall into the 3D dune zone of lower flow regime (Van Den Berg and Van Gelder, 1993). Consequently, a high water flow velocity is necessary for such seabed structures to form. With the relative stratigraphic position and limited lateral extent of the facies taken into account, the distinctive trough-cross bedding is interpreted to have been formed in a sub-tidal to intertidal depositional environment, where it represents tidal channel deposits. Compared to Facies C, the finer grain size distribution is interpreted as silty sediment introduced by the channels from the inland-laying mixed and mud flats. Possibly, the finer grain size and baffles formed by mudstones interbeds between the trough-cross beds could have resulted in decreased groundwater flow and lesser cementation.
4.1.5 Facies E: Flaser-bedded sandstone

Structure and texture: Flaser bedded, very fine to fine grained sandstone (Figure 12). Beds are commonly tens of centimetres thick and are often cliff-forming. Individual beds are subdivided by continuous layers of mudstone, generally tens of centimetres thick. Internally, mud flasers follow ripple bedforms and sometimes include double mud drapes, which highlight internal ripple structure. Ripples are asymmetrical, with opposing paleocurrent directions. Upper boundary of the facies generally shows gradually decreasing mud content and a transition to plane bedded sandstones (Facies D). An important observation of the facies is that the thickest beds of the facies appear above heterolithic facies F.

Thin section analysis: Analysis of the AR010715-1 sample reveals a predominantly a mixed very fine (57.00 %) to fine (40.58 %) sand composition of the flaser bedded sandstone. The mineral composition outlined in Appendix B reveals subarkose sandstone consisting primarily of quartz (57.00 %), with 10 % of plagioclase, completely cemented by calcite (21.75 %) with almost no porosity retained (0.75 %).

SEM analysis of the sample shows very similar features observed in Facies D. The general mineralogy is shown in Figure 13A-B, with abundance of Na representing plagioclase, K representing potassium feldspar Ca together with Mg representing dolomite, Ca alone representing calcite and Al representing kaolinite. Pore-filling clay (kaolinite) and Fe-oxide precipitates are often encountered (Figure 13B). Clay-mineral rich pellets that are present in the sample were identified as glauconite.

Interpretation: Thick, continuous beds of the facies indicate a higher energy environment when compared with underlying Facies F. Internal structures such as mud draping, double mud drapes, herringbones, bi-directional ripples and mud lamina between distinct beds indicate a tidally modified environment.
4. Results

Figure 12: Appearance of Facies E in outcrops and logs. **A:** Fine grained sandstone with lenses (flasers) of siltstone. Photo taken in the location of Log 8, 18.5-19.0 m; **B:** Flaser to horizontal bedded sandstone, Log 5 29.0 m up section.

Figure 13: SEM images of the Facies E sample. **A:** Overview image showing clastic grains (dark grey), calcite cement (light grey) and retained porosity (black); **B:** Element map of picture A, illustrating the distribution of mineralogy. **C:** Pore-filling kaolinite and iron oxides; **D:** Close-up image of a clay-rich pellet (centre-right);
4.1.6 Facies F: Heterolithic mudstone and sandstone with wavy bedding

Structure and texture: Fine to very fine grained sand is interbedded with continuous lamina of silt/mudstone, with the bedding surfaces making up ripple bedforms. Some intervals show fining upwards trends in each individual bed, (Figure 14A), while in other intervals there is no apparent trend of grain size. Herringbone cross-stratification is a very common structure. If the fine-grained bedding surfaces are well-exposed, they usually exhibit 3D ripples and, in rare cases, horizontal bioturbation. Lower boundary of the facies is a semi-abrupt or sharp transition from lenticular bedded sandstone (Facies G). Upper boundary is a gradual coarsening-upwards transition to flaser bedded facies (Facies E) and plane-stratified facies (Facies C). Wavy bedding is also found in combination with IHS Conglomerate facies (Facies I). No samples of the facies were acquired due to thin bedding and high friability.

Interpretation: Abundant opposing paleocurrent directions are indicative of alternating currents, which are interpreted to have been formed during flood and ebb tides. Meanwhile, greenish-grey mudstone interbeds represent background sedimentation during the slack water phase. When the stratigraphic position of the facies is taken into account, it falls between the offshore facies and coarser overlying sand flat facies. The abrupt lower contact of the facies marks the early onset of a prograding sand sheet/tidally influenced shoreface. In other words, it can be considered to belong to an intermediate energy subtidal depositional environment.
4. Results

4.1.7 Facies G: Heterolithic mudstone and sandstone with lenticular bedding

Structure and texture: Greenish-grey mudstone interbedded with lenses of very fine to fine sand (Figure 15). High heterogeneity, herringbone cross stratification and opposing paleocurrent measurements are indicative of the facies (Figure 15B-C). Lower boundary of the facies is sharp, sitting directly on top of the Entrada Sandstone and draping the J-3 unconformity, i.e. in the lower part of Figure 15A. The exact point of contact is rarely well exposed due to scree; however at the lowermost point sediment has a rich dark green colour, is generally finer and little to no sand content. Both the lateral extent and thickness of a succession varies from outcrop to outcrop, however an association between thick successions and lower sand content has been identified, which suggests mud-rich deposition in paleotopographic lows of the J-3 unconformity. The upper boundary of the facies is a semi-abrupt or a sharp boundary, with coarser grained sediment of other facies found on top. No samples of the facies were acquired due to thin bedding and high friability.

Interpretation: High mud content is interpreted as the dominant background sedimentation in the subtidal environment. Low sand content is interpreted to be related to the bathymetric position of the depositional environment, located close to storm weather wave base or the deepest point of tidal current influence which results in limited quantities of coarser clastic material reaching such deeper waters. Ripples made of sandy material are formed during peak water flow in both directions, resulting in deposition of herringbone cross stratification and opposing paleocurrent measurements. Similar lenticular-bedded structures are also formed in intertidal flats (Dalrymple, 2010), however in this case horizontal bioturbation indicate a deep water setting as opposed to the intertidal range, where vertical bioturbation would be expected.
Figure 14: Appearance of wavy-bedded sandstone of Facies F in outcrops and logs. **A:** Wavy beds at the location of Log 6. Sandstone is interbedded with thin layers of silt, each unit is fining upwards. Internal structure of ripples is highlighted by thin mud drapes. **B:** Wavy bedded facies in the location of Log 7, 5.0-5.5 m up section. **C and D:** Horizontal bioturbations in Facies F. Photos taken in the location of Log 8, in 14.5-16.5 m interval up section.

Figure 15: Appearance of Facies G in outcrops and logs. **A:** Lenticular bedded heterolithic deposits in the location of Log 7. A remaining topographic high of Entrada Sandstone is visible in the lower part of the image; **B:** Up-close detail of lenticular-bedded facies: a small ripple (~1 cm in height) made of very fine sand can be seen just below the pencil. Photo was taken at the location of Log 2; **C:** Herringbone cross laminated sandstone set in a muddy matrix. Photo was taken at the location of Log 2.
4.1.8 Facies H: Cross-stratified gravelly sandstone

**Structure and texture:** Medium to coarse-grained tabular and trough cross-stratified sandstone (Figure 17). Beds are around 1-2 meters thick, with a sharp base and top. This facies is laterally extensive on the scale of 10s to 100s of meters and eventually transitions into Facies I. Tidal signatures in the sandstone include ripples with a direction that is opposite to that of the cross-beds and poorly developed inclined heterolithic stratification (IHS). Facies H is only found close to the base of the Curtis Formation, in the lower heterolithic succession, in the lowermost 20 meters of Curtis.

**Thin section analysis:** One sample representative of Facies H was acquired: AR280615-1. The grain size distribution shows a mixture of medium and coarse sand (40.10 % and 46.53 % respectively), with a fraction of very coarse sand (10.40 %) and minor amounts of fine sand. The sample is litharenite sandstone, almost half of which is rock fragments (27.00 %), the rest dominated by quartz (23.25 %) and skeletal carbonate fragments (16.75 %). The sample is completely cemented by poikilotopic calcite cement (26.50 %), with almost no porosity remaining (0.25 %). The composition of minerals in the carbonate rock fragments was also investigated by SEM (Figure 16), showing that they consist of a mixture of calcite, rhombohedral dolomite crystals and, in rare cases, apatite. Furthermore, the sample is completely cemented by clean calcite (almost pure CaCO₃).

**Figure 16:** SEM images of the sample AR280615-1. **A:** variety of grains found in the conglomerate, comprising quartz and feldspar grains, rock fragments of various origins and skeletal carbonate fragments (echinoid spine?), all cemented by poikilotopic calcite with little to no porosity remaining; **B:** Skeletal carbonate fragments (bryozoa) and clastic cemented by poikilotopic calcite. The highlighted carbonate rock fragment points out that the skeletal fragments might be sourced from older reworked sediment.
Interpretation: Well-developed cross bedding indicates a dominant unidirectional current, whereas poorly developed IHS shows a small degree of tidal modification. Therefore, the structures are interpreted as well-developed migrating submarine dunes. Similar to Facies I, the superimposed ripples with an opposing direction to the dip of crossbeds as well as a degree of heterogeneity in the crossbeds are suggestive of a tidally-influenced point bar development. Generally, Facies H make up thicker packages than Facies I, therefore the deposits are interpreted to have been deposited as dunes in larger tidal channels. The presence of medium to coarse grained clasts, which include carbonate and chert rock fragments means that the fine sands observed in samples of Entrada Sandstone might not be the source of sediment for this facies. Consequently, a different extrabasinal source is necessary.

4.1.9 Facies I: IHS conglomerate

Structure and texture: Poorly sorted, medium to coarse grained conglomerate with inclined heterolithic stratification (IHS) which is highlighted by mudstone, sandstone and chert clasts (Figure 18). The chert and sandstone clasts are well rounded; with a diameter of 2-10 mm, whereas mudstone clasts vary in size and roundness, from angular rip-up clasts to well-rounded pebbles. Both mud and coarse-grained clasts are usually concentrated along bedding surfaces. The mudstone clasts are easily eroded when exposed to the atmosphere, which makes the facies easy to identify visually (nicknamed the Swiss-cheese facies). Heterolithic cross-stratification, emphasized by such mud interbeds, appears in the form of trough-cross bedding. The facies is found only in the lower part of the Curtis Formation. It is also laterally limited to tens of meters until it pinches out or transitions to Facies H.

Thin section analysis: A single sample of the facies was collected (AR030715-2, Appendix B). The sample consists primarily of medium sand (77.83 %), with 6.9 % of fine sand, 11.82 % of coarse sand and also a substantial fraction of gravel which was not calculated when point-counting due to the grains being too large to be properly measured under a microscope. For mineral identification, only the medium-grained matrix was also considered. The sample was identified as litharenite, with the matrix consisting primarily of quartz (46.00 %), with some skeletal carbonate fragments (6.00 %), minor amounts of feldspar (5.00 %) and completely cemented by poikilotopic calcite cement which makes up 35 % of the sample.
Figure 17: Appearance of Facies H in outcrops and logs. **A:** a close-up of the Facies H sediment, as seen in the location of Log 8, 8.25-11.0 m up section, displaying poor sorting including gravel clasts. Thickness of the bed is around 1-1.5 m thick; **B:** Ripples with an opposing current direction on the cross-bedding surface. Picture taken at the location of Log 4, 6.0 m up section.

Figure 18 Appearance of Facies I in outcrops. **A:** IHS conglomerate as seen in the location of Log 2. Fine-grained interbeds are easily eroded, highlighting the heterolithic bedding; **B:** Picture of IHS conglomerate facies in the location of Log 2. Cross-stratification is highlighted by mud-rich layers that have been eroded away; **C:** A freshly split-open piece of Facies I conglomerate which shows a well-rounded mud clast. Such mud clasts are commonly found along cross-stratification surfaces. After subsequent erosion they result in easily distinguishable ‘caverns’ in the conglomerate, highlighting the internal bed structure; **D:** A close-up photo of a V-shaped Facies I deposit, found in the lowermost part of Curtis Fm., 5-6 m up section, Log 7.
**Interpretation:** Inclined Heterolithic Stratification is commonly associated with developments of tidally-influenced point bars (Thomas et al., 1987). Facies I is found between lenticular bedded mudstones (Facies G) and wavy bedded deposits (Facies F), both interpreted as subtidal deposits, which limits the facies to the same subtidal environment. Very coarse sand and pebble-sized rock fragments and chert clasts evidently require an extra-basinal source, as such large grains have not been observed in the underlying eolian Entrada Sandstone. Meanwhile, the mudstone clasts, some of which are angular, most likely were sourced from nearby, potentially as close as from the mud substrate underlying the channels. Since coarse clasts are found along bedding surfaces, it also suggests a link to shifting water energy which is interpreted as intermittent influence of storm currents in a tidally-dominated environment. Low amount of feldspar in the facies also supports the high-energy interpretation. Furthermore, as it can be seen from lateral variation of facies in outcrops, Facies I is found at the same stratigraphic level as cross-stratified gravelly sandstone (Facies H). Consequently, the facies represents subtidal channel deposits.

**4.1.10 Facies J: Wavy to low angle cross-stratified red sandstone**

**Structure and texture:** Light red very fine sandstone (Figure 19A). Bed thickness varies from tens of centimetres to 1-2 metres. As it was observed when investigating the J-3 topography, the beds are laterally very extensive, over hundreds of meters to kilometres, with only minor variations of thickness. Internally, the beds primarily show wavy lamination or, in rare cases, poorly developed eolian cross-stratification. Even though the structures are very similar to those of Facies K, the main distinguishing factor is the colour of the rock, lighter in Facies J, and determined by lower mud content.

**Thin section analysis:** Two separate samples of Facies J have been acquired, at different stratigraphic horizons: from ‘deeper’ Entrada Sandstone, ~15-20 m below Base Curtis (AR010715-2), and also from uppermost Entrada Sandstone just below Base Curtis (AR070715-1). Grain size distribution of the samples reveals a very fine sand-dominated composition (~63 %) with lower amounts of either fine sand or silt in the two samples respectively. The samples are both subarkose sandstones, with a high part of the volume made up of a mud-rich matrix (17-22 %)

**Interpretation:** The facies is interpreted to have been deposited during dry periods as small dunes in an erg margin that was in proximity to the marine environment. When compared the
interdune beds Facies K, lower mud content and lighter red colour of the facies point to a better sorting of the sand and can be linked to an increase of eolian reworking during periods of decreased humidity. As the mud-rich matrix constitutes a substantial part of the samples, (17-22 %), this is interpreted as the groundwater table being close to the surface, preventing larges dunes from building, effectively limiting the maximum degree of sorting and the thickness of the beds.

4.1.11 Facies K: Wavy laminated dark red-brown siltstone-mudstone

Structure and texture: Beds of the facies include alternating bands of dark brown mud and silt, sometimes interbedded with evaporites (Figure 19B). The beds rarely make up thick, continuous successions in the studied interval; however several meter thick intervals are present in deeper stratigraphic levels. In outcrops, intervals of the facies either form slopes or create eroded intervals between thicker eolian sandstone units of Facies J. Upon closer inspection, the facies show wavy to horizontal laminated mudstone interbedded with lenses of very fine sand. Exposed bedding surfaces sometimes show polygonal cracks (Figure 19B).

