ABSTRACT

Detailed core analysis from seven wells with cores cut within the overall carbonate succession that makes up the Bluell and Sherwood Members of the Mission Canyon Formation located in Renville County, North Dakota, resulted in the identification of eleven depositional facies. These facies that reflect a range in depositional conditions from inner to back ramp, that is shallow fair-weather to uppermost intertidal and supratidal conditions. Systematic core analysis using a highly detailed digital template for recording of sedimentological details enabled not only a high degree of uniformity in facies identification but also detailed vertical facies stacking patterns for each well. The facies stacking patterns revealed that these shallow marine to marginal marine successions consists of thin (decimetre-scale) beds with rapid upward shifts in facies, reflecting the very shallow sea-level at the time of deposition. While this work enabled detailed facies mapping to be undertaken the seemingly random porosity distribution represented a major challenge in oil exploration and production within the eastern Flank of the Williston Basin.

The core analysis revealed that to preserve porosity (and thus permeability) was dependent on a combination of depositional, intergranular porosity and secondary dissolution, moldic and vuggy porosity, only observed within the pack- to grainstone facies reflecting shallow marine conditions. Systematic core analysis furthermore established a relationship between sediment grain-size, sorting (maturity), development of moldic to vuggy porosity and degree of cementation. Whereby the former is related to location within the depositional processes and the subtle variations within the depositional system. The later to the combination of higher interparticle porosity that together with the secondary porosity, result in that cementation is not sufficient to block all pore-connections. Thereby creating the active reservoir intervals observed in core and from production. However, the limited thickness of these beds (some 40-60 cm) also explains the challenge in prediction location of active reservoir as experienced in the past.

Careful log to core correlation was also undertaken and revealed that for most parts that conventional logs does not have the necessary resolution to predict locations of "active" reservoir as observed from the core analysis. Consequently, there has been established a relationship between facies types and facies distribution and the development of porosity and hence, active reservoir enabling logical prediction of more producing reservoir within the Mission Canyon Formation along the eastern Flank of the Williston Basin

This illustrates the importance of recognition from detailed description of facies, related to the depositional processes and the subtle variations in the depositional system that enables a better understanding and that allows to logically predict the location of best possible and well- sorted packstone and grainstone reservoirs in time and space. This becomes increasingly more significant for finding new potential targets in rapidly depleting and heterogeneous reservoirs, such as the Mission Canyon Formation.

ACKNOWLEDGEMENT

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CHAPTER 1   INTRODUCTION

The sedimentary thickness of observed Phanerozoic strata within the Williston Basin, a so called intracratonic sag basin that developed on the North American craton, are more than 4900 meters thick. The Williston Basin history of producing commercial oil have been ongoing since the early 1950s and its history has undergone three major oil production cycles.

The first commercial oil production and initial oil cycle was established with the 1951 discovery in North Dakota, where following development was focused on the Mississippian Madison Group. The development within the Madison Group have played an important role for many discoveries over the past 60 years and has been the biggest producer of cumulative oil up until 2008 (NDOGD, 2017). Today the Madison Group are the second biggest producer in North Dakota, next to the Bakken Formation with a total cumulative oil production of nearly 953 million barrels of oil (MMBO) produced, which stands for more than 28 % of the cumulative oil production in the region (NDOGD, 2015). The Madison Group are part of a broad carbonate shelf, with accumulation of predominantly repetitive carbonate and evaporite strata and is subdivided into three formations, the basal Lodgepole, the middle Mission Canyon and the uppermost Charles. Where the latter two, are the youngest carbonate oil and gas reservoirs, with production predominately from shallow marine carbonates, since the early 1950s (Gaswirth et al., 2010).

The U.S Geological Survey assessment of undiscovered oil and gas resources in the Mission Canyon and Charles Formation from 2008, estimate the undiscovered resources for conventional reservoirs at median values of 45 MMBO. Specifying that the undiscovered hydrocarbon potential still exists within the local distribution of hydrocarbon-bearing facies and supports the likelihood for unknown reserves (Gaswirth et al., 2010).

However, one of the challenges for oil production within the Mission Canyon Formation is that most of the original porosity and more so the permeability has been cemented throughout most of the particular units that define the formation. Although, few beds have undergone several diagenetic changes, where later diagenetic modifications include leaching of cement and carbonate dissolution, which have introduced improved secondary solution-enhanced porosity. This secondary porosity is the reason for most of the observed porosity in the Mission Canyon reservoir beds (Lindsay, 1988).

However, these thin beds are often complex and inhomogeneous that consists of fast alternating and vertical facies changes and irregular distribution of diagenetic cementation and secondary solution-enhanced porosity.

1 INTRODUCTION

This type of interaction between facies, porosity and cementation, drastically alters the porosity and permeability, which creates complex reservoirs and large uncertainty for the porosity and permeability within. One important conclusion within previous studies is that too broad facies interpretations that cover a large area, makes it difficult to predict this alternating porosity and permeability in a correct way. Since the porosity and permeability within these thin beds in the Mission Canyon Formation are essentially determined in part by the depositional facies, which represents a continuum of sediments deposited in a depositional system that changes rapidly (Lindsay, 1988). More modern studies have also done further and more detailed descriptions of facies and their distribution within similar beds in the Mission Canyon Formation in the Steelman-Bienfait area of southeastern Saskatchewan, Canada. They state the importance of recognition from detailed description of facies and depositional trends becomes increasingly more significant for finding new potential targets in rapidly depleting and heterogeneous reservoirs such as the Mission Canyon Formation (Qing and Nimegeers, 2008). Consequently, the key for further success and additional exploration will likely be within the detailed recognition and understanding of the relationship between facies distribution, their porosity development and diagenetic alterations.

This is one of the major challenges in the Mission Canyon Formation, due to the seemingly random porosity within these complex thin beds with irregular distribution of diagenetic cementation and porosity. The challenges with reservoir distribution and porosity development are widely known within these particular beds.

Therefore, the main objective for this thesis is to enable a better understanding of the depositional system, especially to understand the sediment distribution and the control of porosity as a consequence of the depositional system and create a logical understanding of observed porosity seen from cores. By using a more detailed and systematic method of facies description and interpretation on the relatively narrow stratigraphic, but still main producing, Bluell and Sherwood units in The Mission Canyon Formation within Renville County, North Dakota. Because a classic oil field in this region produces only 15-20 % of the original-oil-in-place and the goal is to develop a better understanding of the apparently random porosity, and find a relationship so that a logical prediction of the observed porosity in cores can be made from recognizing various producing and non-producing reservoirs, tied to detailed facies interpretation, to see if a relationship actually can be observed between porosity and identified facies.