Interpretation: The dark brown colour of the mudstone points to a continental depositional environment. With the stratigraphic position of the beds taken into consideration, which is limited to interbeds between sets of eolian sandstone (Facies J), the depositional environment of the facies is interpreted as an interdune/sabkha setting. In this environment, ephemeral water bodies appear, trapping eolian-transported mud- and silt-sized particles, forming mud rich, wavy and ripple laminated successions. Minor influence of waves and intermittent flow of water during high precipitation is considered to be the primary mechanism for reworking of sediment in such water bodies. The polygonal cracks that can be seen on some bedding surfaces are either shrinkage cracks or water drainage channels in the mudstones. Both interpretations support the supratidal setting and are not contradictory of each other, although, better control of the structures is necessary in order to have a definitive answer. Due to high evaporation rates in an arid environment, evaporite precipitation is also locally present.
4.1.12 Facies L: Dark brown mudstone and sandstone (Summerville Fm.)

**Structure and texture:** Dark brown mudstone interbedded with thin layers of sand and evaporites (Figure 20). The mudstone interval is poorly exposed in the area, as it is slope forming, easily eroded and therefore generally covered in scree, except for the protruding scattered sandstone beds. The lower boundary of the facies is a gradual fining upwards transition from Facies A, where thickness and abundance of sandstone beds decreases and the colour of the mudstone becomes darker. The upper boundary of the facies was not determined in the study area, however it is known from previous research to be truncated by the J-5 unconformity (Peterson, 1994). In some outcrops, the mudstone is capped by a 2-3 m thick succession of evaporites.

**Interpretation:** The succession represents deposits of an upper intertidal to supratidal flat. The laterally constricted lenses of sand with fluvial structures that are found in the muddy matrix are interpreted as water runoff channels that were only active during high tides or storm events. The intermittent activity is explained by the bathymetric position of the facies, as the upper intertidal to supratidal environment would only be affected during the previously mentioned high water energy events, whereas at other times, mud-dominated sedimentation would prevail.
Figure 19 Appearance of Facies J and K (FA6) in outcrops. **A**: Light sandstone beds (Facies J) are interbedded with intervals of dark brown siltstone and mudstone (Facies K); **B**: Polygonal cracks as seen on a bedding surface in an overhanging bed of Entrada Sandstone in Stove Gulch. Photo: Arve R. N. Sleveland

Figure 20: Appearance of Facies L (FA7) in the field, overlying the Curtis Formation. Person for scale in the uppermost part of the picture. Photo: A. R. N. Sleveland, Sven's Gulch
4.2 Facies associations

In this chapter, facies have been grouped to facies associations, which describe assemblages of genetically-related facies, which in turn comprise distinct sedimentary units of the succession. A total of 7 facies associations have been identified. Descriptions and depositional interpretations are given for each facies.

The distribution of facies associations in a typical logging route is shown in Figure 21. The red sandstones of FA6 form a substantial cliff forming unit. They are followed by a succession of alternating mudstones and sandstones in the slope-forming heterolithic FA1-2-3 package of lowermost Curtis Formation. FA4 is cliff forming above its lower contact and forms gentle relief in the upper part. It covers a major part of the study area, seen in the figure as yellow-grey sandstones. On top of the sandstones, light-brown siltstones and sandstones of FA5 are deposited, which grade into the red and brown beds of FA7, belonging to the Summerville Formation. Figure 22 and Figure 23 show the typical distribution of these facies associations in a vertical outcrop and therefore are used in the subsequent descriptions.

![Figure 21](image-url): Oblique aerial overview of facies association distribution occurring in a logging route. The route of Log 3 is marked in cyan. Photo source: Bing Maps
4. Results

Figure 22: Interbedded FA1 and FA2, overlain by FA4, sitting above a sinuous J-3 unconformity. Photo taken facing Stove Gulch from Price River, slightly northwards of Log 7.

Figure 23: Distribution of facies associations at the location of Log 4. All facies associations make up laterally extensive, homogeneous units with the exception of FA2, which pinches out towards the left side of the image and downcuts into FA1 towards the right. The succession of Curtis Formation is around 60 m in the locality.

4.2.1 Facies association 1: Subtidal shelf deposits below fair weather wave base

Description: Facies association 1 (FA1) includes heterolithic mud-rich facies F and G (lenticular and wavy bedded) in the study area: facies. The heterolithic deposits are found at the base of the lower mud-rich interval of the Curtis Formation, generally directly overlying the Entrada Sandstone. The facies association is recognized in most outcrops of the study area; however, its thickness varies substantially. Commonly, the thickness is highest where
local incisions into the Entrada Sandstone exist, as is evident with thickness fluctuations in Figure 22 and Figure 29, however the thickness can also vary due to the incising nature of the overlying FA2 bodies, for example in Figure 23, where it decreases from 4-5 meters thick in the southern part of the outcrop, to less than 1 meter towards the north. At the lower boundary, FA1 has the lowest amount of sandy material, whereas at the upper boundary, the facies association is always cut by coarser-grained sediment.

**Interpretation:** It has been argued during early investigation that the facies association represents tidal flat deposits that belong to the early transgressive phase of a transgressive-regressive sequence. However, first of all, the colour of the mudstone intervals is dark greenish-grey, signifying a reducing depositional environment (Tucker, 2001), whereas upper intertidal to supratidal deposits would be expected to have a dark brown or red colour due to prolonged exposure to the atmosphere, as it is evident if FA5-7. The sandstone lenses in the outcrops are dark brown, but this appearance is attributed to differential erosion of the deposits. The sand intervals are not eroded as easily as the friable mudstone and therefore have prolonged exposure to the atmosphere.

Sedimentary structures, which include both lenticular and wavy bedding commonly point to the intertidal environment, however are not limited to it (Dalrymple, 2010). What determines the lithology and structures is first and foremost the water flow regime, which in this case includes reversals of current directions, as suggested by opposing paleocurrent directions (Figure 27B). Moreover, marine fossils and palynomorphs have been identified in the mudstone interval by Wilcox and Currie (2008). Finally, the underlying Entrada Sandstone has been interpreted as a intertidal to supratidal depositional environment by (Hicks, 2011), further backing the marine depositional environment of the Curtis Formation based on the surrounding stratigraphy. The relation between thickness and incisions of the J-3 unconformity also supports a widespread draping of the unconformity in the marine environment. Therefore, FA1 is considered to represent tidally influenced shelf deposits.

### 4.2.2 Facies association 2: Subtidal channel infill

**Description:** Facies Association 2 (FA2) is identified by its protrusion from heterolithic beds as it comprises cliff-forming Facies E, F, H and I (flaser and wavy bedded sandstones, IHS and TCB conglomerates), laterally grading into horizontal and low angle cross-bedded
Facies C. Initially, FA2 was identified as aggrading, laterally migrating tidal channels, due to their characteristic stacking pattern, for examples as it is seen in Figure 24.

![Figure 24: Stacked IHS conglomerate units building up Facies Association 2 in the location of Log 2. Person for scale. Photo: Arve R. N. Sleeland](image)

Laterally, Facies I grades into Facies H. This change is seen the easiest in wide cliff-forming outcrops or in Lidar imagery (i.e. Figure 25). This firstly includes changes in bed and cross-bed thickness, also, changes in the degree of heterogeneity. Moving in the direction of sediment transport, facies transitions from heterolithic trough-cross bedded conglomerates to cross-stratified conglomerates back to TCB conglomerates as the dune progrades. This indicates potential fluctuation of water energy during deposition. Moreover, new prograding dunes are superimposed on top of older ones, creating compound dunes as a part of the channel infill.
Figure 25: Compound dune in the Location of Log 2, outcrop located opposite of Figure 24.

In a flow-perpendicular orientation, such sandstone bodies grade laterally into homogeneous fine sandstone lenses that are 10-15 m thick, illustrated by Figure 26. This transition is described in more detail in Section 4.3.2. The lateral transition is interpreted as an interfingering of larger, yet finer grained sand bars and pebbly channel infill deposits surrounding such bars. The interpreted compound dunes exhibit lithology that is similar to FA4, however due to their genetic relation and architecture are assigned to this facies association.

Figure 26: Compound dune identified in a FA2 sandstone body, location adjacent to Log 5. Photo: University of Bergen Lidar Group
4. Results

Both gravelly facies show a very strong northeast-oriented paleocurrent direction component, which is at a slight angle to the generally northbound transport direction (Figure 27F).

Sand body thickness and distribution varies from outcrop to outcrop. This suggests a limited lateral distribution, as in some cliff faces a single compound dune appears (Figure 24), whereas in other areas one or two simple dunes are present (Figure 22), or, in some cases, no sand body is present and the facies changes directly from lenticular bedded to overlying wavy bedded.

**Interpretation:** Caputo and Pryor (1991) interpreted the equivalent of FA2 as gravel sheet palimpsest deposits that were sourced from pre-Curtis alluvial drainage and intermixed with Curtis sediment by tidal forces. This was based on the observations made by Stride et al. (1982). However, as it is described by the same authors, shelf gravel sheets found offshore the United Kingdom are generally only a few centimetres thick, whereas individual well-developed beds of the cross-bedded gravelly FA2 units are at least half a meter thick. Furthermore, the lateral extent of the gravel sheets previously described is generally considered to be uniform whereas the FA2 units, even though recognized in most Curtis outcrops even beyond the study area, generally consist of laterally constricted bodies.

Offshore gravel dunes with heights of up to 1 m have been reported (Stride et al., 1982), but their internal structure is unknown. Due to this observation, the gravel sheet hypothesis remains plausible, even though unlikely. Fine gravel dunes have also been described in the intertidal environment of the macrotidal Severn Estuary, United Kingdom (Carling et al., 2006). However, the intertidal setting for the dunes is considered unlikely based on the interpretation of underlying and overlying deposits.

The sharp base and interfingering of FA2 corresponds well with the description Olariu et al. (2012) and the references therein, that tidal bars in estuaries and deltas are intimately associated with channels that migrate laterally and therefore produce an erosionally-based fining-upwards succession, analogous to the one observed in FA2, whereas shelf ridges are not dissected by channels and also coarsen upwards as the current speed and wave energy are considered to be highest at the crest of the ridge.

Tidally-deposited compound dunes have been described at the mouth of the laterally-constricted San Francisco Bay (Barnard et al., 2006). In this setting, a large, laterally...
extensive dune field with wavelengths of ~220 m and heights of 10 m cover the floor of the bay. The dunes consist primarily of coarse sand and pebbles, completely different from beaches or nearby ebb tidal shoals in the proximity, where the dominant grain size is fine to medium, similar to the interpreted environments of the Curtis Formation.

Due to its high thickness and laterally constricted nature and interfingering of channels with bar-form deposits, FA2 is therefore considered to represent pebbly dunes and sand bars dissected by coarse-grained tidal channels, both of which are a part of a larger estuarine/tidal channel system as opposed to an open marine shelf. However, even to this day, due to limited research of modern offshore tidal deposits, the true origin of such beds remains a matter of discussion.

4.2.3 Facies Association 3: Subtidal shelf at or above fair weather wave base

Description: Found above FA1 and FA2, Facies Association 3 (FA3) is identified by relatively higher sand-to-mud ratio compared to FA1 (Figure 22, Figure 24). Flaser and wavy bedded sandstones dominate (Facies E, F), whereas lenticular beds are not present. The degree of heterogeneity in the sub-horizontal beds is nevertheless still similar to FA1. Lower boundary of the facies association is either abrupt transition from lenticular-bedded facies. In most cases, FA1 and FA3 are divided by a FA2 interval, also illustrated by the aforementioned figures. Where FA1 is not present, FA3 sits directly on the J-3 unconformity, i.e. adjacent to Log 6, where a FA2 bed that is present at the base of Curtis Formation is no longer recognized ~100 m to the side.

Interpretation: The facies association is an expression of a passive infill with an increasing sand content between fair weather and storm wave bases, which is deposited in a more proximal position in relation to FA1, but distally from the sand flats of FA4. Formed by subtidal shelf processes similar to the ones described in FA1, the thicker and laterally more extensive beds show an increased impact of tides and waves. This development is followed by the deposition of homogeneous FA4 sand.
4. Results

4.2.4 Facies Association 4: Sand flat deposits: tidal bars and dune fields

Description: Facies Association 4 (FA4) comprises the sand-dominant, homogeneous middle part of the Curtis Formation (Figure 21, Figure 23). The facies association comprises facies C, D and E (Horizontal, cross-bedded, trough cross-bedded and flaser bedded sandstones), with predominantly horizontally to low-angle cross-stratified sandstones. Minor intervals include cross-bedded, and trough cross-bedded sandstones. The definitive characteristic of the facies association is its lateral extent, uniformly covering the study area and beyond. The lower boundary of the facies is sub-horizontal, laterally extensive and easily recognized in both logs and photographs, therefore it is considered as an alternative for a datum surface in Section 4.3.4. The upper boundary of the facies is an upwards-thinning trend, gradually transitioning into the overlying FA5. Facies Association 4 is also the kind of lithology that is typically associated with the Curtis formation, due to its striking greenish-grey colour and spheroidal weathering.

Interpretation: Wide, uniform distribution of the sandstone points to deposition on a broad, sand rich shelf. As the succession shows a fining and therefore shallowing upwards trend, it is interpreted to represent a progradational development as it transitions to FA5. The dominant fine grained sandstone indicates consistent water energy and sediment supply, interpreted as the one found above fair weather wave base; meanwhile the typical sedimentary structures that are found internally illustrate the variety of processes occurring in water levels where tide and wave action is at its highest energy. The shallow marine to lower intertidal origin of the deposits is supported by the presence of glauconite pellets throughout the deposits of FA4. Even though glauconite is typically associated with depths of at least 30 m (Porrenga, 1967), more recent studies have shown that it is also likely to form in much shallower depths (Chafetz and Reid, 2000). The relationship between the depositional environment and both peloids and ooids has also been demonstrated by Kearsley (1989). The author suggested that these mineralogical constituents appear together only in an embayment-type environment, which is further supports the interpretation of the environment that the Curtis Formation was deposited in.

As the thin section analysis has shown, horizontally-bedded sandstones are rich in ooids, therefore such intervals are interpreted as ones that have been formed in elevated marine areas such as breaker bars or swashes, i.e. as described by Lloyd et al. (1987), Sanders and
Friedman (1967). Similar ooid-bearing shoals have also been interpreted in the underlying Entrada Sandstone by Hicks (2011). Horizontal-bedded Facies C has fairly high degree of NNW-SSE bi-directionally oriented currents (Figure 27D); although there is also a prominent peak of westwards-oriented paleocurrent measurements interpreted as longshore currents along an east-west oriented shoreline.

The distinction between tidal dunes and tidal bars has been discussed by Olariu et al. (2012). Distinguishing between the two types of deposits is especially important for reservoir characterization due to different the migration directions of the bodies, as tidal dunes migrate sub-parallel to their master surfaces whereas tidal bars migrate laterally. However the fact that in compound dune fields, superimposed dunes migrate at an angle of the main dune orientation complicates the evaluation (Olariu et al., 2012). Paleocurrent measurements of low-angle cross stratified Facies C sandstones show a very strong NW-SE oriented bidirectional component (Figure 27E), which is at an angle of the interpreted E-W oriented shoreline, valid for both the dune and ridge interpretation, therefore better control on the architecture and paleocurrent directions is necessary to give a definitive answer.

Trough-cross bedded intervals dissect the deposits described previously. This is interpreted as tidal channels dissecting the sand flats, in which tidal currents are concentrated, resulting in formation of 3-D dune bedforms and cross-bedding. In contrast, the trough cross-bedded sandstones of Facies D, interpreted as tidal channels found in the subtidal flat show much more variety and consequently are interpreted as to have been deposited in meandering tidal channels (Figure 27F).

4.2.5 Facies association 5: Mixed and mud flats

Description: The uppermost part of the Curtis succession, termed Facies Association 5 (FA5) is a distinct slope-forming unit (Figure 22) where ripple and horizontal laminated sandstones (Sandy intervals: Facies A and B) protrude from scree-covered slopes (inferred muddy intervals). The amount of information acquired from this interval is scarce firstly due to limited lateral extent of the interval itself, due to the fact that it has been eroded in all of the area except for several hilltops scattered throughout the study area. Second, the slopes are scree covered, which leads to problems in distinguishing between sandstones which are in-situ and larger fragments of scree. Finally, since the facies are mostly covered, it is hard to accurately determine an accurate ratio of sand and mud in the interval. Nevertheless, a
general trend is observed: the beds decrease in abundance as well as thin upwards. In stratigraphic logs, this appears as outcrops filled with blank intervals, which correspond to the assumed mud-rich successions, with only some beds represented in the uppermost succession. Inside the protruding sandstone beds, ripple laminations, ripple cross-bedding or horizontal laminations can be identified.

**Interpretation** Due to their limited distribution and fluvial structures, the scattered sandstones observed in the outcrops are interpreted as fluvial/tidal channel deposits dissecting a silty tidal flat. Typically to the facies, reddish to dark brown colours of the intertidal facies become gradually more pronounced stratigraphically upwards (e.g. Figure 21), in the fining upwards succession towards the Summerville Formation. The change in colour can be interpreted by gradually increasing exposure to the atmosphere closer to the shoreline, leading to oxidation of fresh sediment. The dirtying-upwards trend in the uppermost Curtis Formation can be compared to typical fining-upwards developments in prograding tidal flats (Dalrymple, 2010), which is caused by decreasing water energy as the shoreline progrades.

### 4.2.6 Facies association 6: Upper intertidal to supratidal wet dune system

**Description:** The combination of Facies J and K makes up Facies Association 6 (FA6) which describes the vertical succession of alternating sand-rich (Facies J) and mud-rich (Facies K) intervals which represent eolian and interdune deposits respectively. As it has been observed in Lidar imagery by tracing a selected bed, intervals of both associated facies are laterally extensive in the scale of the study area with limited thickness variations. Therefore, the beds of Entrada are considered as a valid alternative to be used as a datum surface. As FA6 association comprises the lowermost studied succession, the lower boundary is not known. Upper boundary of the facies is an erosional unconformity, described in more detail in Section 4.3.1.

**Interpretation:** Fluvial and marine structures discovered in by Hicks (2011) suggest a proximity of the depositional system to the marine environment. Even though not documented, structures similar to the ones discovered by the aforementioned author were noted in this study area as well. Consequently, this vertical succession developed in an arid erg-marginal continental environment where scattered dunes were ubiquitous. However as
either the water table was potentially close or, during periods of increased precipitation, above the surface, or due to the facies being deposited in the uppermost intertidal environment, the dune fields were intermittently flooded.

4.2.7 Facies association 7: Supratidal mudflat

**Description:** Facies association 7 summarizes the alternating red coloured mudstones and sandstones of Facies L (Figure 20). The mudstones are prone to erosion, which has resulted in almost complete removal of such intervals. As the only outcrop of the facies is constricted to the area seen in Figure 21, knowledge about the lateral extent of this facies association is limited. However, it is known that the appearance of FA7 has to occur at various stratigraphic levels. This is governed by the fluctuating thickness of the Curtis Formation in the study area. Similar thickness variations are also evident in regional studies, e.g. Caputo and Pryor (1991).

**Interpretation:** As within the dark brown mudstones of FA7, only very rare siltstones and fine sandstones with current structures are present, the facies association represents a supratidal sabkha depositional environment, with the clastic material introduced only during high water energy events such as storms or spring tides. Bodies of standing water with high evaporation rates were a part of the environment, as thin gypsiferous beds are also found within the mudstones.
Figure 27: Rose diagrams of paleocurrent measurements in individual successions.
4.3 Log correlation

Correlation of logs was established utilizing lithological and field observations and was further supplemented by Lidar imagery. In this section, correlation of distinct surfaces and sedimentary units in the Curtis Formation is presented.

4.3.1 Sequence Boundary: the J-3 unconformity

The J-3 unconformity (SB) dividing Top Entrada Sandstone and Base Curtis Formation is the first sharp boundary of the studied succession. This is a highly undulating erosive surface with changes in elevation of up to 15 meters over the distance of several km. The surface is identified in all outcrops.

As described in Section 2.3.3, the J-3 unconformity is known to have an erosive relief of 14 m over the course of 3 km (Pipiringos and O'Sullivan, 1978), or highs of up to 7 m (Eschner and Kocurek, 1986). This is comparable to the findings of this study.

Figure 28 illustrates the amount of incision into the Entrada Sandstone which is recorded over the course of several hundred meters. In the figure, an elevation change of approximately 7 m happens over the course of 100-200 m. Minor sinuous undulations of the topography can be also seen in good exposures, for example in Figure 22. In one outcrop, a fault with minor displacement (~0.5 m) that is not cross-cutting through the overlying FA1 is observed. Even though the displacement is small, the structural topography has been preserved to some degree. This is different from other instances faulting observed at the contact which are discussed in Section 4.4.2

The topography of the J-3 unconformity was finally characterized by making a surface in Petrel 2015 software using the procedure described in Section 3.5. The results are shown in Figure 30. In the illustration, two apparent incisions are visible, highlighted in magenta. A topographic high is present around the location of Log 4. While the depression in the western part of the study area is somewhat unreliable due to a low number of points, the incision in the central part of the study area has very good coverage and therefore is considered valid. The change in topography seen in Figure 28 is marked by an arrow in the southern part of the figure.
Figure 28: Major incision in the Entrada Sandstone and correlation of sand bodies in the lowermost Curtis Formation. The picture was taken ~1 km south of Log 5. Photo: Universitetet i Bergen Lidar Group. Wide angle outcrop overview is taken from Lidar imagery (vertical exaggeration of Lidar image=1.5x).

Figure 29: FA1 onlapping the J-3 unconformity, with minor faulting FA6 that does not cut through the layers of FA1. The lower boundary of FA2 also does not show any displacement. Photo: Universitetet i Bergen Lidar Group, Stove Gulch opposite of Log 5.
Figure 30: Erosive topography of the J-3 unconformity in the extended study area with the thickness of the Entrada Sandstone above the reference bed used as a relief proxy. Dots mark areas where Lidar coverage is present.
4. Results

4.3.2 Correlation of the lower Curtis Formation

Two distinctly sharp, laterally widespread internal surfaces have been recognized in the lowermost Curtis Formation. The first surface (Surface 1) is a boundary dividing lenticular and wavy bedded sediment of FA1 from overlying cross and trough-cross bedded conglomeratic sand bodies of FA2. Inspection of outcrop faces showed that some horizontal bedded sandstone bodies overlying the S1 surface laterally grade into trough-cross bedded conglomeratic sand bodies, decreasing in thickness and eventually completely pinching out. However, after the pinch-out, the former sharp lower boundary continues, dividing the underlying lenticular FA1 and overlying wavy bedded FA3 facies associations, and eventually building up into a new sand body again. The sharp surface appears to have a downcutting lower boundary, especially where the overlying sandstone succession is at its thickest, as it creates an apparent broad incision into the underlying mudstones, for example in the location of Log 4 (Figure 23). In rare occasions, there are some small channel-shaped heterolithic conglomerate bodies at the boundary, as in the site of Log 7 or Log 2, i.e. Figure 18D.

The second identified internal surface (Surface 2) is similar in its appearance to S1 due to a marked increase in grain size, and, without careful tracing of the surface, can be mistaken with S1. However in this case it appears stratigraphically higher and divides somewhat coarser-grained wavy-bedded sediment of FA3 from overlying horizontal bedded and trough cross-bedded sandstone facies of FA4. Correlation of this surface becomes hard in some parts due to recent erosion; however the marked lithological change is identifiable in sedimentary logs, supplemented by Lidar images where coverage is present.

Due to a complex architecture present in the lowermost Curtis Formation, correlation of sandstone bodies and sequence stratigraphic surfaces between log sites is presented individually in this section, with pictures illustrating the distribution where exposure is available. This section focuses primarily on correlation of the Curtis Formation between the sequence boundary (SB) and the base of FA4 (Surface 2).

Logs 4-7 (Figure 31): At the site of Log 4, the easternmost end of the study area, there is a ~4 m thick conglomeratic sand body (FA2), comprised of several cross-bedded units which are superimposed on top of each other. Laterally, over the course of 200-300 m it gradually pinches out until it is no longer present at the location of Log 7. Also, at the site of Log 7,
there is a small heterolithic V-shaped incision found at the Surface 1 stratigraphic level (Figure 18D).

**Logs 4-6:** As the log sites are separated by the Stove Gulch, the correlation becomes more complicated as continuous surfaces cannot be directly traced from outcrop to outcrop; therefore their correlation is accomplished by comparing logs and photographs. The succession of Log 6 roughly resembles the one found between logs 7 and 1. At the base of the Curtis Formation in Log 6 there is a single conglomeratic bed which is not present at the location of Log 4, however it starts appearing after ~100 m to the west of the log site. This bed is followed by a wavy-bedded interval of FA3 and then followed by FA4 in both outcrops.

**Logs 7-1 (Figure 32):** Moving westwards from the site of Log 7, a FA2 body appears and gradually begins to thicken towards the location of Log 1. Over this distance, it thickens from several barely distinguishable sub-horizontal beds to a package of two distinct trough-cross bedded units with a thin inter bed of mudstone. It must be noted that the previously mentioned cross-bedded unit at Log 7 does not belong to the thick TCB sandstone unit found at Log 1; it simply appears at the same stratigraphic level as a separate body.

**Logs 1-5 (Figure 33):** Between the localities, through-cross bedded sandstones of lowermost Curtis Fm. in Log 1 gradually thicken and become more homogeneous approximately halfway between the two sections and then begin to thin and increase in heterogeneity again towards Log 5 (Figure 33). The upper FA4 sandstone body is not seen in the figure; however in both sections it comprises horizontal bedded sandstones just above the Surface 2.

Just north of the outcrops, on the opposite side of the canyon ~300 m away, there is a sand lens that correlates with the FA2 body shown in the figure. Moreover, a similar sandstone body has been identified in a location not considered in this study, ~0.8 km south of Log 5 (FA2 unit in Figure 28), potentially outlining a roughly N-S trending elongated sandstone body, approximately 10-15 m at its thickest, extending at least 1.2 km, with its widest part spanning roughly 100 m. The continuity is unknown as parts of the unit between the locations have been eroded. Even though the connectivity is unclear, this observation of a potential elongated sandstone body is extremely important for the reservoir potential as well.
as the interpretation of the geological environment, which is illustrated in more detail in Section 4.4.4.

**Logs 5-2 (Figure 34):** Between the locations, the two conglomeratic beds (FA2) found in a heterolithic matrix (FA1) converge, with the FA1 interbed gradually decreasing in thickness. Overlying this heterolithic succession is a FA4 cross bedded unit which appears much close to the base of the Curtis Formation as the FA1-FA2-FA3 succession begins to decrease in thickness.

**Logs 2-8 (Figure 35):** The FA2 body, represented by a thin interval of conglomerate at Log 2, gradually pinches out and then begins to thicken again between the log sites. One more important change begins between the log sites, as FA1 pinches out at the base of the Curtis Formation and the FA2 conglomerate body gradually begins to rest directly on top of the Entrada Sandstone. In general, the thickness of the lower mudstone-sandstone succession decreases to around 7 m.

**Logs 8-9-10-3:** Correlation between these log sites was established solely in sedimentary logs, due to the fact that logs 8 and 9 are not connected by a continuous outcrop and also because there are no Lidar images from the Sulphur Canyon. However, in adjacent areas, the relief of the J-3 unconformity is gentle; therefore it is assumed that the contact is a sub-horizontal surface. Correlation of sand bodies in the heterolithic succession was also established by using top Entrada Sandstone as a sub-horizontal datum and correlating overlying sediment packages based on lithological similarity.
Figure 31: Correlation between logs 4 and 7. The red line indicates Top Entrada Sandstone (SB), the orange line indicates base and top of the FA2 sandstone body and the yellow dashed line indicates the lower contact of FA4. Photo: Universitetet i Bergen Lidar group

Figure 32: Correlation of sedimentary units between logs 7 and 1. Photo: Universitetet i Bergen Lidar group

Figure 33: Correlation of sand bodies in a heterolithic matrix between Logs 1 and 5. Full logs are not included in the figure. Photo: Universitetet i Bergen Lidar group
Figure 34: Correlation of sand bodies between logs 5 and 2. Photo: Universitetet i Bergen Lidar group

Figure 35: Correlation between the outcrops of Log 2 and Log 8. Log 2 is located roughly 150 m outside of the photograph; however the stratigraphy in the outcrop is almost identical. Photo: Universitetet i Bergen Lidar group

4.3.3 Correlation of the upper Curtis Formation

The succession above S2 is lithologically homogeneous; however it comprises a variety of highly amalgamated structures, which makes identifying major continuous surfaces problematic. This is further complicated by the lack laterally extensive of outcrop material, as the upper part of the Curtis Formation in the study area is divided by broad gulches. Consequently, correlation between the log sites is based solely on lithological changes identified in sedimentary logs.

Gradual transitions between plane bedded, rippled silty and supratidal sabkha facies are also approximated from lithological changes, as this type of lithology is only present in scattered
hilltops. Finally, the current topography and erosional relief is essentially represented by tops of the logs, as in most cases they continue up to the highest point nearby.

4.3.4 Correlation panel

Based on the observations made in the field and the correlation established from photographs and Lidar images, several panels using alternative horizontal datum surfaces have been made, outlining different options for visualizing the correlation of lithology in the study area. It must be noted beforehand that the correlation of facies in the Curtis-Summerville transition extends above the present-day erosion as hypothetical surfaces, due to the fact that this interval is represented only in limited scattered areas and has not been preserved elsewhere in the study area. Thickness of the logs illustrates the present day topography as they were carried out to the highest points of elevation in the area.

The first option for visualization of the stratigraphy is utilizing the J-3 unconformity (Sequence Boundary) of the studied succession as a horizontal datum surface (Figure 36A), as it also represent a flooding surface draping the unconformity. However, as it has been previously described, the Sequence Boundary represents an erosive surface with substantial topography; therefore it is not a correct representation of either the present-day situation or the ancient depositional environment. Nevertheless, it is useful for demonstrating the distribution of sandstone bodies in the heterolithic succession of lowermost Curtis Formation.

Instead, a reference bleached bed in the Entrada Sandstone was used as a horizontal datum (Figure 36B). Faulting and folding presents a challenge for the correlation, however when the reference bed is flattened, the structural effect is removed. The vertical scale used in Figure 36B exaggerates the topography, displaying how the erosion of Entrada Sandstone is concentrated at quite narrow areas, however this leads to distortion of the overlying succession.

The reference bed might not have been horizontal during the deposition of the Curtis Formation, as the incision of the Entrada Sandstone is associated with slight faulting and tilting of the strata; therefore an internal surface inside the Curtis Formation was also utilized for a correlation panel (Figure 36C). For this purpose, the base of FA4 (Surface 2, yellow dashed line in Section 4.3.2) was chosen, as it represents a laterally widespread sharp coarsening of lithology and therefore is identified easily in most logs. According to the
facies association interpretation, this surface also marks the turnaround point for the transgressive-regressive sequence; therefore it represents the most landward position of the shoreline, the maximum flooding surface (MFS)

When this horizontal datum is used, the underlying succession shows a relationship between thickening of FA2 bodies and apparent paleoincisions and given that the datum surface was actually horizontal during the time of deposition, it supports the initial tidal channel deposit interpretation of FA2.