CHAPTER 2   GEOLOGICAL SETTING

The Williston Basin is an intracratonic sag basin that developed on the North American craton during the Ordovician around 495 million years ago, and has undergone episodic subsidence through the Phanerozoic (Gerhard et al., 1990). The basin is approximately 345,000 km^2 that covers North Dakota, north-western South Dakota, eastern Montana and southern parts of Saskatchewan and Manitoba in Canada (Fig. 2.1). Compared to many basins worldwide, the Williston Basin is structurally, a very simple basin. Roughly circular, deepest in its centre, and becomes shallower and thinner towards the margins.
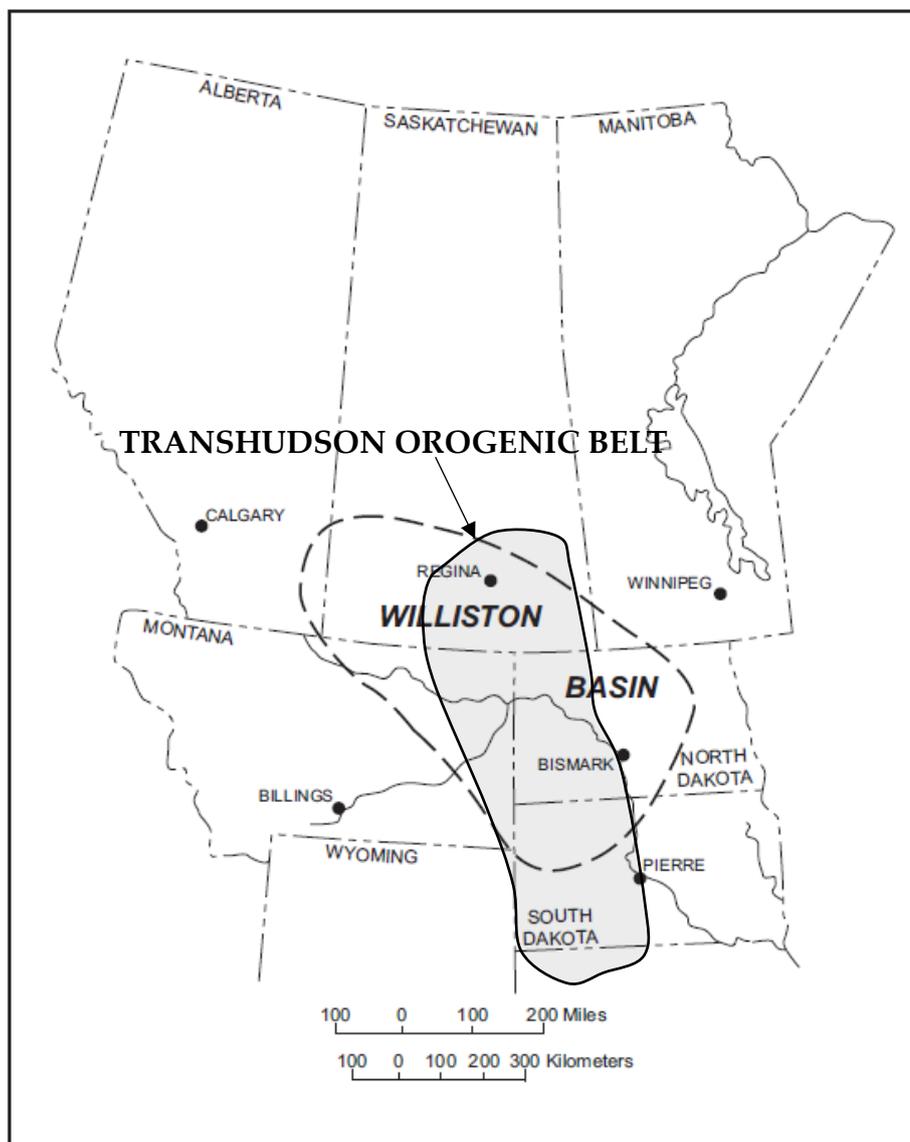
Figure 2.1. Map showing extent of the Williston Basin; the shaded area is the Trans-Hudson orogenic belt. Modified from (Pitman et al., 2001).

The Williston Basin is underlain by three Archean cratons, the Churchill and Wyoming craton in the west and the Superior craton in the east (Fig. 2.2). The Churchill and Wyoming craton, underlying eastern Montana, and possibly extending into western North Dakota include gneissic, or banded to lenticular feldspar and quartz-rich rocks that were emplaced between 2.75-2.6 billion years ago (NDGS, 2017). The Superior craton underlies the eastern half of North Dakota and is a part of the North American Canadian Shield. The craton is Archean in age, consists mainly of granites and greenstones, and are approximately the same age as rocks from the Churchill and Wyoming craton (NDGS, 2017).
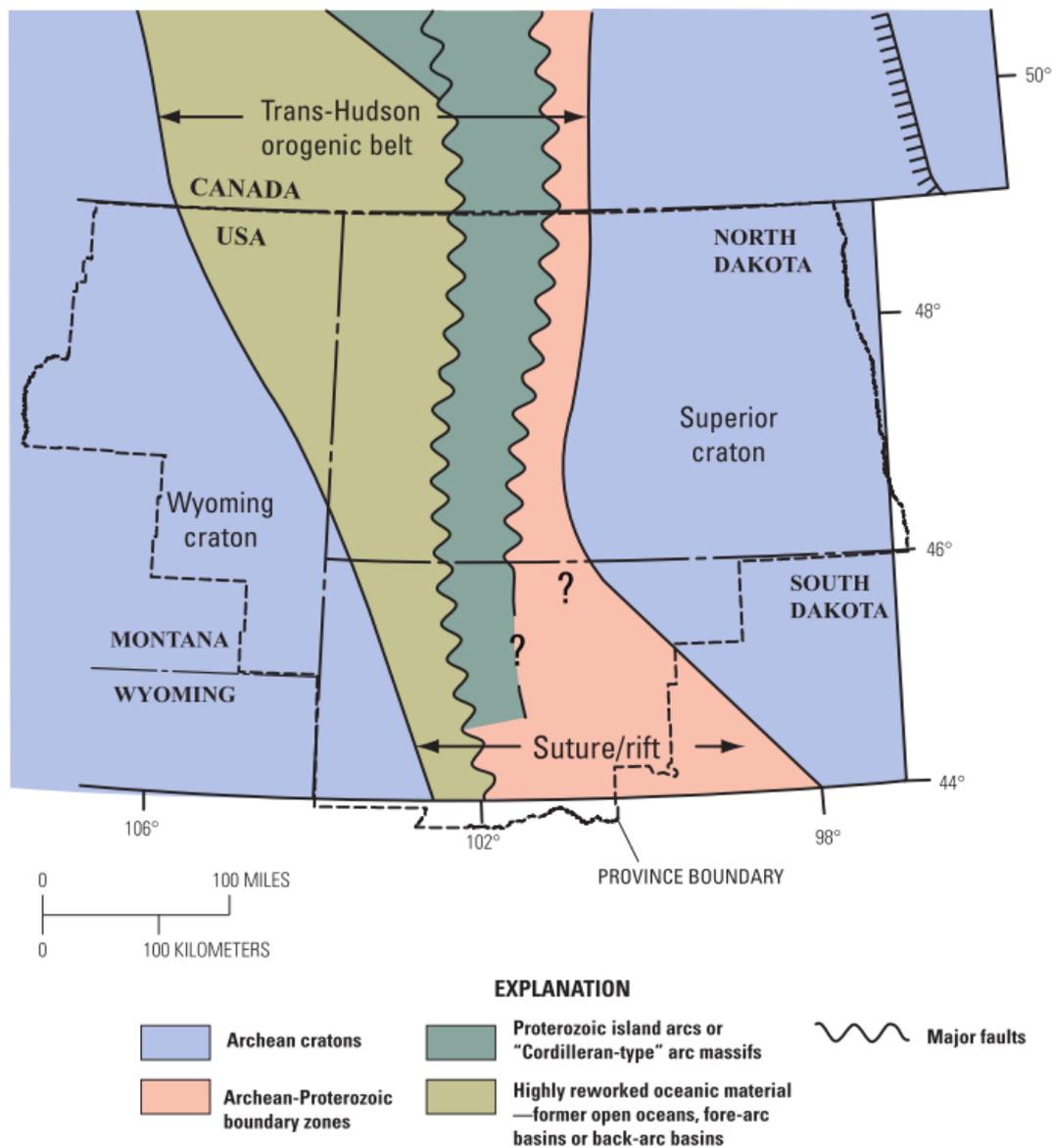

Figure 2.2. Precambrian structural and tectonic configuration of the Williston Basin. Shows the configuration of the Trans-Hudson orogenic belt and Archean cratons. The U.S province boundary (red line) for Williston Basin is shown for scale. From (Nelson et al., 1993) and modified from (Anna et al., 2010).

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Between these two cratons lies the Trans-Hudson orogenic belt, which represents a continent-to- continent suture zone that's located between the west and east cratons (Gerhard et al., 1990). It is composed of oceanic material from an early rifting event within the Superior craton. A later collision between the Superior craton and the Churchill and Wyoming craton provided volcanic island-arc material to the orogen. The internal structural geology by the three Archean cratons are complex, as are the structural relationships between them (NDGS, 2017).

Two major Archean shear systems, the Brockton-Froid-Frombert and the Transcontinental Arch (Fig. 2.3) formed a depressed block between these two systems, which formed the basin and initiated accumulation of sediments during the Late Ordovician. Structural features, including major folds, faults and fractures in the basin are related to regional wrench-fault tectonism and movement along the two major shear systems (Gerhard et al., 1990).
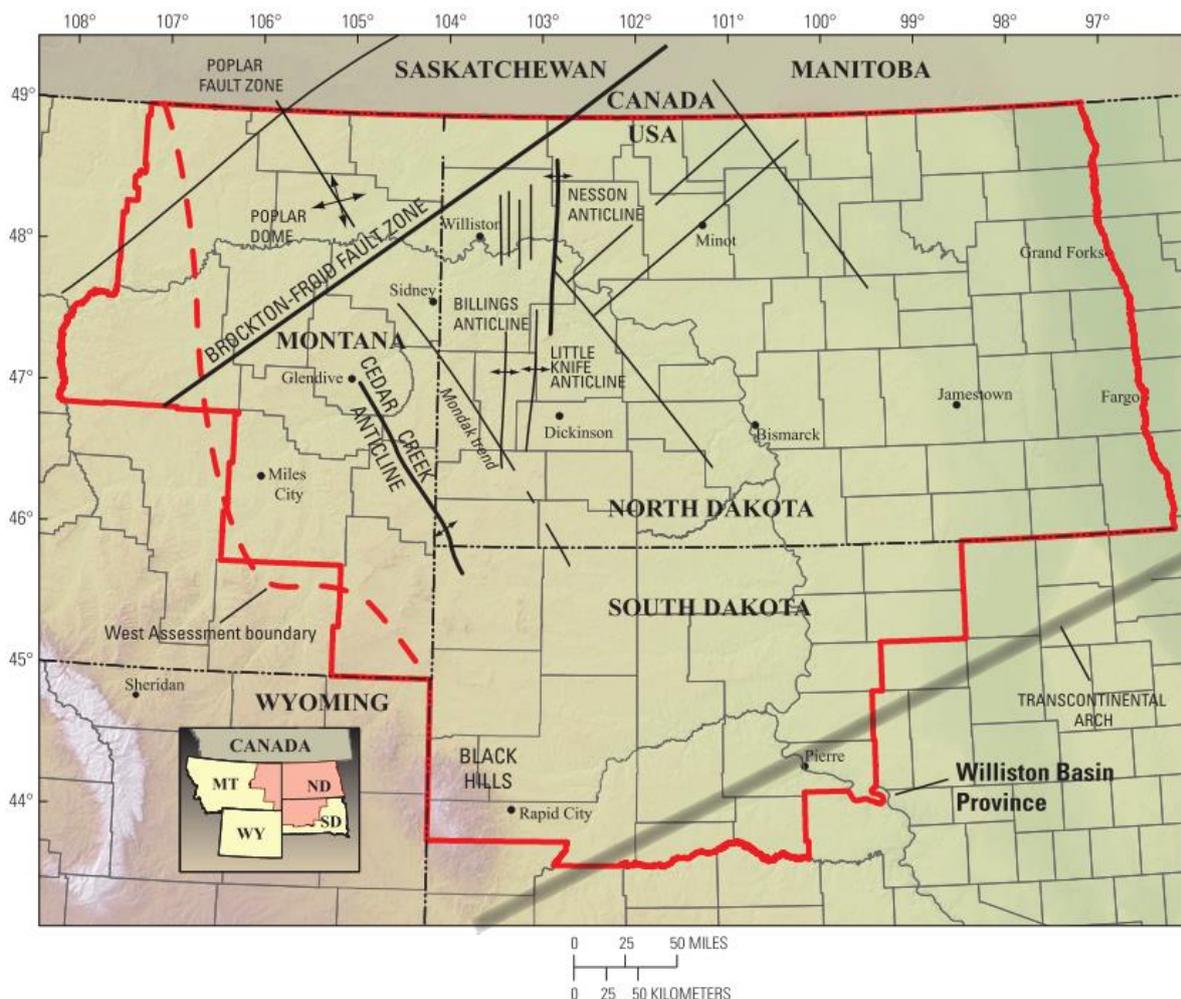

Figure 2.3 Major structural features of the Williston Basin Province in the U.S (red line). From (Anna et al., 2010).