Figure 36: Correlation of logs utilizing alternative horizontal datum surfaces. **A:** the J-3 unconformity **B:** a reference bed in the Entrada Sandstone; **C:** lower boundary of FA4
4.4 Geological development

The geological development of the studied stratigraphic interval is reconstructed based on the observations made when interpreting the depositional mechanism of each facies, and also the architectural elements of individual facies associations. It is also supported by descriptions of modern and ancient tidally-influenced marine deposits that are considered relevant analogues for this study. The broad subdivision of depositional sub-environments is sub- and inter-tidal flat deposits and also supratidal erg margin and sabkha deposits. Modern analogues include examples from the tidal shorelines of Australia, i.e. the Exmouth Gulf shown in Figure 37 (Orpin et al., 1999), wet dune fields of South America (Mountney, 2012) and flooded dunes of Australia (Eschner and Kocurek, 1988), Yellow Sea (Fan, 2012), tidal flats and sabkhas of the Arab peninsula (Strohmenger et al., 2010) , the North Sea (Stride et al., 1982) and the Bahamas (Rankey and Reeder, 2012).

Given the paleogeographic configuration of the basin resulting in an arid climate, discussed in more detail in Section 2.2, vegetation was limited to non-existent in the supratidal environments of both the Entrada Sandstone and the Summerville Formation, as opposed to local plant growth present in the wetlands of Morrison Formation (Dunagan and Turner, 2004). Therefore the marginal marine environments of Australia and the Arab peninsula are ideal as an analogue of the climate and the intertidal to supratidal transitions of Entrada-Curtis and Curtis-Summerville. It must be noted that Western Australia and the Arab peninsula are developing in different tectonic settings than that of the strata studied here, and are employed purely for their distribution of sedimentary sub-environments in the present.

The conceptual model of the depositional environment upon which the geological development is based is illustrated in Figure 38. This figure shows the lateral distribution of facies and gives a broader perspective of the environment which may not be evident from the individual figures. A small version of the conceptual model is given for each stage of the development for the Curtis Formation, with the relative paleobathymetric position marked with an arrow.
4. Results

Figure 37: Tidal flats, Exmouth Gulf, Western Australia. Photo modified after Williams (2016)

Figure 38: Conceptual model of the depositional environment for the Curtis Formation. The figure is included in the subsequent figures illustrating individual stages of stratigraphic development. The colours used correspond to the intervals of the succession shown in Section 4.3.4. Geographical orientation not intended.
4.4.1 Stage 1: Entrada erg

The first stage of the vertical development in the study area comprises the deposition of alternating sandstone-mudstone beds (Facies Association 6) with occasional interbeds of gypsum, belonging to the Earthy Facies of the Entrada Sandstone (Figure 39). As it was described in Section 2.3.2, this is commonly interpreted as a wet dune system.

![Stage 1: Entrada erg (Earthy Facies)](image)

Figure 39: Stage 1 (Entrada Sandstone): deposition of eolian sandstones and interdune deposits which consist predominantly of mudstones with rare interbeds of evaporites. Orientation and scale not intended.

A high amount of dark brown mudstone intervals signifies intermittent, frequent floodings of the interdune area, which in turn marks a relative proximity of the surface to the groundwater table. This could be linked to an increasing relative paleogeographic proximity to the shoreline, or, in other words, a transition from a continental eolian setting to a marginal marine sabkha environment. Due to the fact that an unknown amount of the Entrada Sandstone was removed during the development of the J-3 unconformity and also due to limited exposure, this gradual conformable shift of facies at the study area is only inferred.

4.4.2 Stage 2: Incision of Entrada Sandstone

The incision stage of the Entrada Sandstone (Figure 40) records the development of the regional J-3 unconformity, characteristics of which were described in Section 4.3.1.

The full extent of erosion of the Entrada Sandstone cannot be established quantitatively in the scope of this study. However, some observations are of major importance when
describing the unconformity surface. In some outcrops, the unconformity surface shows a sub-horizontal sinuous contact, with erosional relief amplitude of ∼1 meter. In other sections, substantial relief changes in the scale of vertical 10-20 m are present, occurring over the course of several hundred meters, with most of it occurring at steep channel walls (Figure 28). Moreover, substantially larger channel incisions have been reported by (Sleveland, 2016), illustrated in Figure 41.

**Stage 2: Tilting and incision of Entrada Sandstone**

*Figure 40: Stage 2: Incision of the Entrada Sandstone. Light brown areas show cliff walls forming due to the incision, as described in Section 4.3.1, whereas dark brown areas show zones of flat topography. Vertical scale not intended, with the exception of ∼14 m high erosive relief.*

In photographs provided by the University of Bergen Lidar group, lenses of coarse-grained clastic material at the Curtis-Entrada contact were identified in several locations of this study area (Figure 42). Unfortunately the beds were not investigated in more detail, as the data was received after the field work was completed. However, they potentially represent paleo-wash deposits formed during the incision stage. Such deposits have been described by other authors, i.e. Facies C1 (Incised channel-form sandstone) of Wilcox (2007). The very limited amount of coarse-grained material in the study area suggests a local paleotopographic high diverted these sediments into other areas. Both beds shown in Figure 42 are located around the location of Log 2, however constraining the distribution of such beds would require a systematic investigation which is beyond the scope of this study.

Several modern and ancient dune field flooding events with varying original topography preservation degrees have been described by Eschner and Kocurek (1988), including the
boundary of Entrada-Curtis formations. The bounding surfaces have been categorized as the following: surfaces preserving all original dune topography, surfaces with partially reworked dune topography, planate surfaces and also erosional relief. Based on the fact that exposures Entrada-Curtis formations show the contact cutting through several generations of interdune surfaces (Facies K of FA6), the contact therefore falls into the category of erosional relief.

Such features lead to the following question: if the unconformity represents a short amount of time missing from the sedimentary record with the sediment being still unconsolidated, slumping, mass flows, soft sediment deformation and other structures typical to erosion of loose would be present just below the unconformity. Mass flow deposits resting on top of the J-3 unconformity have been described by Eschner and Kocurek (1986) in northeastern Utah. However, as mass-flow deposits were not discovered in the study area, but instead fairly steep incisions such as in Figure 28 were identified, the Entrada sands must have been lithified to some degree at the time of erosion. Consequently, the degree of incision and reworking varies in different areas.

Faulting of the Entrada Sandstone (Figure 43) has been reported by Sleveland (2016). This faulting does not cut through the Curtis Formation, which shows that tectonic activity was present between the deposition of the uppermost Entrada Sandstone and the development of Curtis Formation deposits resting directly on the unconformity. An angular unconformity has also been reported by Keach et al. (2006), where the authors have identified the unconformity by utilizing geophysical methods. The most important conclusion that can be made from this observation is that if the Entrada Sandstone is tilted, using a reference bed as a horizontal surface will lead to an inaccurate estimation of incision depths.
4. Results

Figure 41: Incision into the Entrada Sandstone at Sven’s Gulch, interpreted as a tidal channel. Human for scale directly below the incision. Photo: Valentin Zuchuat

Figure 42: Sandstone bodies at the Entrada-Curtis boundary, identified as potential paleo-wash deposits formed during the incision stage. The bed shown on the left is located approximately midway between logs 5 and 2; the bed shown on the right is located in the proximity of Log 2.

Figure 43: Apparent angular unconformity with faulting in Entrada that is not cutting through the Curtis Formation. The photo is taken ~7.5 km southeast of the study area. Photo: Arve R. N. Sleveland
4.4.3 Stage 3: Flooding and first passive infill

The oldest sediment belonging to the Curtis Formation is a succession of locally constricted lenticular-bedded mudstones (FA1, **Figure 44**). This type of sediment signifies deposition in a tidally-influenced shelf environment where mudstones were interbedded with ripple-shaped sandstone lenses that display opposing paleocurrent measurements, draping the underlying erosional relief and resulting in a distinctly heterolithic succession.

![Stage 3: Flooding and passive infill](image)

**Figure 44**: Stage 3: Flooding of the Entrada Sandstone: lenticular-bedded marine heterolithics (FA1) onlap the erosive J-3 relief. Due to tidal currents, ripples build up locally on the seabed, highlighted by yellow lines. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. Vertical scale not intended

Multiple thin-bedded gravelly conglomerates (Figure 45) were identified at lowermost Curtis Formation in an adjacent locality, the Sulphur Canyon by Zuchuat and Sleveland (2016, pers. comm.). These features suggest that the marine incursion took place over several stages, creating transgressive lags multiple times. This type of development can be expected in a low-gradient marginal marine environment, where slight base level changes would result in the shoreline shifting large distances (Catuneanu, 2006). They also act as a precursor to the development of Stage 4 (Section 4.4.4), highlighting gradually increasing tidal influence and showing that coarse-grained clastic material was present in the system during the whole development of the heterolithic lower part of the Curtis Formation.
4. Results

Figure 45: Thin-bedded pebble conglomerates, Sulphur Canyon (adjacent canyon to the north of Stove Gulch, see Figure 5 for location of the canyon). Geological hammer for scale. Photo: Valentin Zuchuat

4.4.4 Stage 4: Development of S1, formation of FA2 sand body

Stage 4 (Figure 46) is a high-energy time interval, resulting in the development of coarse clastic subtidal dunes. The stage begins with the formation of the S1 surface, a widespread sharp boundary dividing the FA1 succession of Stage 3 and the FA2 succession of Stage 4, interpreted as an erosive lower boundary of a sub-tidal channel incising into a mud-rich substrate. The channel is consequently filled by a development of conglomeratic dunes and tidal bars (FA2).

Conglomeratic dunes pinch out in the order of 10s to 100s of meters. Laterally extensive cross-bedding does not develop due to most likely limited coarse-grained sediment supply, as the facies has been identified as tidal palimpsest deposits with the coarse sediment emplaced by pre-Curtis alluvial drainage (Caputo and Pryor, 1991). Meanwhile, tidal bars create elongated, laterally extensive bodies inside the channels. The hypothesis of erosion in the interdune areas and channel banks is supported by mudstone rip-up clasts found along cross-bedding surfaces of the conglomeratic sandstone bodies, which, based on lithological similarity, were most likely eroded from the substrate during high-energy events such as storms or spring tides. However, in order to prove tidal cycles as the primary mechanism of this development, further investigation of any apparent cyclicity of the crossbeds would be necessary.
Figure 46: Illustration of lateral facies distribution during Stage 4. The conglomeratic dune deposits (grey colour, Facies H) interfinger with fine-grained tidal bars (Facies C, E, fine grained sandstone). On the fringes of the main channel, smaller incisions appear, represented by dark-grey lines (Facies F, I). The arrow in the map highlights the postulated proximal-distal position in the depositional environment.

FA2 rests directly on top of the Entrada Sandstone at the location of Log 8. As it was determined in Section 4.3.2, this body laterally correlates with FA2 units resting on FA1, with the underlying mudstone beds pinching out towards the aforementioned location, where a FA2 bodies rests directly on top of the J-3 unconformity. It demonstrates that the S1 surface, that is, the lower boundary of FA2, is a sub-horizontal laterally extensive surface, cutting into the underlying FA1 or FA6 sediment.

Mud-rich interbeds divide the compound dune packages. In some cases, such interbeds can be traced between log sites, or in other cases they pinch out laterally. These interbeds represent local low-energy deposition between the active dunes where erosion was not taking place.

During storms and spring tides, due to channel bank erosion, underlying cohesive mudstones are locally eroded. Clasts of mudstone are consequently reworked to some degree during transport and finally deposited along bedding surfaces of the conglomeratic dunes, resulting in the so called “Swiss-cheese facies”, where such interbeds of both angular and well-rounded mud clasts have been consequently eroded.
As it is evident in the correlation established in this study, FA2 sand bodies are the thickest at the interpreted paleoincisions, which indicates that the sand units were deposited in such bathymetric lows where accommodation was highest. This is interpreted as concentration of strong tidal currents in sub-tidal channels that in turn resulted in a build-up of conglomeratic dunes.

### 4.4.5 Stage 5: Flooding and second passive infill

Following the FA2 development in Stage 4, heterolithic intervals are deposited, draping the underlying channel infill topography ([Figure 47](#)). The wavy-bedded sandstone represents a minor flooding of the area, with the relative position from the shoreline remaining approximately the same as where FA2 is deposited. Higher sand content compared to FA1 of Stage 3 is explained by higher water energy in a constricted bay environment as opposed to the open shelf. In this heterolithic succession, thin channel-form Facies I beds were deposited, interbedded with the wavy sandstone beds, showing that the subtidal environment was still dissected by occasional tidal channels, analogous to the channels in the fringe zone of Stage 4.

**Figure 47:** Stage 6 is the second passive infill stage, draping the channel-infill deposits of FA2. In contrast to early passive infill deposits of Stage 3, FA3 comprises laterally continuous wavy and flaser sandstone beds as opposed to lenticular bedded mudstones. This denotes sustained sand input into the subtidal environment, resulting in deposition of extensive beds. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. The arrow points to the channel-infill facies, however the stage denotes a second flooding of the bay environment.
4.4.6 Stage 6: Prograding tidal flats: formation of FA4 sandstone unit

Passive infill of Stage 5 is in turn replaced by the highstand deposits of Stage 6. It began with the formation of a semi-abrupt to sharp lower boundary (S2). As similar sharp contacts have been described as the bottomset of a prograding sand flat (Desjardins et al., 2012b), this surface is interpreted as a corresponding development. The overlying homogeneous sandstone beds of FA4 are interpreted to represent prograding sand flats, interpreted to consist of breaker bar and sand flat deposits in the lower part (Figure 48) and mixed flat deposits in the upper part of FA4 (Figure 49).

Figure 48 illustrates a predominantly subtidal environment that can be subdivided into sand shoals and sand flats. Subaerial exposure of bathymetric highs is possible, but limited to spring tides, when the difference between low and high tides is at its highest.

A similar vertical development has been described in a marginal-to-shallow-marine succession of Cambrian age in Jordan by Mángano et al. (2013). In the study, marginal- and open-marine carbonate beds are overlain by trough cross-bedded and tabular cross-bedded fine- to medium-grained sandstones, interpreted as moderate-sized tidal bars, compound dunes and simple dunes, locally dissected by channels, and interbedded with bottomset heterolithics. The heterolithic intervals in the Cambrian beds are described as “<...> consisting of thinly bedded current-ripple cross-laminated very fine- to fine-grained sandstone and mudstone, displaying flaser-, wavy-, and lenticular-bedding, and recording deposition in the bottomsets of tidal dunes and in the low-energy areas between the dunes“.

This type of architecture is almost identical to the one found in the lower and middle Curtis Formation, with the exception of the grain size, which is limited to fine-grained sands in the case of the middle Curtis Formation. However, such a difference can potentially be attributed to a difference in sediment supply.

As the tidal flats prograded, water energy began to decrease in the intermediate intertidal environment (Figure 49). As the environment was partly shielded from wave action by the aforementioned sand shoals of Stage 6.1, wave influence was diminished. This is exhibited in the sedimentary record by upwards-thinning sandstones of FA4 corresponding to the late part of Stage 2. The whole stage is characterized by a lack of bioturbation in the study area. It must be noted that extensive bioturbation has been reported in other locations at roughly
the same stratigraphic level by (Sleveland, 2016). As it was described by Desjardins et al. (2012a) and the references therein, the lack of bioturbation in tidal sandy sediment could be explained by a high energy environment with rapidly migrating bedforms, essentially inhibiting colonization of the seabed due to rapid sedimentation. This type of environment can be attributed to Stage 6, where the lithology and structures found suggests consistent reworking and rapid sedimentation, resulting in a lack of bioturbation.
Stage 6.1: Early prograding tidal flats
Subtidal to lower intertidal sand flats

Figure 48: Stage 6.1: Deposition of channelized (TCB – trough cross bedded) and horizontal bedded (hor. bed.) homogeneous sandstone bodies. This stage represents an environment where tide and wave energy was at its highest. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. Vertical scale not intended. MLW – mean low water.