2 GEOLOGICAL SETTING

Stratigraphy, Williston Basin

The sedimentary thickness of Phanerozoic strata within Williston Basin is more than 4900 meters thick in the basin centre and occurred during every geologic period and contains an unusually complete rock record with rocks from each period preserved (Fig. 2.4). However, erosional events dominated a significant amount of the Phanerozoic strata (Anna et al., 2010). A summary of the Williston Basin stratigraphy can be described with initial sedimentation occurring over a surface of weathered Precambrian basement, followed by carbonate deposition in the Palaeozoic, characterized by repetitive events of marine transgressions that filled the basin, followed by marine regressions that drained the basin, with repeated accumulation varying from carbonates and siliciclastic that were interrupted by major erosional events (NDGS, 2017). During Palaeozoic sedimentation, evaporites are particularly abundant in association with carbonate rocks, indicating low basin-subsidence rates, restricted circulation, and low-to mid- latitude topography (Gerhard et al., 1990). The Palaeozoic period in the Williston Basin is the most significant for the petroleum industry, since it contains nearly all the region's oil and gas resources (Gaswirth et al., 2010).

During Mesozoic and Cenozoic, the accumulation of sediments within many formations was predominantly siliciclastic. Uplift and progradation during Post Cretaceous, terminated marine deposition in the basin. The last marine rocks are of Paleocene age and all succeeding stratigraphic units are of terrestrial source, including the youngest carbonates (Gerhard et al., 1990).

Figure 2.4. General stratigraphy for Williston Basin. The Paleozoic stratigraphic section (541-252 ma) contains all the oil and gas resources in the basin. The red box is the stratigraphic section (Madison Group) that contains the Mission Canyon Formation, which is the particular zone of interest for this thesis.

2 GEOLOGICAL SETTING

Major Sequences, Williston basin

The Phanerozoic strata in the Williston Basin can be divided into six major stratigraphic sequences, separately bounded by major unconformities, which in an ascending order, are the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas (Fig. 2.4). These major sequences consist of first-order and second-order cycles in the Williston Basin and are possibly the consequence of eustatic changes in sea level. However, third-order and fourth-order cycles in the basin may be the result a combination of tectonic activity and eustacy. Since during the Phanerozoic the water depths in the basin were relatively shallow, which means that a small change in water depth caused substantial changes in sedimentation and depositional environment (Anna et al., 2010).

Sauk Sequence (Cambrian- Early Ordovician)

The first major sequence Sauk (Fig. 2.4), contains the Upper Cambrian Deadwood Formation and it represents the early stages of a major first-order transgression over the Precambrian surface in Williston Basin. At the end of Sauk sequence, the basin started to subside as a result of strike-slip movement on major northeast–southwest trending faults (Gerhard et al., 1990). This resulted in subtle structural features, such as block and linear horsts and grabens. This began changing the sedimentation patterns on a broad scale in the basin. The sediment source for the Deadwood Formation was from weathered and eroded Precambrian rocks from highlands to the east or from the Transcontinental arch to the southeast (Gerhard et al., 1990).

The Deadwood Formation can be divided into several members because there are several minor transgressions and regressions within the formation. At the end of the Deadwood Formation, a major unconformity developed, resulting in the truncation of most of the upper Deadwood strata as well as the lower parts of the strata near the basin margins, which marks the end of Sauk deposition. Depositional environments of the Deadwood include shallow marine, coastal plain, and rare alluvial plain, with successions of sandy carbonate, mudstone, siltstone, and quartz arenites (NDGS, 2017).

Tippecanoe Sequence (Ordovician-Silurian)

The Tippecanoe sequence (Fig. 2.4) marks the start of the second transgression-regression cycle in the Williston basin, which also marks the beginning of the Ordovician sedimentation. Depositional shapes specify that as the basin started to form during this time, a seaway connection to the Cordilleran sea to the southwest existed (Gerhard et al., 1990).

2 GEOLOGICAL SETTING

The Winnipeg Formation unconformable overlies the Deadwood Formation except in the eastern part of the basin where it lies directly on Precambrian basement. During the early transgression, the Winnipeg Group was deposited as a succession of shallow marine sandstone, shale, and shaly carbonate (Anna et al., 2010).

The Red River Formation conformably overlies the Winnipeg Formation. This is the first and initial formation deposited during several events of shallow marine carbonate and anhydrite and salt deposition. Each event consists of shelf limestone overlain by laminated dolomite and anhydrite (Anna et al., 2010). Conformably overlying the Red River Formation are the Stony Mountain and Stonewall Formations and the Interlake Group.

 Third-and fourth-order cycles in these strata continue the pattern of repetitive events of shallow marine carbonate and anhydrite and salt sedimentation. That consists of subtidal limestone, intertidal dolomite, dolomitic limestone, and peritidal or supratidal anhydrite or salt deposits (Anna et al., 2010). After the deposition of Stony Mountain and Stonewall Formation there was a short regression, followed by a short transgression in the Silurian period that later created the Interlake Group, which is also made up by several repetitive events. The Tippecanoe sequence was ended by a major regression near the end of the Silurian, where erosion removed parts of the Interlake Group, together with the Stony Mountain, Stonewall and Red River Formations, particularly near the basin edges (Anna et al., 2010).

Kaskaskia Sequence (Devonian-Mississippian)

The Kaskaskia major sequence begins with a second-order transgressive event in the Early Devonian and ends as a major regression at the end of the Mississippian. During this time, the uplift of the Transcontinental arch created a major change in basin, from a largely circular basin in north-western North Dakota with a south-western marine connection to the Cordilleran sea, to a northwest–southeast trending elongated shelf basin. This basin extended from north-western North Dakota to the northern part of Alberta, Canada, with a marine connection to the Arctic Ocean. The Williston Basin became the south-eastern corner of the newly formed Devonian Elk Point Basin (fig. 2.5).

In the newly formed basin, numerous events of restricted marine settings were followed by episodes of normal circulation united with sea level change, giving rise to a variety of lithological successions of limestone, dolomite and evaporites. There are three second-order cycles in the Kaskaskia major sequence. First cycle started initially with a transgression, which deposited the Ashern and Winnipegosis Formations.
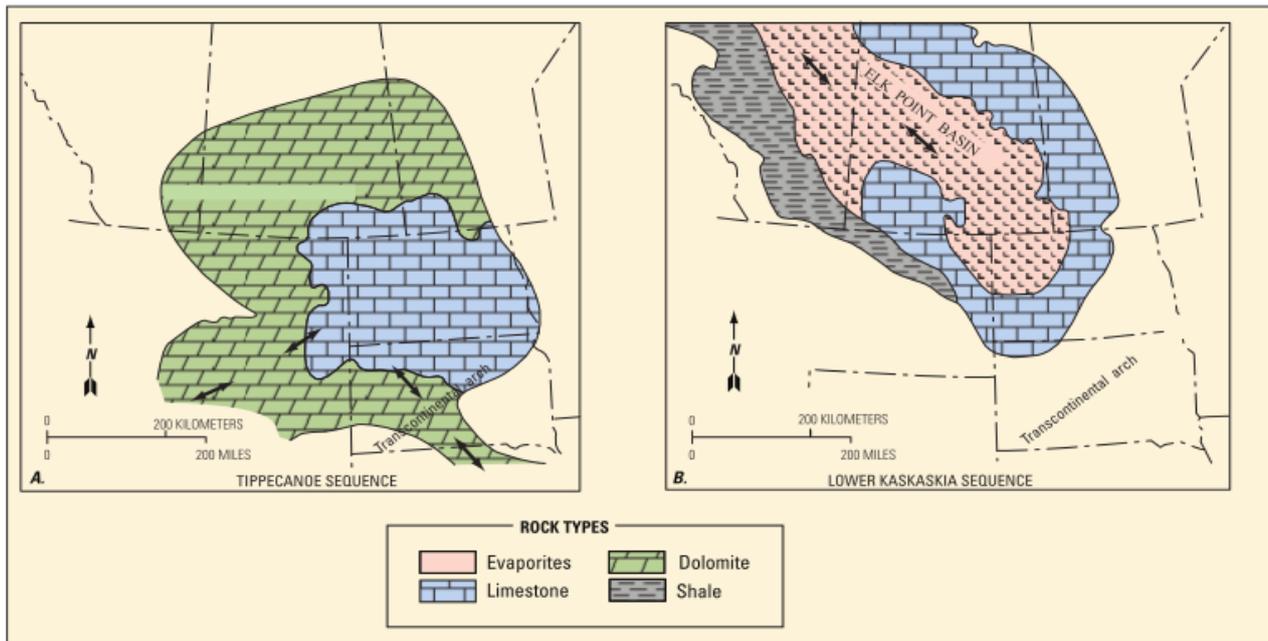
*Figure 2.5. Showing the major change in the Williston Basin during the Tippecanoe and lower Kaskaskia sequences. **A.** Ordovician to Late Devonian, showing south-west and south-east seaway connections **B.** Late Devonian to Early Mississippian, showing a north-west seaway connection through the Elk Point Basin in Canada. Arrows indicate the water flow. During the Middle Mississippian period, the Williston Basin changed to its original shape, which can be seen in figure 2.6.*

Afterwards due to a major restriction at the margin of the Elk Point Basin a regression followed and the Prairie Formation was deposited. During a second transgression, normal marine circulation was recreated in the basin and the deposition of the Dawson Bay Formation took form. As sea level started to move basin ward due to regression the Souris River, Duperow, Birdbear, and Three Forks Formations were deposited. The third and major transgression during the Kaskaskia in the Late Devonian, the deposition of the Bakken Formation occurred. The Bakken Formation consists of organic-rich marine shale and it characterize the first major input of siliciclastic material in the Williston Basin since the deposition of the Deadwood and Winnipeg Formations during the Cambrian period (Fig. 2.4).

As the sea level retreated, the major input of siliciclastic material was reduced and the Mississippian Lodgepole Formation was deposited, consisting more of limestone, which was deposited in subtidal conditions. Early Mississippian, during middle Lodgepole Formation period, there was a shift in sediment source from the northwest–southeast Elk Point Basin back to a circular basin configuration, with the depocenter re-established in north-western North Dakota. At that time, the sedimentation and structural adjustment in central Montana created a narrow marine connection, the Montana Trough to the Cordilleran Sea (Fig. 2.6) (Gerhard et al., 1990).
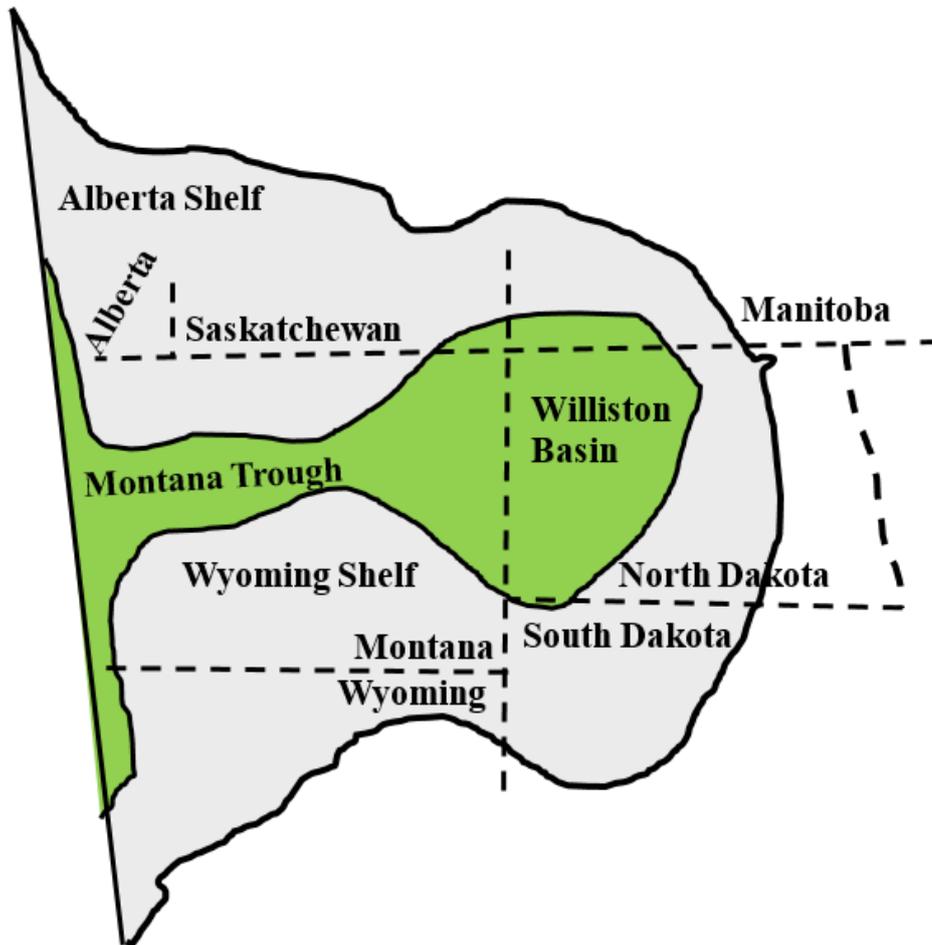
Figure 2.6. Seaway connection of the Williston Basin to the ocean during Upper Kaskaskia deposition. From (Gerhard et al., 1982) Modified from (NDGS, 2017).