Stage 6.2: Intermediate prograding tidal flats
Mixed flat

Figure 49: Intermediate stage of prograding tidal flats. As the environment is partly shielded from wave action by shoals of Stage 6.1, water energy levels are reduced. Sedimentary patterns are governed by the movement of currents in tidal channels and deposition in adjacent mixed flats. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. Vertical scale not intended. MLW – mean low water; MHW – mean high water.
4.4.7 Stage 7: Prograding tidal flats: formation of rippled silty facies

Stage 7 encompasses the deposition of mud-rich strata in the upper intertidal environment, that is, mud flats (Figure 50). This part of the depositional system was flooded only during the high tide, subaerially exposed most of the time. The flats were dissected by tidal channels in which rising and falling water was concentrated, resulting in deposition of relatively coarser material compared to the adjacent mud flats (Facies Association 5). The gradually fining upwards transition between FA4 and FA5 shows a very high vertical and lateral variability of lithology, attributed to a dendritic network of channels present in the tidal flats.

Deposits belonging to this stage of development are considered to be equivalent to the C5 Facies Assemblage of Wilcox and Currie (2008). According to the authors, mudstones in the succession contain sand-filled polygonal desiccation cracks, salt hopper casts, sparse vertical/horizontal burrows and rare sauropod tracks. In the case of this study, mudstone intervals are only inferred as in the outcrops they are slope-forming, mostly scree-covered, which results in no adequate exposures. Consequently, such fine structures described in the mudstones are unfortunately impossible to identify in the study area.

Stage 7: Upper intertidal mud flat

Figure 50: Stage 7 encompasses sediment deposited in the uppermost intertidal environment, which consist of mudstones, locally dissected by sandy tidal channels. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. Vertical scale not intended. MLW – mean low water; MHW – mean high water.
4.4.8 Stage 8: Intertidal to supratidal deposition: transition to Summerville

The final stage of the studied succession (Figure 51) comprises upper intertidal mudflat deposits (FA7), with the area dissected by channels where tidally modified unidirectional current structures prevail. In the succession, dominant grain size is fining upwards, with sandstone intervals decreasing in thickness and abundance, which is interpreted as gradually decreasing tidal influence. In the environment, dark brown mudstones were deposited in supratidal mudflats. Water input into the environment is considered to be ephemeral: the flats were intermittently flooded by spring tides, storm surges or by drainage from wadis. This resulted in parts of the flats covered by bodies of standing water, resulting in local deposition of evaporites, whereas sandstone intervals were deposited in drainage channels.

Stage 8: Mud flat to supratidal sabkha transition

Figure 51: Transition from the Curtis Formation to the Summerville Formation. The continued regressive development sets up a supratidal environment in the area, marked by Ephemeral ponds and sabkhas, occasionally disturbed by tidal channels during spring tides and/or storms. The arrow in the map highlights the postulated proximal-distal position in the depositional environment. Vertical scale not intended. MHW – mean high water.
4. Results

In **Figure 52**, an overview of all the stages belonging to the Curtis Formation (Stages 2-8) is given in. This figure shows the contrast between all of the environments that were present during the development.
Figure 52: Overview figure of stages 2-8 of the geological development of the Curtis Formation.
5. Discussion

Sedimentary successions are formed by processes which work at different time scales, ranging from tens of millions of years to seconds Miall (2010). Individual layers (laminae and beds) are formed by processes which last seconds to days, i.e. formation of ripple cross-lamination, formation of dunes etc. Meanwhile, complete stratigraphic sequences are formed by processes with a longer duration and express long-term trends. Primary driving mechanisms behind such sequences include long-term eustasy and epeirogeny, tectonics, orbital forcing and climate (Catuneanu, 2006, Miall, 2010).

In general, identifying both higher and lower order sequences and also intra- and extra-basinal forcing mechanisms allows for better prediction of the distribution of sedimentary packages. This is especially important when characterizing reservoir quality which is affected by both lateral and vertical facies changes and their respective relationships.

5.1 Driving mechanisms behind the geological development

Distinguishing between the two primary sequence-generating mechanisms, orbital forcing (eustasy and climate) and tectonic influence (flexural loading and dynamic topography), is based on key differences between the two alternatives (Miall, 2010). Identification of orbital forcing involves correlating studied sedimentation patterns with global sea level fluctuations, due to the fact that such fluctuations determine the style of sedimentary infill. Meanwhile, linking sequence developments to tectonic activity requires proving correlation of the recorded cycles with episodes of tectonic activity.

Deconstructing the interplay of climate and tectonics behind the Curtis transgressive-regressive sequence is complicated and is considered unrealistic to be determined from a single area. However, in the case of the Curtis Formation, climate change is unlikely as the primary forcing mechanism. The Curtis embayment was connected to the ocean via the Sundance Seaway, establishing full marine conditions in the area (Peterson, 1994). This is in contrast with saline lake conditions in the Permian Rotliegend of Europe, where base level was controlled by cyclic climate fluctuations (Yang and Nio, 1993). Nevertheless, climate change could have had an effect on the depositional patterns during the time when the Curtis
Formation was deposited, specifically affecting the areas bordering the basin, being an important controlling factor of sediment supply.

The sediment source of the ubiquitous chert pebbles has been interpreted by Peterson (1994) as the first influx of coarse sediment from the newly elevated highlands to the west which came into existence in the Middle and Late Jurassic during the Elko orogeny (Lawton, 1994), however this is based solely on lithological similarity with pebbles found in the Morrison Formation, therefore the beds would benefit from a proper provenance study in the future.

The correlation of the marine cycles of the Western Interior and global sea level curves was discussed by Brenner and Peterson (1994) and the references therein. On a global scale, starting in the Callovian and through the Kimmeridgian, global sea level curves suggest a rise in sea level, however in the northern Western Interior the development is generally regressive, eventually resulting in the development of the regional J-5 unconformity. This also includes the development of the J-3 unconformity, which correlates poorly with other regressions in the continent (Peterson, 1994), consequently the J-3 unconformity is considered to be caused solely by tectonic movements.

As it was mentioned in Section 4.3.1, the J-3 unconformity is reported to sometimes show an apparent angular unconformity. Bordering angular unconformities are also a reliable indicator when relating sequences to tectonic events (Miall, 2010). Unfortunately, characterizing the angular unconformity is difficult, as the degree of tilting is low. This is further complicated by the topographic relief of the J-3 unconformity and subsequent tilting of the strata, which locally may cause the contact to look as an apparent angular unconformity. The only solid piece of evidence that supports the tectonic origin of the unconformity is the faulting which does not cut through the overlying Curtis Formation, identified in several locations. Finally, the angle of tilting in the Entrada Sandstone can be reliably evaluated in wide outcrops by utilizing Lidar imagery.

The unconformable facies transition from continental to offshore marine facies shows that there must have been a period during which the base level dropped, leading to faulting and erosion in the area, followed by high rates of sea level rise, where the structural topography was preserved. The base level drop could have been caused by a substantial drop in
5. Discussion

groundwater level or by eustatic fluctuations; meanwhile the transgression is most likely linked to a tectonic event.

Regarding the type of tectonic movements, Lawton (1994) discussed the origin of the Middle Jurassic basin, as it has been interpreted as a flexural basin by some authors, relating the formation of the basin to Elko Highlands or Central Nevada thrust belt. However, there are two arguments which question such an origin: firstly, widespread-presence of arch-derived detritus is not common in foreland basins, where sediment is typically derived from the thrust wedge. Secondly, based on thickness patterns, even though the San Rafael Group thickens westwards, in the case of a flexural model, the thickening only accounts for a part of the basin’s volume. Therefore, it is considered by Lawton (1994) to have been formed by dynamic topography related to a flattening of the subducted slab.

The Curtis Formation is postulated to have been deposited during a transgressive-regressive cycle which lasted roughly 1 million years, with an average sedimentation rate around 65 m/my (Peterson, 1994). Such periodicity is similar to the Cretaceous transgressive-regressive cycles of the Western Interior, as discussed in great detail in Section 10.4.3.1 of Miall (2010), where cycles of $10^6$ years were identified in the Cretaceous succession and were consequently interpreted by further research to have been caused partly by tectonic movements and also partly by eustasy, as some intervals show correlation with time-equivalent European strata.

Cycles with a $10^6$-year duration have also been identified in the Upper Rotliegend of Europe (Yang and Nio, 1993, Bailey, 2001). In this case, lowstands are characterized by an arid climate, where eolian lags, dune fields and dry sand flats form in the basin margin, flank and centre respectively. As the climate gradually becomes semi-arid to subhumid, dune fields disappear and are replaced by wadi and fluvial systems and sabkhas in the basin margin and flank, and damp sand/mud flats towards the basin centre, representing a transgressive to highstand development. As the Rotliegend basin is considered to have been isolated from eustatic sea level fluctuations, the $10^6$-year sedimentary cyclicities were caused solely by climatic fluctuations. Upon these cycles, higher order fluctuations are superimposed, interpreted to be caused by orbital forcing.

Even though the cycles of the Western Interior were not controlled primarily by climate due to the fact that the basin was connected to the ocean, the setting of the Rotliegend is an
excellent example of climate fluctuations affecting sedimentary supply patterns in arid continental settings; consequently, it can be used an analogue for the deposition of the Entrada Sandstone. Moreover, an assumption of a constant climate over a few million years most probably is unlikely. Extensive dune fields such as the Entrada or Navajo ergs are not known during the Curtis-Summerville time, except for local deposition of eolianites such as the Moab Tongue and the Romana Sandstone. With the concept of a climate-driven eolian-lacustrine sequence stratigraphic model of Yang and Nio (1993) applied, a general wetting of the climate can be assumed during the Curtis-Summerville time.

The wetting of the climate could have caused a development of inland fluvial and wadi systems, which would have served as a source of the coarse siliciclastic grains in the Curtis Formation. Even though such coarse grains were not identified in the underlying Entrada deposits, an alluvial plain is postulated in the western flank of the basin by Peterson (1994), where pebbly beds have been identified in the Romana Sandstone, considered to be a late Curtis to Summerville-correlative (Peterson, 1988). However, as the western margin of the Curtis basin is not exposed, the exact relationship between the westwards-lying alluvial plain and the Curtis Sea itself remains unknown.

Interpretation of autogenic mechanisms relies on a correct interpretation of the depositional environment and typical processes occurring in it, and reliable control on the configuration of the basin. Even in a relatively small area, tidal regimes occur in a variety of environments (Dalrymple and Choi, 2007). Consequently, capturing the full complexity involves investigations of a regional scale, which was not the target of this study. However, based on the observations made in this study, important conclusions can be made about the configuration of the shoreline and autogenic processes within the small part of the basin that was studied.

In the Colorado Plateau, tidal conditions have been identified in the Middle Jurassic Carmel Formation (Kocurek and Dott, 1983, Tang et al., 2000) and are also known in parts of the Cretaceous succession (Willis and Gabel, 2001, Ericksen and Slingerland, 1990), essentially showing that tidal signatures are present in most Mesozoic marine deposits of the Western Interior. Even though epeiric seas have previously been considered as lacking tidal regimes, research of ancient successions has demonstrated that it is in fact the opposite (Klein and Ryer, 1978). The presence of sedimentological (e.g. current reversals) and paleontological evidence (e.g. fossil species which require tidal fluctuation of water) serves as a solid
5. Discussion

argument for tidal regimes serves in Precambrian, Paleozoic and Cretaceous epicontinental seas. The Curtis Formation is also not an exception, as the documented sedimentary structures support a tidal regime.

According to Caputo and Pryor (1991), transport direction trends in the Curtis Formation suggest that the Curtis sea was embayment where shorelines were oriented east-west in the southern part of the basin and southwest-northeast in the eastern part of the basin. The embayment potentially had a counter-clockwise circulation pattern (Peterson, 1994), which is similar to several localities of the North Sea (English Channel, German Bight) (Caputo and Pryor, 1991).

The interpretation of ancient open-coast tidal flats (Fan, 2012) is based on the identification of storm-generated structures such as interbedding of coarse storm and fine post-storm deposits, occurrence of structures created by the interaction of waves and tides and also scarce tidal-channel deposits. The abundance of such structures is attributed to the coast not being shielded from storm action. On the contrary, tidal channels are frequent, in barred tidal flats which are protected from reworking by waves and storms. This is evident in the studied succession, where shoals have been identified. Such elevated areas would have effectively reduced wave influence in the interpreted inland part of tidal flats which developed during Stage 6 and upwards.

The postulated east-west oriented shoreline in the study area is founded on the general transport direction determined by paleocurrent measurements (Figure 27). The lateral distribution of lithologies does not show any apparent proximal-distal trend, which is most likely attributed to the profile orientation of this study, positioned approximately parallel to the inferred shoreline. Moreover, in a highly amalgamated environment like the one that the Curtis Formation is thought to have been deposited in, seeing a clear proximal-distal trend can be difficult altogether in any orientation, especially at the scale of this study, as the shoreline is thought to be highly complex, i.e. similar to Figure 37.

One of the most extensively discussed subjects during the preparation of this study was the mechanisms creating the channels during Stage 4, responsible for the deposition of FA2 channel infill and tidal bar deposits. Even though virtually ideal exposures of this interval are present in the study area, understanding the complex architecture and the reasons behind it is
challenging. Therefore, other examples of similar deposits offering solutions to this problem are employed.

Modern conglomeratic tidal dunes have been described by Dyer (1971) in the Solent, Southern England. In this location, the seafloor is covered by 0.25-2 m high gravel dunes spaced every 5-18 m, shaped by tidal currents moving through the strait. The gravel is sourced from the nearby shoreline, transported by longshore currents, introduced into the strait by wave action and consequently reworked by tides. Gravel dunes have been interpreted in the intertidal environment (Carling et al., 2006) of the macrotidal Severn Estuary, where straight-crested fine gravel dunes with typical heights of 0.7 m and wavelengths of 7 m are migrating across the bedrock platform. All of these studies show that tidal forces are able to generate such structures. It must be noted that similar conglomeratic dunes can be found in wave-dominated environments as well, demonstrated by Lo Iacono and Guillén (2008). In the western Mediterranean Sea, the northwestern Sicilian shelf is covered by dunes consisting of coarse sand and gravel. The wavelength of the dunes is 1–2.5 m and the height is 0.15–0.30.

Nio (1976) identified a link between the build-up of sand wave (dune) complexes and transgressions, which was based on an investigation of several ancient and modern examples of subtidal dune fields. For example, the Lower Tertiary Roda Sandwave complex consists of four distinct facies. The pre-sandwave facies comprise lenticular and flaser bedded sandstones. The initial sandwave facies, followed by the sandwave facies, both consist of 5-6 m thick intervals of cross-bedded sands that are laterally extensive and show scouring at the base. It is followed by post-sand wave facies, marked by lower energy sedimentation and increased bioturbation. This vertical development in its entirety is very similar to stages 3-5 of the Curtis Formation, except for the lack of gravel-sized clasts in the Roda sandwaves. Most of the discussed sand wave complexes are situated within narrow, elongated trough-like topography, which was also interpreted in the erosive relief of the J-3 unconformity. During a transgression, a strong tidal regime is gradually established in the area, which with sufficient sediment supply results in a distinct vertical succession, consisting of stacked subtidal dune deposits.