During the uppermost deposition of the Lodgepole Formation, there was events of alternating transgressions and regressions, resulting in an environment of open marine and intertidal limestones and peritidal and sabkha anhydrite and salt deposits (Gerhard et al., 1990). This period is connected to the upper part of the Madison Group, which includes the Mission Canyon and Charles Formation. A major regression marks the top of the Mississippian Big Snowy Group, consisting of the Otter and Kibbey Formation, which overlies the Madison, and is the uppermost formation of the Kaskaskia sequence. This major regression marked the end of the last major Palaeozoic marine sedimentation in the Williston Basin (Gerhard et al., 1990). The Kaskaskia sequence stratigraphy consists of different depositional environments from subtidal, intertidal and supratidal with shifting lithologies of dolomite, limestone, and evaporites (Anna et al., 2010).

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Absaroka Sequence (Pennsylvanian-Triassic)

The Absaroka major sequence characterizes the upper part of a first order regression, and includes several secondary transgressive and regressive events in a relatively low sea level environment. The initial second-order transgression was from the southwest, synchronised with uplift from areas to the east, west, and south in the Williston Basin, which became major sources of clastic sediment deposition into the basin (Anna et al., 2010). The strata within Absaroka sequence includes the Pennsylvanian Tyler Formation, which consists of interbedded sandstone, siltstone, shale, and limestone (Anna et al., 2010). The overlying Minnelusa Formation consists of sediments from the Ancestral Rocky Mountain orogenic belt and the transcontinental arch. The sediments were deposited in alluvial plains and shelf environments from prograding delta systems and in barrier island environments (Anna et al., 2010). With continued regression during the Minnelusa Formation period, the sedimentary processes were influenced partly of restrictive conditions by the deposition of thin platform carbonates and prograding sands over shallow marine sediments, and thick accumulations of salt in the centre of the basin, as well as by subaerial exposure of units during the Permian period (Anna et al., 2010). During the Absaroka sequence major unconformities occurs at the end of Pennsylvanian, the Permian and at end of the Triassic period (Gerhard et al., 1990). The outcome from eroding substantial parts of pre-Triassic strata created many stratigraphic traps in the basin, especially near the north and eastern flanks of the Williston Basin, which are the reason for most of the production at the eastern flank in U.S and in Canada.

Zuni Sequence (Jurassic-Tertiary)

The Zuni major sequence characterises the Jurassic and early Tertiary period. The sequence consists of strata, which are similar to the upper part of the Absaroka sequence, with successions of sandstone, siltstone and some carbonates and salt deposits (Anna et al., 2010). The Zuni sequence are separated by major unconformities in the Middle and Upper Jurassic, Lower Cretaceous, and Upper Cretaceous and Tertiary through Paleogene (Anna et al., 2010).

Zuni Sequence deposits mark a shallow marine transgressive event during the Jurassic, where the Lower Jurassic consists of anhydrite and salt at the basin centre and with shale in the direction of the basin flanks, and of carbonate and sandstone at the flanks of the basin (Anna et al., 2010). The top of the Jurassic is marked by marine regression and subaerial exposure, where the end of the Jurassic was a transition from marine subtidal and intertidal environments to continental sandstone and mudstone (Anna et al., 2010).

In the Lower Cretaceous a second and significant transgressive event occurred, and deposition continued in shallow marine conditions throughout most of the sequence (Gerhard et al., 1990). In the Upper Cretaceous, there were four major transgressions and regressions with a depocenter that developed in the south- western part of the Williston Basin. The end of the Zuni was marked by the fourth regression that coincides with the lower and early part of the Paleogene. The last marine sediments in the Williston Basin were deposited during this period in the late Zuni Sequence. Strata in the Zuni sequence have not produced any hydrocarbons, only biogenic gas has been produced in the Upper Cretaceous sandstones and siltstones (Anna et al., 2010).

Tejas Sequence (Tertiary-Quaternary)

The Tejas major sequence represents the final first-order regression in the stratigraphic strata of the Williston Basin (Fig. 2.4), which includes three regional transgression and regression events with strata ranging in age from the mid-Paleocene through the Quaternary period. The strata consist of continental gravel, sandstone, siltstone, mudstone, and low-grade coal (Anna et al., 2010).

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CHAPTER 3   BACKGROUND AND THEORY

The Eastern Flank of Williston Basin, North Dakota

The development on the Mississippian Madison Group (Fig. 3.1) has been the biggest producer of oil in North Dakota for nearly 60 years and still is a steady producer for North Dakota. The Madison Group is a thick sequence with a maximum thickness of 600 meters near the centre of the Williston Basin and thins near the basin margins, generally between 250-500 meters. The Madison Group was part of a broad carbonate shelf, causing accumulation of predominantly repetitive carbonate and evaporite strata and is subdivided into three formations, the basal Lodgepole, the middle Mission Canyon and the uppermost Charles (Table 3.1).

Many of the units within the Madison Group serves as important oil producers and its equivalent strata extend from the Black Hills of western South Dakota to western Montana and eastern Idaho, and from the Canada–United States border to western Colorado and the Grand Canyon of Arizona (Gaswirth et al., 2010).
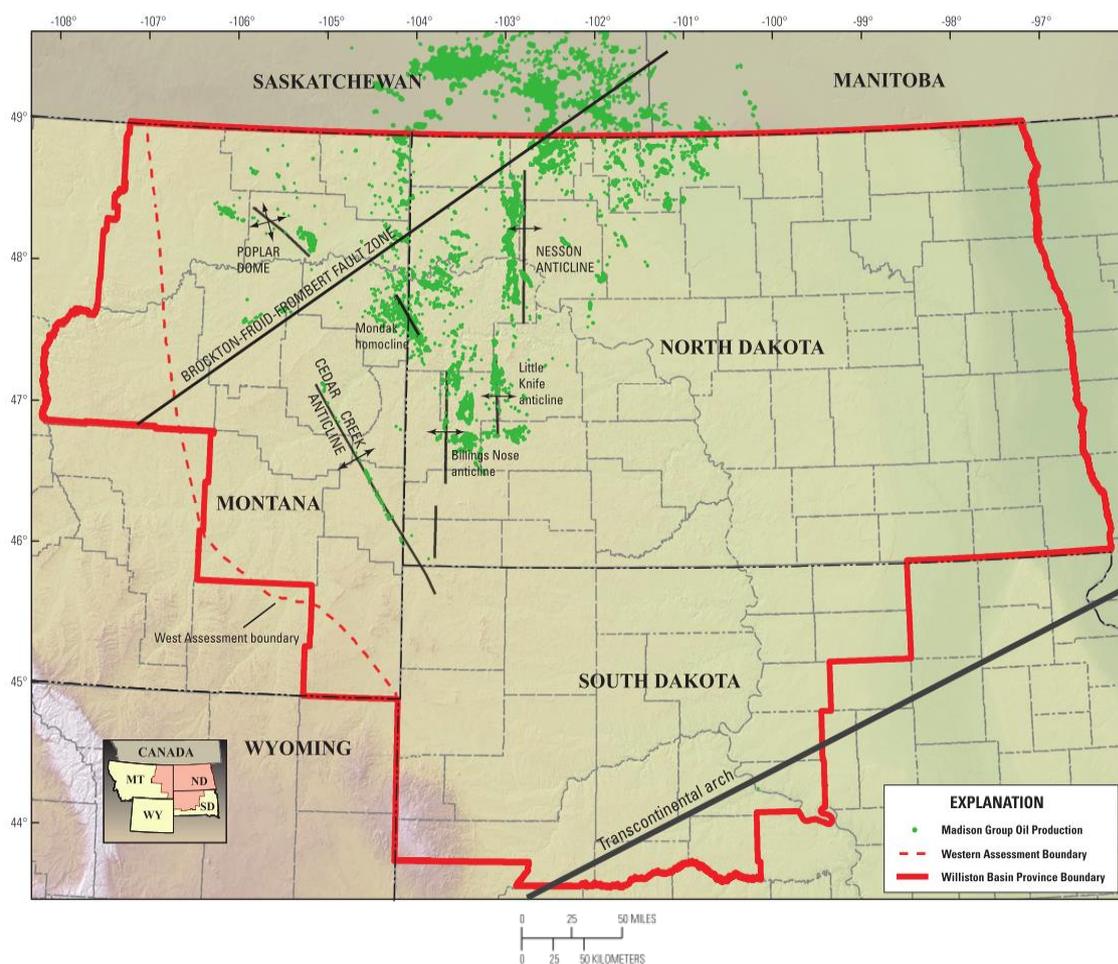