In conclusion, due to the observed relationship between the thickness of FA2 sandstones and paleoincisions, the most likely explanation for this development is deposition in a laterally
constricted embayment. This also explains how strong tidal currents could have been formed by acceleration of tidal currents in a constricted environment as opposed to the open shelf.

It has to be noted that the FA2 sandstones are laterally widespread, with ~4 m thick crossbeds present in the angular unconformity location ~10 km south of the study area and thin beds of conglomerate recognized as far as 30 km south of the study area. This shows that the development of such channels is extensive, even though the interpreted channel-infill deposits are not always present. Due to this variability, extrapolating the observed FA2 distribution outside the study area should be done with care, especially in reservoir models. This can only be alleviated by further studies, targeting the paleotopography of the J-3 unconformity and its relation to distribution of the FA2 sandstone bodies, partly addressed by the work of Sleveland (2016).

Another issue that was faced early on was the high thickness variations of the Curtis Formation between the log sites. Thickness variations of the heterolithic succession deposited during stages 3-5 are explained by varying accommodation related to the paleotopography of the J-3 unconformity. However, the paleotopographic lows are unable to account for the full amount of thickness changes. Much higher thickness of FA4-FA5 units is especially evident around Log 1, decreasing slightly in adjacent areas (Figure 36). The thickness variation is interpreted as persisting deposition of tidal channel facies in a mixed to mud-flat environment, illustrated in Figure 48 and Figure 49. The lack of exposures in the study area prohibits identifying maintained large channel sedimentation in the Summerville Formation.

Even though the position of the main channel was interpreted to remain roughly in the same location, migration of adjacent tributary tidal channels is evident, especially in the Facies I, for example in Figure 24. In this location, stacked units of Facies I are present, representing lateral migration and decreasing width of the channel with time, potentially due to the currents being diverted elsewhere. A similar development could also be present in the channels units of FA4. It was unfortunately not observed directly, potentially due to the lack of cliff-forming exposures in the upper half of the Curtis Formation.

Consequently, based on the processes affecting the studied Entrada-Curtis-Summerville succession, its sequence stratigraphic development can be categorized into the following stages:
• Lowstand: Stage 1 is characterized by an arid climate resulting in the formation of the Entrada Erg. Stage 2 marks a further drop in base level resulting in the development of the J-3 unconformity.

• Transgression: Stages 3-5, characterized by a widespread flooding of the area, during which sea level rise exceeds sedimentary influx. Due to a tidal regime that is established in the basin, the shorelines are characterized by estuarine/bay developments. In such constricted environments, pebbly sandstone dune fields and tidal bars form. In the flanks of the basin, due to the climate becoming more humid, fluvial drainage and sedimentary supply increases.

• Highstand: Stages 6-7, during which rates of sea level rise decrease, consequently the sedimentary influx exceed the available accommodation space. Prograding tidal flat sedimentation prevails, with depositional trends dictated by autogenic mechanisms. The final part of the highstand is marked by deposition of the Summerville Formation.

After the full succession developed, it is followed by a subsequent drop in base level, resulting in widespread erosion and development of the J-5 unconformity (Peterson, 1994).
5.2 Implications for reservoir quality

Due to their inherent complexity, heterogeneous geological reservoirs receive a large amount of attention in research. Some of the best-known heterolithic reservoir examples include rocks in the Norwegian Continental Shelf (Martinius et al., 2005), i.e. the Lower Jurassic Tilje (Martinius et al., 2014) and Cook (Livbjerg and Mjøs, 1989) formations. Meanwhile, exposed rocks which are regarded as analogues of such reservoirs, are used to improve the understanding of such deposits, e.g. the Early Jurassic marginal marine Neill Klinter Group in East Greenland (Ahokas et al., 2014), and tidal deltas of the Sego Sandstone (Mancos Shale), deposited in the Western Interior (Willis and Gabel, 2001).

Heterogeneities in reservoirs appear in a range of scales, from micrometre-scale variations in the pore-network, to centimetre-decimetre scale lithology shifts and sedimentary structures in individual beds, to interwell and field-scale facies transitions and depositional trends occurring over 100s of meters to kilometres (Slatt and Galloway, 1993). Consequently, integrated studies investigating reservoirs at all scales are necessary in order to fully comprehend such systems.

Microscopic scale heterogeneities are often related to the depositional mineralogy and subsequent diagenetic alterations. In some cases, a link is identified between the depositional mechanisms and diagenetic alterations, for example, coating of clastic grains by authigenic chlorite, preserving porosity at depth by preventing quartz overgrowth (Ehrenberg, 1993).

Heterogeneity in sedimentary successions at the centimetre-decimetre scale is often interpreted to be a result of tidal influence in a variety of marginal marine environments such as deltas, estuaries, tidal flats etc. (Dalrymple and Choi, 2007). The reasoning behind this interpretation is that frequent current reversals and fluctuations of sediment transport that are typical to tidal systems (Wang, 2012) result in heterogeneities caused by interbedded mudstones and sandstones (Massart et al., 2016).

At an interwell to field scale, tidal reservoirs at provide a multitude of challenges regarding the amount of hydrocarbons that can be recovered from such reservoirs (Wood, 2004). These difficulties primarily arise from variations in the orientation, width, length and thickness of tidal sand banks, as observed in both ancient and modern tidal deposits (Wood, 2004). Such differences are attributed to different basin configurations regarding the tidal current velocities, water depth and sediment supply. Therefore, in order to accurately predict the
distribution and connectivity of the sandstones, reliable control of the configuration of the basin and the tidal regime is necessary.

Outcrops on their own generally lack the three-dimensional resolution to serve as self-sustained reservoir analogues due to their two-dimensional nature (Grammer et al., 2004). Therefore, modern analogues (discussed in Section 4.4) are commonly used to constrain lateral facies distribution in reservoir models. At the same time, outcrops provide invaluable information about vertical developments, sand body connectivity and direct measurements of reservoir properties (Grammer et al., 2004).

Due to recent advances in technology, the issues related to resolution are solved by acquiring Lidar data, which allows outcrop analogues to provide both the vertical and lateral resolution and consequently to be utilized in field-scale reservoir models (e.g. Hampson et al. (2012), Buckley et al. (2010a), Buckley et al. (2010b), Moore et al. (2012)). Obtaining Lidar data accomplishes the following goals:

1. Interpretation of Lidar images alleviates the issue of constraining lateral connectivity, as continuous images of whole outcrops can be taken in the field and analysed at any given time without the need for spending more time in the field.
2. Images provide an opportunity to identify interwell- to field-scale facies changes with great accuracy, leaving much less room for interpretation when compared to conventional correlation.
3. Three-dimensional models of depositional systems can be constructed, as opposed to interpretation of two-dimensional outcrops photographs. As the Lidar measurements are tied in to global coordinates, surfaces of interest can be interpreted and implemented in reservoir models.

In this study, images of cliff walls allowed to constrain the complex architecture of the lowermost Curtis Formation. As the study area is essentially limited to a profile of ~3km, this study does not consider field-scale heterogeneities. Instead, it focuses on micro- to interwell-scale structures of the Curtis Formation. The meandering nature of exposures in the Stove Gulch allows having a three-dimensional overview of such structures; however some questions regarding sandstone body interconnectivity still remain. This can partly be avoided in the future by carefully planning the placement of Lidar scans, but correlation in eroded intervals still remains a challenge for the geologist.
5. Discussion

As it is evident from the correlation panels (Section 4.3.4), substantial changes can occur laterally over the course of several hundred meters in the succession (less than 10s of meters when the erosional topography of J-3 or channel incisions of FA2 are considered). The distinct lower, middle and upper parts of the Curtis Formation have characteristics unique to each of them, and therefore will be discussed separately.

Lateral variation is the most prominent in the lower heterolithic part of the Curtis Formation. In this interval, the features of interest with regards to reservoir rock units are the channelized conglomeratic sandstones. The sandstones are interbedded with lenticular-bedded mudstones which are considered of low permeability (non-reservoir). The conglomeratic sandstones are also interfingering with fine sandstone bodies interpreted as tidal bars, meaning they are elongated, potentially extending 1,2 km and more, and ~100m wide at their thickest part. The complete pinchouts evident around Log 7 (Figure 36C) is the most important observation in FA2, as this type of small-scale thickness variation would not be evident when correlating wells, making such inter-well scale studies especially valuable.

The sandstone bodies of FA2 show potentially good reservoir properties prior to diagenesis, especially the cross-bedded units of Facies H, as they have high minus-cement (Paxton et al., 2002) porosity and are laterally extensive. At the opposite end are channelized Facies I bodies, which are rare, thin, and have more frequent mud interbeds. Typical to the facies association, the cement is poikilotopic calcite, making up 26-35 % of the samples. As it is evident from the lack of mechanical fracturing, the poikilotopic calcite cement formed during early diagenesis, effectively preventing such sandstones from becoming prospective reservoir candidates.

The siltstones and mudstones of the lowermost Curtis Formation are currently regarded as the regional seal of the Entrada Sandstone reservoir (Monn, 2006). Breaching of the seal and migration of both petroleum and CO₂ through the Curtis Formation have been demonstrated in study areas located towards Moab, exhibited today as petroleum staining and bleaching of the sands (Dockrill and Shipton, 2010). These migration zones are commonly associated with faulting in the area. It must be noted that towards southeast, the stratigraphy of the Curtis Formation becomes considerably different from the northern San Rafael Swell.

In the western part of this study area, FA2 sandstones locally overlie the Entrada Formation. Samples of these sandstones currently show little to no porosity, as they are completely
cemented by carbonates. They could serve as hydrocarbon migration pathways from the underlying sandstones, however due to the aforementioned early cementation of the deposits, this scenario is considered unlikely. This is supported by the lack of evidence for such migration in the study area, but it nevertheless should at least be taken into consideration in further studies. In conclusion, the sealing quality of the heterolithic lowermost Curtis Formation remains a matter of discussion, although apparently it is adequate for the Entrada Sandstone to be a proven hydrocarbon play today.

The middle part of the Curtis Formation comprises relatively homogeneous, regionally extensive sandstones of FA4 which are roughly 20 m thick in the study area. The succession is interpreted to have been deposited in an environment where tide and wave energy was at its highest. Even though the sandstones are fairly homogeneous and laterally extensive, vertical permeability could be affected by frequent mud draping between the horizontal beds typical to the facies. Good interconnectivity has also been described in other wave-dominated deposits, e.g. Ainsworth (2005) who contrasted shoreface deposits with channelized fluvial deposits, the former being similar in heterogeneity to FA4, and the latter being comparable to the FA1-2-3 package.

Primary porosity of FA4 is considered lesser when compared to the pebbly sandstones of FA2 (cement makes up ~15-25% of the representative samples). It must be noted that the amount of early calcite cement by volume is the lowest in sediment belonging to this interval and gradually increases upwards towards the upper portion of the succession. The least amount of calcite cement most likely led to a higher degree of mechanical compaction and the biggest quartz overgrowths of all the facies, but prior to chemical compaction the permeability and porosity of these sandstones was most likely high given the dominant fine grain size and good sorting.

Investigating the uppermost Curtis and Summerville formations has limitations which are related to the quality of exposures in this particular study area. Implementation of this study in field scale models could be problematic due to partial erosion of the fining-upwards succession which would be regarded as the seal. Based on the data that are available, the conformable transition also does not seem to appear at a constant stratigraphic level; therefore this sealing interval is most likely more complex than a simple laterally extensive horizon. These uncertainties prevent from giving a definitive answer about the sealing properties of the succession without further investigations.
5. Discussion

As it becomes evident at a microscopic scale, diagenetic processes have completely destroyed porosity by calcite cementation during early diagenesis and by quartz overgrowths during late diagenesis in some parts of the succession (Bjørlykke and Jahren, 2015). This has left the deposits with little to no porosity and permeability remaining. Even though ooids related to preservation of porosity by (Ehrenberg, 1993) are present in Facies C, chlorite coatings inhibiting quartz overgrowths have not been observed. A link between climate and pore-preserving chlorite coatings was identified by Dowey et al. (2012), who reasoned that the precursor minerals to chlorite coating are formed in coastal, deltaic and fluvial systems which are found in temperate and tropical climates. In the case of the Cook Formation on the Norwegian Continental Shelf, chlorite precursor minerals are postulated to have been introduced into the sandstones by subaerial exposure of bars during low tides, creating a vadose zone, or also by storm action (Kjølstad, 2014). In the case of the Curtis Formation, the arid environment is most likely the right explanation for the lack of chlorite coatings.

Furthermore, the extensive cementation has unfortunately introduced obstacles for sedimentological investigations. Due to the lack of dust rims, quartz overgrowths have concealed the depositional shape of many of the grains in the sands. Therefore, determining original porosity, textural trends and extrapolating them to other reservoir rocks becomes a challenge.

Besides the early diagenetic cementation by calcite, the following quartz cementation of most facies is attributed to the burial history of the studied succession. As it has been demonstrated by the investigation of Permian beds at the rim of the Grand Canyon, maximum burial heating occurred in the Late Cretaceous (Dumitru et al., 1994). The total thickness of the Mesozoic section in southern Utah is 2.5-3.5 km, which is comparable to the postulated burial depths of 2.7-4.5 km for Permian strata (Dumitru et al., 1994). Even though the Curtis Formation was not targeted in burial history studies, this means that it must have been subjected to depths at least several kilometres deep, enough for chemical compaction to take over.

Unfortunately there is little to no consideration of the Curtis Formation in previous research regarding its reservoir quality, potentially due to the fact that its present-day characteristics are less favourable than of the underlying Entrada Sandstone. However, it is considered as a reservoir analogue in ongoing research (Swindell, 2015) which shows that even though the succession might not be an excellent reservoir, it is nevertheless as a very interesting and
purposeful study object. The complex architecture and lithology that is observed in this study should serve as a basis for further studies, with the aim to investigate the heterogeneities at a field scale and apply the findings in constructing full-scale reservoir models.
6. Conclusions and closing remarks

In the Stove Gulch, the Curtis Formation consists of three distinct units with contrasting reservoir properties, deposited in different, but closely related marginal marine sedimentary environments which were located in a tectonically active region.

- The lower heterolithic unit was deposited in an offshore to constricted estuarine setting, dominated by strong tidal forces. This resulted in deposition of a succession that consists of predominantly lenticular- and wavy-bedded heterolithic deposits which are locally interbedded with gravelly sandstone bodies up to 10 m thick. The FA2 sandstones show high lateral variations of thickness and limited connectivity between the individual packages.

- The middle homogeneous sandstone unit was deposited in a sub- to inter-tidal depositional environment interpreted as sand flats that were dissected by channels and bars, where tide and wave energy was at its highest. This resulted in deposition of a 15-25 m thick fairly homogeneous sandstone succession; however due to variations of current velocities, frequent mudstone drapings between individual beds occur.

- The upper part of the Curtis Formation consists of a 10-15 m thick fining-upwards succession of upper intertidal siltstones and sandstones which are either poorly exposed or have been completely eroded in some parts of the study area.

- The surfaces recognized at the base of FA2 and at the base of FA4 are both easily identifiable in the study area and surrounding outcrops and can serve as reference horizons in the succession. Identifying the lateral extent of these surfaces by investigating more distant localities would help to evaluate their sequence stratigraphic significance.