Figure 3.1. Major structures with few important areas associated with oil production for the Madison Group in the Williston Basin. From (Gaswirth et al., 2010).

Table 3.1. Summary of the Madison Group, showing formations, thickness, main lithology and estimated time at the Eastern Flank, Williston Basin.

Group	Formation	Thickness (m)	Main Lithology	Time (ma)
Mississippian Madison Group	Charles	90-150	Anhydrite, lime-mudstone, dolomite & carbonate	347-323
	Mission Canyon	120-215	Anhydrite, dolomite, lime-mudstone & carbonate	
	Lodgepole	150–240	Lime-mudstone, carbonate & silisiclastic mud-sandstone	359-347

Oil in North Dakota was discovered 1951 on the Nesson anticline (Fig 3.1), since then, oil exploration has been nearly continuous in the state (NDGS, 2017). The discovery well was completed in the Silurian Interlake Formation but following development on the anticline was focused on the Mississippian Madison Group (Fig. 2.4) (NDGS, 2017). According to North Dakota Oil and Gas Division (NDOGD, 2015), the annual oil production for North Dakota peaked in 1984 at more than 52 MMBO or nearly 5 MMBO per month (Fig. 3.2). Since the early 1990s the production went down significantly and it leveled off for several years until 1994 (NDOGD, 2017). The decline was temporarily reversed in the late 1990s but it wasn't until 2005 when a third cycle began. Increasing production slightly level of 8-10 MMBO per month towards 2010 and then production significantly increases up to over 35 MMBO per month (NDOGD, 2017).

Today, the Madison Group are listed as the second biggest producer in North Dakota since the first well was drilled 1951, with a total cumulative oil production (available from 2015) of nearly 953 MMBO produced, which stand for more than 28 % of the cumulative oil production with 5606 wells within the Madison Group (NDOGD, 2015). Related to the biggest producer today, The Bakken Formation (Fig. 2.4), which recently went past the Madison Group during the year 2008 and now currently stand for almost 47 % of the total cumulative oil production with more than 1,59 BBO produced with 10930 wells (NDOGD, 2015).
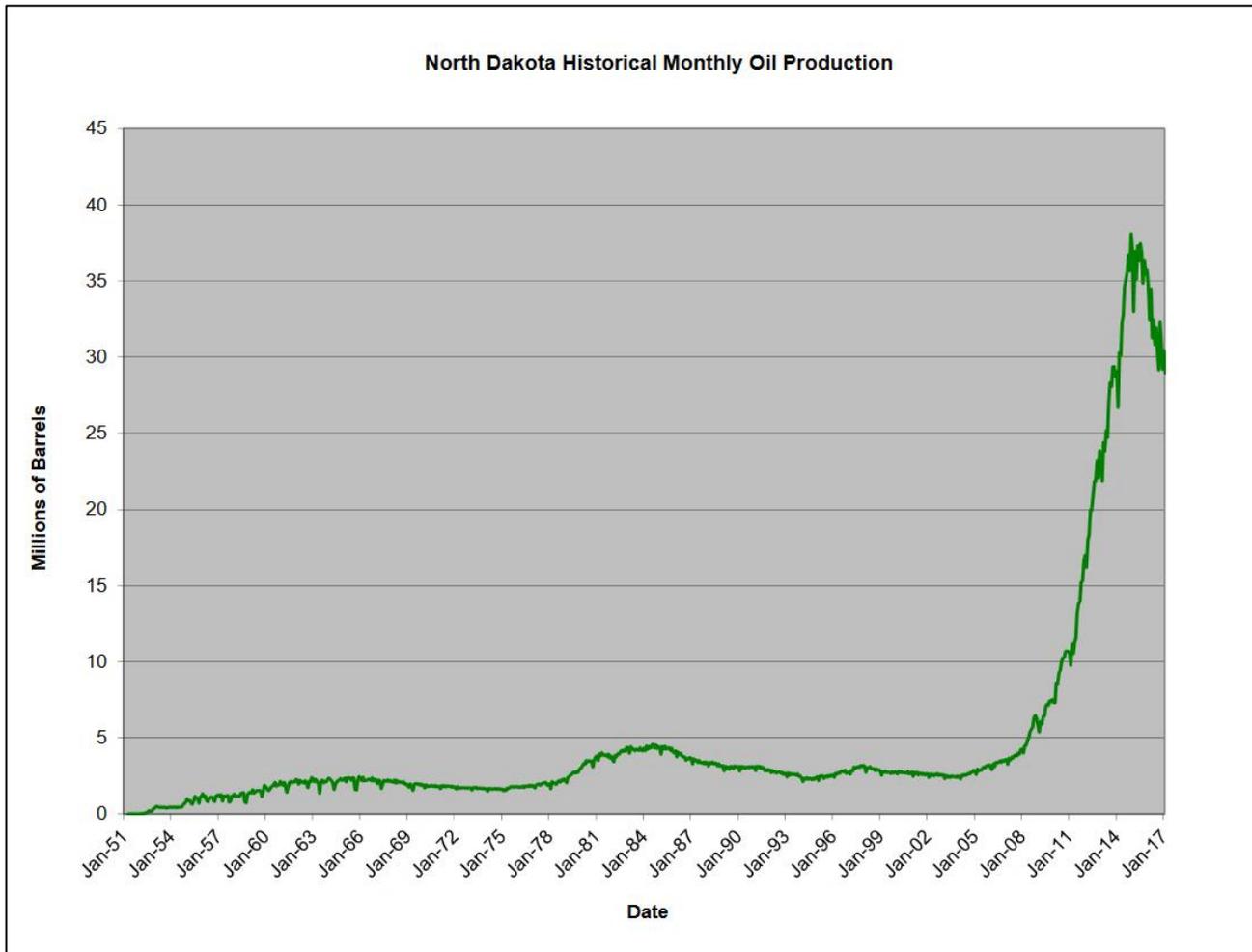
Figure 3.2. Showing the historical and monthly oil production in North Dakota from the 1950s to today. From (NDOGC)