- The discoveries of this study regarding the variety facies and their distribution patterns can be extrapolated to other successions of the Curtis Formation; however, it should be done with care due to substantial lateral changes occurring even in the scale of this study. As the distribution of the lowermost part of the succession appears to be linked to the underlying erosive topography, it is possible that it represents a local geological feature. However, similar incisions are likely to be present in other parts of the basin.
In the perspective of reservoir geology, the following conclusions can be made about the Curtis Formation:

- The sedimentary units of the Curtis Formation are below vertical seismic resolution, therefore the observed thickness fluctuations and pinch-outs therefore not likely to be identified in seismic profiles. Consequently, inter-well scale studies of outcrop analogues allow constraining thickness changes for volume estimations and determining the connectivity of such sandstones for fluid flow models.
- The Curtis Formation may serve as an analogue for heterolithic reservoir rocks, and as an example of ancient tidal depositional systems. Diagenetic alterations caused by a complex burial history followed by uplift and weathering makes it challenging to apply directly as a reservoir analogue with respect to porosity and permeability distribution, but the architectural trends are nevertheless applicable.

The aforementioned challenges present opportunities for future research, as the complex depositional environment of the Curtis Formation might reveal more unique features and solutions for other geological problems. Future investigations of the J-3 unconformity should target expanding the same study area by acquiring more Lidar scans, in order to capture a broader image of the J-3 unconformity and how the overlying succession is affected by it. Also, additional imagery would help to constrain the heterolithic FA1-2-3 interval, the high lateral variability of which is one of the most fascinating parts of the studied succession. Such studies could also prove the applicability of the interpreted horizons as datum surfaces for the studied succession.


HICKS, T. C. 2011. Facies Analysis and Reservoir Characterization of Subtidal, Intertidal, and Supratidal Zones of the Mudstone-rich Entrada Sandstone, South-Central Utah. MS, Brigham Young University.


KJØLSTAD, C. 2014. Reservoir quality, diagenesis and depositional environments of Early Jurassic Sandstone reservoirs located in the northern North Sea area. MSc, University of Oslo.


MONN, W. D. 2006. A multidisciplinary approach to reservoir characterization of the coastal Entrada erg-margin gas play, Utah. MS, Brigham Young University.


SLEVELAND, A. R. N. 2016. *The sedimentology and sequence stratigraphy of the Curtis Formation along the eastern San Rafael Swell, Utah.* MSc, University of Oslo.


SWINDELL, T. 2015. A Reservoir Model for Exploration in an Estuarine Embayment: The Curtis Formation of the Western San Rafael Swell, Emery County, Utah. AAPG Search and Discovery [Online], Article #90249.


Appendix A: Sedimentary logs

Abbreviations used in the sedimentary logs:

TCB – trough cross-bedding

IHS – inclined heterolithic stratification

X-strat, XS - cross-stratification

XB – cross-bedding

SCS – swaley cross-stratification

LB – lenticular bedding

WB – wavy bedding

FB – flaser bedding

R – ripple

DMD – double mud drapes

HB – herringbone cross-stratification

M – massive (structureless) sandstone

f.u. – fining upwards

c.u. – coarsening upwards

Sst. – sandstone

**GEOLOGIST:** Algirdas Rinkus

**FORMATION:** Entrada - Curtis

**AGE:** Middle Jurassic (Callovian)

---

W.B.

- P1030529.jpg

- 3D ripple

- Conglomerate mudst+pebbles (P1030528.jpg)

- TCB

- Lenticular sst. w/ ripples in the red sst. lenses

- Base Curtis Formation

- Climbing ripples
Appendix A: Sedimentary logs


GEOLOGIST: Algirdas Rimkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

<table>
<thead>
<tr>
<th>E</th>
<th>CLAY</th>
<th>SILT</th>
<th>Silt Clay</th>
<th>SAND</th>
<th>Bioturbation</th>
<th>Lamination</th>
</tr>
</thead>
</table>

254°
P103041-042
wave ripples on bedding surface

288°
TCB marine sst begins

312°
Beds becoming thinner

328°
Oppositely oriented ripples
P1030535-8
Left - dominant, right - thinner, smaller ripples

FA4

346°
P1030532-4
Plane bedding

F87
Top of hill
Ripple laminated facies
Laminated fine gr. sst w/ mudstone intervals

Beds pinch out laterally
Cleaning upwards succession
Appendix A: Sedimentary logs

GEOLOGIST: Algirdas Rimkus
FORMATION: Entrada - Curtis
AGE: Middle Jurassic (Callovian)

Locality: N 39°20.448 W 110°31.875  Sheet 1 of 3  Date: 26/06/15  Scale: 1:50

Some v. coarse grained and f. gravel clasts
IHS 103_561,562
Massive w/ mud clasts

Sand lens sketch:

Poorly exposed due to scree
Poorly sorted w/ chert&sand pebbles
up to 20 mm. Channelized bedform
Some org. rich layers
Some distinctly green coloured sandstone beds
Non-bleached

Thin (mm scale) evaporite

Bleaching front
Low angle planar

FB, small ripples between mud drapes
Reactivation surfaces
Bidirectional transport

No HB - reworked sand?

FB
Double mud drapes
HB

Mud draping

A lot of current direction variability on bedded surf.
FB
HB

Ripple surface top-bottom, laterally extensive
Thickening and later pinch ing out towards south

Conglomerate with clasts up to 25mm
IHS 35 cm
HB 45°, 225°

Laterally extensive, IHS

WB
LOCALITY: N 39°20.448 W 110°31.875

| E  | LITH |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 
**LOCALITY:** N 39°20.506 W 110°33.136  SHEET 1 OF 4  DATE: 27/06/15  SCALE: 1:50

**GEOLOGIST:** Algirdas Rimkus  
**FORMATION:** Entrada - Curtis  
**AGE:** Middle Jurassic (Callovian)

* Sample AR150627-1

**dunes**  
**no structure inside**  
**downcutting lower boundary**

- Dune
- FB
- FB
- XB  **Organic rich drapes**
- HB  **Channelized bed**  
  **Conglomerate interbedded w/ mudstone - IHS**  
  **Chert pebbles up to 10 mm**  
  **Very small channelized conglomerate beds**  
  **Base Curtis**
Appendix A: Sedimentary logs

**Locality:** N 39° 20.506 W 110° 33.136  Sheet 2 of 4  Date: 27/06/15  Scale: 1:50

<table>
<thead>
<tr>
<th>Lith</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Geologist:** Algirdas Rimkus  
**Formation:** Curtis  
**Age:** Middle Jurassic (Callovian)

- 320°: XS  
- 120°: XB  
- 310°: XS  
- 300°: Dune  
- 30°: Ripples on bedding plane  
- 24°: XS  
- 306°: Low angle cross stratification  
- 124°: Laterally extensive sub-horizontal surface capping the sst. beds  
- TCB sandstone pinching out laterally
Algirdas Rimkus

Locality: N 39°20.506 W 110°33.136

Sheet 3 of 4

Date: 27/06/15

Scale: 1:50

Geologist: Algirdas Rimkus

Formation: Curtis

Age: Middle Jurassic (Callovian)

---

Wave ripples

Wave ripples, very low relief

Wave & current ripples w/ mud drapes

FB

Wave ripples

Low angle planar

Ripples on bedding surface

Low angle planar

WB

Mud draping of ripples

Symmetric ripples - crest oriented WNW-ESE

FB

DMD

Low angle cross-stratification
Appendix A: Sedimentary logs

Locality: N 39°20.506 W 110°33.136
Sheet: 4 of 4
Date: 27/06/15
Scale: 1:50

Geologist: Algirdas Rimkus
Formation: Curtis-Summerville
Age: Middle Jurassic (Callovian)

- Evaporites
- Red mudstone
- Some thin coarser beds in Summerville
- Colour gradually becoming more red
- Transition to Summerville
- Scree covered slope
- Brownish-red
- Ripples
- FB
Algirdas Rimkus


GEOLOGIST: Algirdas Rimkus
FORMATION: Entrada - Curtis
AGE: Middle Jurassic (Callovian)

Ripple measurements
WB
Wave ripples, some preferential direction P103-591,2

Erosive boundary

XB
Mud clasts
No clear upw. fining trend
Individual u.f. crossbeds
Crossbed angle changes a lot laterally

Poorly sorted (more muddy)
XS
Ripple
Mud clasts at cross-bedding
Pebbles up to 10 mm

Earthy facies

GEOLOGIST: Algirdas Rinkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

<table>
<thead>
<tr>
<th>E</th>
<th>LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td>38.0</td>
<td></td>
</tr>
<tr>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td>37.0</td>
<td></td>
</tr>
<tr>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>36.0</td>
<td></td>
</tr>
<tr>
<td>35.5</td>
<td></td>
</tr>
<tr>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td>34.5</td>
<td></td>
</tr>
<tr>
<td>34.0</td>
<td></td>
</tr>
<tr>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td>33.0</td>
<td></td>
</tr>
<tr>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>32.0</td>
<td></td>
</tr>
<tr>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>31.0</td>
<td></td>
</tr>
<tr>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>28.5</td>
<td></td>
</tr>
<tr>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>26.5</td>
<td></td>
</tr>
</tbody>
</table>

C.U.
XS Mud clasts
Ripple lamination
Bidirectional ripples
Ripples on bedding surface

Ripples on bedding surface
Ripples on bedding surface
Fluvial sst. (white) on top of the hill (ex situ)
5m above last log bed.

FB
gradually u.f. sst (increasing mud content).

103-0636

Poorly exposed ripple laminated very fine sst.
Lenticular bedding
3D ripples
Bedding surface ripples in mudstone
IHS, mud clasts along bedding

Dominant direction north
Some opposing direction, not much

Lenticular bedding

Bleaching
Appendix A: Sedimentary logs

**LOCALITY:** N 39° 20.389 W 110° 31.639  SHEET 2 OF 4  DATE: 29/06/15  SCALE: 1:50

**GEOLOGIST:** Algirdas Rimkus
**FORMATION:** Curtis
**AGE:** Middle Jurassic (Callovian)

<table>
<thead>
<tr>
<th>E</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FA4</td>
<td></td>
</tr>
<tr>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>FA3</td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>FA2</td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>FA1</td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>FA2</td>
<td></td>
</tr>
</tbody>
</table>

**Bedding surface ripples**
**Mud clasts**
**WB to FB**

**XS**

**Bedding surface ripples**

**Chert and sst. clasts up to 10mm, on some bedding surfaces**
**XB**

**Poorly sorted**
**Some very coarse sand and gravel fraction**
**XB**

**Mud content increases upwards**
**More finely laminated (more heterolithic - IHS)**

**Pinching out laterally**
**XB**

**LB to WB**

**Ripple**
**Mud clasts, IHS, Ripples on bedding surface**

**Ripples on bedding surface, mud clasts**
Bedding surface ripples

Opposing ripples

Ripples on top of storm bed
SCS - storm bed
P103-0618

FB
P103-0616

XS

Bedding surface ripples
FB/WB
### Appendix A: Sedimentary logs

**Locality:** N 39°20.389 W 110°31.639  
**Sheet:** 4 of 4  
**Date:** 29/06/15  
**Scale:** 1:50

<table>
<thead>
<tr>
<th>E</th>
<th>Lith</th>
<th>Clay</th>
<th>Silt</th>
<th>Mud</th>
<th>Grain</th>
<th>Peper</th>
<th>Oxides</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Geologist:** Algirdas Rimkus  
**Formation:** Curtis  
**Age:** Middle Jurassic (Callovian)

**Top of log**

Dessication cracks and evaporites along bedding surface?

- Sample AR250615-2  
- 103-0620

Bedding surface ripples

- Sample AR250615-1  
- 10 cm
LOCALITY: N 39°20.807 W 110°31.394 SHEET 1 OF 2 DATE: 01/07/15 SCALE: 1:50

GEOLOGIST: Algirdas Rinkus
FORMATION:
AGE:

TCB, channelized
Wavy XS
WB

XB

Whole unit gradually pinching out laterally

Tidal barrier? Very well sorted (clean) sst.
Transport direction unclear; unit sharply cliff forming; apparent direction only

Sample AR010715-1

Horizont. bioturb.
Mud clasts on the bedding surface
WB
Ripple
Ripple
Ripple small ripple

IHS - green mudstone between XB
XB
Facies J: Red dune sst.

Top of Facies K succession
**Appendix A: Sedimentary Logs**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA4</td>
<td>Low angle cross stratification</td>
</tr>
<tr>
<td></td>
<td>Small fault going across section: moving from HW to FW a short section might be lost in the log</td>
</tr>
<tr>
<td></td>
<td>Wavy bedding</td>
</tr>
</tbody>
</table>

**Locality:** N 39°20.807 W 110°31.394  
**Sheet:** 2 of 2  
**Date:** 01/07/15  
**Scale:** 1:50  
**Geologist:** Algirdas Rimkus  
**Formation:**  
**Age:**

<table>
<thead>
<tr>
<th>E</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**  
- CLAY  
- SILT  
- SAG  
- SAND  
- G  
- PER  

**Notes:**
- 338° XII
Algirdas Rimkus

LOCALITY: N 39° 20.743' W 110° 31.128 SHEET 1 OF 4 DATE: 02/07/15 SCALE: 1:50

FORMATION: Entrada - Curtis AGE: Middle Jurassic (Callovian)

GEOLOGIST: Algirdas Rimkus

- FA4: 272° R, XB
- FA3: 324° BSR
- FA2: 270° X, H, IHS, medium gr. sst and mudstone, WB
- FA1: 228° LB
- FA6: Topography of erosion/drowning of dune?

No development, measured one direction 1st and other 2nd:

- Topographic high of Entrada Sst?

Not well exposed below
Appendix A: Sedimentary logs

LOCALITY: N 39°20.743 W 110°31.128  SHEET 4 OF 4  DATE: 02/07/15  SCALE: 1:50

GEOLOGIST: Algirdas Rimkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

Fluvial str on top of the hill (ox situ) on top of the hill
grey mudstone
N 39° 20.677
W 110° 31.191

298° XS
Ripple laminated

46° BSR

FA4
FA5
LOCALITY: N 39°20.562 W 110°32.055 SHEET 1 OF 3 DATE: 02/07/15 SCALE: 1:50

GEOLOGIST: Algirdas Rinkus
FORMATION: Entrada - Curtis
AGE: Middle Jurassic (Callovian)

Pebbles up to 10 mm
XB
IHS Poorly sorted
Appendix A: Sedimentary logs

LOCALITY: N 39°20.562 W 110°32.055 SHEET 2 OF 3 DATE: 02/07/15 SCALE: 1:50

GEOLOGIST: Algirdas Rimkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

<table>
<thead>
<tr>
<th>E</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.5</td>
<td>TCB + Mud clasts</td>
<td>XB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td>Rippled laminated</td>
<td>FB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td></td>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td></td>
<td>LB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>Abundant grazing traces</td>
<td>ISR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.0</td>
<td></td>
<td>ISR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td></td>
<td>ISR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td></td>
<td>ISR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td>Randomly oriented 3D wave ripples</td>
<td>103-0654</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td></td>
<td>103-0653</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td></td>
<td>LB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Poorly sorted ripple laminated
XS
XS

114°
110°
140°
318°
294°
170°
LOCALITY: N 39°20.562 W 110°32.055  SHEET 3 OF 3  DATE: 02/07/15  SCALE: 1:50

GEOLOGIST: Algirdas Rinkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

Hilltop

Ripple laminated

Poorly defined internal structure
Appendix A: Sedimentary logs

LOCALITY: N 39°20.620 W 110°32.456 SHEET 1 OF 3 DATE: 03/07/15 SCALE: 1:50

GEOLOGIST: Algirdas Rimkus
FORMATION: Entrada - Curtis
AGE: Middle Jurassic (Callovian)

<table>
<thead>
<tr>
<th>E</th>
<th>G</th>
<th>CLAY</th>
<th>SILT</th>
<th>SAND</th>
<th>PER</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>90° X8</td>
<td>ripple laminated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>30° X5</td>
<td>mudclasts along cross-stratification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td>244° R</td>
<td>FB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.0</td>
<td>244° R</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>103-0659</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Base Curtis poorly defined - gradual transition?

2 m above a thick dune unit
N 39° 20.595'
W 110° 32.325'
Top of section

Brown laminated sst. - no ripples on bedd. surf.
Gray sst.
Ripple laminated brown sst.

103-0665

Poorly defined structure
Algirdas Rinkus

LOCALITY: N 39°20.573 W 110°32.664  SHEET 1 OF 3  DATE: 03/07/15  SCALE: 1:50

FORMATION: Entrada - Curtis
AGE: Middle Jurassic (Callovian)

E

FA4

12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

294° XB
198° XB

Organic rich draping
WB

Ripples on bedd. surf. show a rough trend towards N
140° XB
DMD

FA1-FA3

242° R
106° XB

26° XS
AR03071S-2
Matrix w/ pebbles up to 10 mm
Poorly sorted
Well sorted
Base Curtis
Appendix A: Sedimentary logs

LOCALITY: N 39° 20.573 W 110° 32.664 SHEET 2 OF 3 DATE: 03/07/15 SCALE: 1:50

GEOLOGIST: Algirdas Rimkus
FORMATION: Curtis
AGE: Middle Jurassic (Callovian)

350° X5
going from large scale TCB to planar

24° X5
Brown ripple laminated sst.

280° XB

248° XB
Gradual transition to Summerville
Brown sst. and mudstone, easily eroded

N 39° 20.446'
W 110° 32.781'

Ripple laminated brown sst.

Laminated brown sst.

Eroded muddy interval

Laminated brown sst.
## Appendix B: Thin section analysis

### Location: Log 3, 12 m up section

**Facies:** Facies D (Trough-Cross Bedded sst.)

**Grain size distribution (n=224):**

<table>
<thead>
<tr>
<th>Silt</th>
<th>Very fine sand</th>
<th>Fine sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.25 %</td>
<td>58.48 %</td>
<td>35.27 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th>Qtz</th>
<th>Mc</th>
<th>Pl</th>
<th>Carb. grain</th>
<th>Cal cement</th>
<th>Por</th>
<th>PFC</th>
<th>Acc/o pq</th>
<th>Iron precip</th>
<th>Glauc. Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.00 %</td>
<td>4.50 %</td>
<td>10.25 %</td>
<td>5.50 %</td>
<td>10.50 %</td>
<td>4.00 %</td>
<td>4.75 %</td>
<td>1.25 %</td>
<td>10.00 %</td>
<td>2.25 %</td>
</tr>
</tbody>
</table>

### Location: Log 4, 7 m

**Facies:** Facies H (Cross-stratified gravelly sandstone)

**Grain size distribution (n=202):**

<table>
<thead>
<tr>
<th>Fine sand</th>
<th>Medium sand</th>
<th>Coarse sand</th>
<th>Very coarse sand</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.48 %</td>
<td>40.10 %</td>
<td>46.53 %</td>
<td>10.40 %</td>
<td>0.50 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th>Qtz</th>
<th>Mc</th>
<th>Pl</th>
<th>Carb. grain</th>
<th>Cal cement</th>
<th>Por</th>
<th>PFC</th>
<th>Acc/o pq</th>
<th>Carb rich RF</th>
<th>Clastic rich RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.25 %</td>
<td>1.00 %</td>
<td>4.25 %</td>
<td>16.75 %</td>
<td>26.50 %</td>
<td>0.25 %</td>
<td>0.50 %</td>
<td>0.50 %</td>
<td>14.25 %</td>
<td>12.75 %</td>
</tr>
</tbody>
</table>
### Location: Log 4, 23.7 m

**Facies:** Facies B (Ripple laminated fine sand)

**Grain size distribution (n=200):**

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>19.00 %</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>70.50 %</td>
</tr>
<tr>
<td>Fine sand</td>
<td>10.50 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qtz</td>
<td>48.50 %</td>
</tr>
<tr>
<td>Mc</td>
<td>3.75 %</td>
</tr>
<tr>
<td>Pl</td>
<td>5.25 %</td>
</tr>
<tr>
<td>Cal cement</td>
<td>18.00 %</td>
</tr>
<tr>
<td>Por</td>
<td>6.50 %</td>
</tr>
<tr>
<td>PFC</td>
<td>4.25 %</td>
</tr>
<tr>
<td>Acc/o pq</td>
<td>0.25 %</td>
</tr>
<tr>
<td>Iron precip. pellets</td>
<td>10.50 %</td>
</tr>
<tr>
<td>Glauc. pellets</td>
<td>2.00 %</td>
</tr>
<tr>
<td>Chl pellets</td>
<td>1.00 %</td>
</tr>
</tbody>
</table>

### Location: Log 5, 42.5 m up section

**Facies:** Facies D (Trough-Cross Bedded sst.)

**Grain size distribution (n=200):**

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>2.00 %</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>27.50 %</td>
</tr>
<tr>
<td>Fine sand</td>
<td>64.50 %</td>
</tr>
<tr>
<td>Medium sand</td>
<td>6.00 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qtz</td>
<td>56.50 %</td>
</tr>
<tr>
<td>Mc</td>
<td>3.25 %</td>
</tr>
<tr>
<td>Pl</td>
<td>5.00 %</td>
</tr>
<tr>
<td>Carb grain Cal. cem</td>
<td>2.50 %</td>
</tr>
<tr>
<td>Por</td>
<td>14.00 %</td>
</tr>
<tr>
<td>PFC</td>
<td>4.00 %</td>
</tr>
<tr>
<td>Acc/o pq</td>
<td>5.75 %</td>
</tr>
<tr>
<td>Iron precip</td>
<td>0.25 %</td>
</tr>
<tr>
<td>Glauc. pellets</td>
<td>5.00 %</td>
</tr>
<tr>
<td>Chl pellets</td>
<td>3.75 %</td>
</tr>
</tbody>
</table>
Appendix B: Thin section analysis

### Location: Log 6, 7.5m

**Facies:** Facies E (Flaser bedded sst.)

**Grain size distribution (n=207):**

<table>
<thead>
<tr>
<th></th>
<th>Silt</th>
<th>Very fine sand</th>
<th>Fine sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.42 %</td>
<td>57.00 %</td>
<td>40.58 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th></th>
<th>Qtz</th>
<th>Mc</th>
<th>Pl</th>
<th>Carb. grain</th>
<th>Cal cement</th>
<th>Por</th>
<th>PFC</th>
<th>Iron precip</th>
<th>Glauc. Pellets</th>
<th>Chl. pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>57.00 %</td>
<td>4.75 %</td>
<td>5.25 %</td>
<td>0.25 %</td>
<td>21.75 %</td>
<td>0.75 %</td>
<td>3.75 %</td>
<td>2.25 %</td>
<td>1.75 %</td>
<td>2.50 %</td>
</tr>
</tbody>
</table>

### Location: Upper Entrada (not logged)

**Facies:** Facies J (Wavy to low angle cross-stratified red sandstone)

**Grain size distribution (n=215):**

<table>
<thead>
<tr>
<th></th>
<th>Silt</th>
<th>Very fine sand</th>
<th>Fine sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.77 %</td>
<td>63.26 %</td>
<td>26.98 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th></th>
<th>Qtz</th>
<th>Mc</th>
<th>Pl</th>
<th>Carb. grain</th>
<th>Cal cement</th>
<th>Por</th>
<th>PFC</th>
<th>Acc/o pq</th>
<th>Iron precip</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>51.50 %</td>
<td>4.75</td>
<td>3.00</td>
<td>0.25 %</td>
<td>17.75 %</td>
<td>2.50 %</td>
<td>1.25</td>
<td>0.50 %</td>
<td>1.25 %</td>
<td>17.25 %</td>
</tr>
<tr>
<td>Location:</td>
<td>Log 7, 13.5m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facies:</td>
<td>Facies C (Horizontal bedded sst.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grain size distribution (n=200)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>Very fine sand</td>
<td>Fine sand</td>
<td>Medium sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50 %</td>
<td>18.00 %</td>
<td>72.50 %</td>
<td>9.00 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Petrographic analysis (n=400):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qtz</td>
<td>Mc</td>
<td>Pl</td>
<td>Ooids</td>
<td>Cal cement</td>
<td>Por</td>
<td>PFC</td>
<td>Acc/o pq</td>
<td>Iron precip</td>
<td>Glauc. Pellets</td>
<td></td>
</tr>
<tr>
<td>57.00 %</td>
<td>5.25 %</td>
<td>2.75 %</td>
<td>11.25 %</td>
<td>18.50 %</td>
<td>0.75 %</td>
<td>1.25 %</td>
<td>0.25 %</td>
<td>1.75 %</td>
<td>1.25 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location:</th>
<th>Log 9, 22.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies:</td>
<td>Facies C (Horizontal bedded sst.)</td>
</tr>
<tr>
<td><strong>Grain size distribution (n=200)</strong></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>0.50 %</td>
<td>32.50 %</td>
</tr>
<tr>
<td><strong>Petrographic analysis (n=400):</strong></td>
<td></td>
</tr>
<tr>
<td>Qtz</td>
<td>Mc</td>
</tr>
<tr>
<td>32.25 %</td>
<td>3.75 %</td>
</tr>
</tbody>
</table>
Appendix B: Thin section analysis

**030715-2**

**Location:** Log 10, 2,4 m

**Facies:** Facies I (Heterolithic gravelly sandstone)

**Grain size distribution (n=203, medium grained matrix only)**

<table>
<thead>
<tr>
<th>Grains</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand</td>
<td>6.90 %</td>
</tr>
<tr>
<td>Medium sand</td>
<td>77.83 %</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>11.82 %</td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>0.49 %</td>
</tr>
<tr>
<td>Gravel</td>
<td>2.96 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=200, only sand matrix):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qtz</td>
<td>46.00 %</td>
</tr>
<tr>
<td>Mc</td>
<td>2.00 %</td>
</tr>
<tr>
<td>Pl</td>
<td>3.00 %</td>
</tr>
<tr>
<td>Carb. grain</td>
<td>6.00 %</td>
</tr>
<tr>
<td>Cal cement</td>
<td>35.00 %</td>
</tr>
<tr>
<td>Mud matrix</td>
<td>8.00 %</td>
</tr>
</tbody>
</table>

**070715-1**

**Location:** Uppermost Entrada (not logged)

**Facies:** Facies J (Wavy to low angle cross-stratified red sandstone)

**Grain size distribution (n=203)**

<table>
<thead>
<tr>
<th>Grains</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>28.00 %</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>63.00 %</td>
</tr>
<tr>
<td>Fine sand</td>
<td>8.00 %</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.50 %</td>
</tr>
</tbody>
</table>

**Petrographic analysis (n=400):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qtz</td>
<td>41.75 %</td>
</tr>
<tr>
<td>Mc</td>
<td>7.75 %</td>
</tr>
<tr>
<td>Pl</td>
<td>4.25 %</td>
</tr>
<tr>
<td>Carb. gr</td>
<td>11.00 %</td>
</tr>
<tr>
<td>Mud matrix</td>
<td>21.75 %</td>
</tr>
<tr>
<td>Por</td>
<td>8.00 %</td>
</tr>
<tr>
<td>Acc/opq</td>
<td>0.75 %</td>
</tr>
<tr>
<td>Iron precip.</td>
<td>4.75 %</td>
</tr>
</tbody>
</table>

144
# Appendix C: List of Facies and Facies Associations

<table>
<thead>
<tr>
<th>Facies</th>
<th>Description</th>
<th>Grain size</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Horizontal laminated sand-silt</td>
<td>Silt to very fine sand</td>
<td>Upper intertidal mud flats</td>
</tr>
<tr>
<td>B</td>
<td>Ripple and horizontal laminated silty sandstone</td>
<td>Very fine sand</td>
<td>Intermediate energy deposition in tidally influenced</td>
</tr>
<tr>
<td>C</td>
<td>Horizontal and low-angle cross-bedded sandstone</td>
<td>Fine sand</td>
<td>Upper flow regime: plane bed. Mud draping during slack water phase</td>
</tr>
<tr>
<td>D</td>
<td>Trough cross-bedded fine sandstone</td>
<td>Very fine to fine sand</td>
<td>Unidirectional tidally modified migration of dunes in channels/inlets</td>
</tr>
<tr>
<td>E</td>
<td>Flaser-bedded sandstone</td>
<td>Very fine sand with mudstone flasers</td>
<td>Subtidal sand bars</td>
</tr>
<tr>
<td>F</td>
<td>Heterolithic mudstone and sandstone, wavy bedded</td>
<td>Alternating mudstone and very fine to fine sandstone beds</td>
<td>Estuarine passive infill</td>
</tr>
<tr>
<td>G</td>
<td>Heterolithic mudstone and sandstone, lenticular bedded</td>
<td>Mudstone with lenses of very fine to fine sand</td>
<td>Offshore low energy deposition. Lithological variations caused by minor tide influence</td>
</tr>
<tr>
<td>H</td>
<td>Cross-stratified gravelly sandstone</td>
<td>Medium and coarse sand with extrabasinal gravel-sized particles</td>
<td>Strong unidirectional component: migration of 3D dunes in a major tidal channel</td>
</tr>
<tr>
<td>Facies Association</td>
<td>Description</td>
<td>Interpretation</td>
<td>Bedding boundaries</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
<td>----------------</td>
<td>--------------------</td>
</tr>
<tr>
<td><strong>FA1: Facies F, G</strong></td>
<td>Lenticular and wavy bedded heterolithic material, laterally constricted to paleotopographic lows</td>
<td>Subtidal shelf deposits</td>
<td>Onlapping the J-3 unconformity</td>
</tr>
<tr>
<td><strong>FA2: Facies E, F, H, I</strong></td>
<td>Channelized pebbly medium gr. Sandstones and elongated fine grained sandstones bodies</td>
<td>Subtidal channel infill: gravelly dunes and sand bars</td>
<td>Incising into the underlying FA1</td>
</tr>
<tr>
<td><strong>FA3: Facies E, F</strong></td>
<td>Wavy and flaser bedded sandstones</td>
<td>Estuarine passive infill</td>
<td>Draping FA2</td>
</tr>
<tr>
<td>Facies</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA4: Facies C, D, E</td>
<td>Horizontal, low angle cross-beded and through cross-beded fine sandstones</td>
<td>Subtidal to intertidal sand flats</td>
<td>Conformably overlying FA3, abrupt transition</td>
</tr>
<tr>
<td>FA5: Facies A, B</td>
<td>Silty sandstone and siltstone, horizontally stratified and ripple laminated</td>
<td>Mixed and mud flats</td>
<td>Gradual conformable transition from FA4</td>
</tr>
<tr>
<td>FA6: Facies J, K</td>
<td>Horizontally interbedded red sandstone and dark brown mudstone intervals</td>
<td>Upper intertidal to supratidal erg-margin deposits (Entrada Sandstone)</td>
<td>Cut erosionally at the top by the J-3 unconformity</td>
</tr>
<tr>
<td>FA7: Facies L</td>
<td>Dark brown mudstone interbedded with thin red sandstone lenses</td>
<td>Supratidal mudflat (Summerville Formation)</td>
<td>Gradual conformable transition from FA5</td>
</tr>
</tbody>
</table>