The Mission Canyon Formation

Mississippian Mission Canyon Formation, together with the Charles Formation are the youngest carbonate oil and gas reservoirs in the Williston Basin (Table 3.1), which belongs to the Madison Group (Gaswirth et al., 2010). The uppermost Lodgepole beds grade laterally into the Mission Canyon and maximum thickness is near the central part of the basin and thins near the basin margins at the Eastern Flank, North Dakota (Fig. 3.3).

The largest oil fields produce along major structures within the U.S. part of the basin, which is generally separated into four important areas. (1) The Nesson anticline, (2) northeast of the Nesson anticline, (3) eastern basin margin fields, and (4) southern basin margin fields (Gaswirth et al., 2010).

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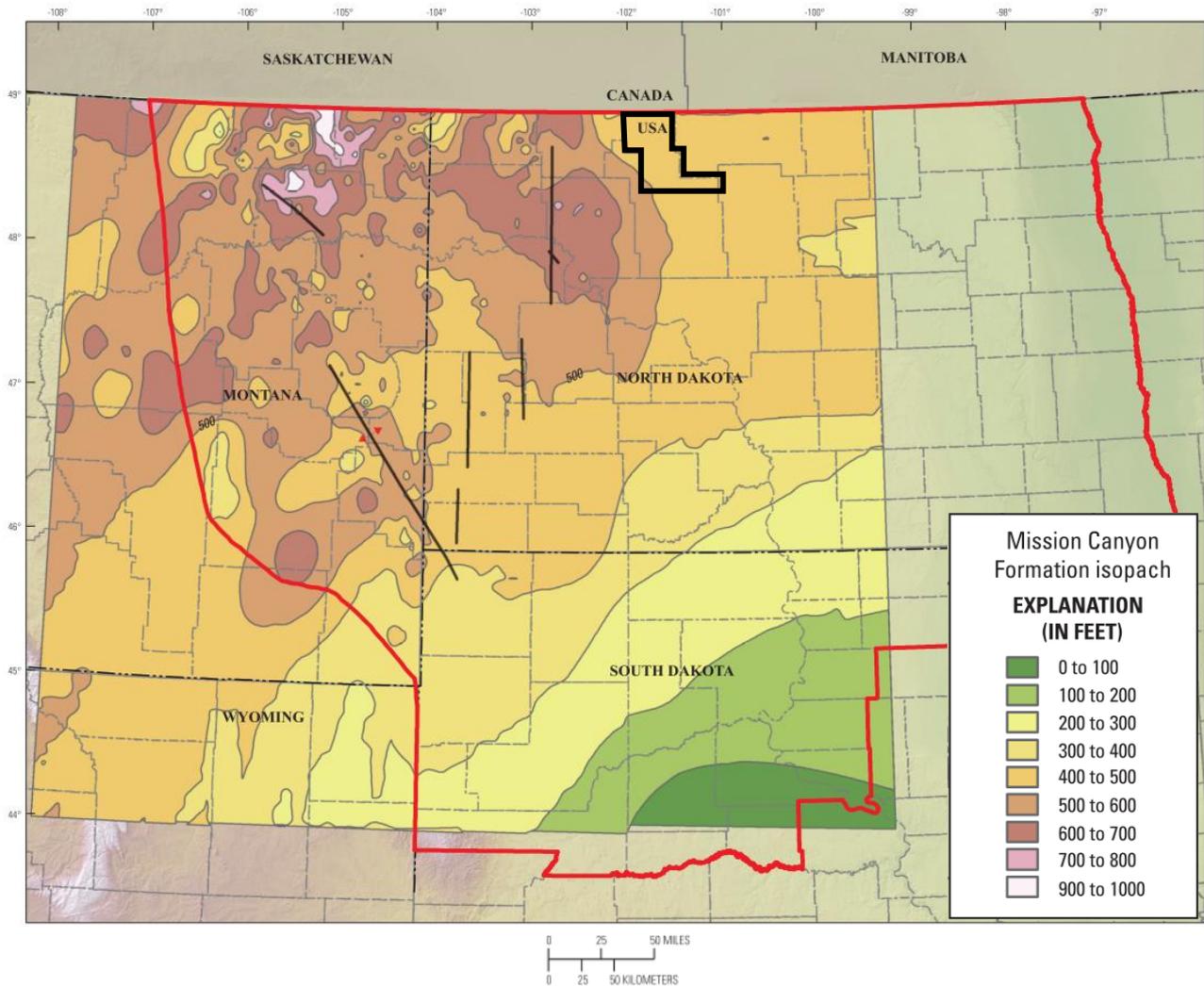
Figure 3.3. Isopach map for the Mission Canyon Formation. Contour interval is 100 feet (30 m) and based on thickness from the top of the Lodgepole Formation to the top of the Mission Canyon Formation. The black box shows the area of interest at the Eastern Flank. According to the map, the thickness range in that area is 120-150 meter. From (Gaswirth et al., 2010).

The Mission Canyon Formation was deposited on a gently dipping ramp during the Mississippian period. During deposition, the sedimentation shifted to the west with marine connection to the Central Montana trough, which was established during that time (Fig. 2.6), described in chapter 2. Sediment accumulation consists of shallow marine to marginal marine carbonates to evaporites, where the carbonates indicates shallow water depth with a shoreline regression into the basin from East to West (Petty, 1988).

Short intervals of sea-level fluctuations caused shoreline progradation into the basin, and occasional transgressions flooded the ramp, allowing repeated progradation, where maximum accumulation of the Mission Canyon was in the north-eastern Montana (Petty, 1988).

The Mission Canyon Formation have been divided within two informal intervals involving two major regressive sequences that was referred to as the Tilston and Frobisher-Alida intervals (Fig. 3.4).
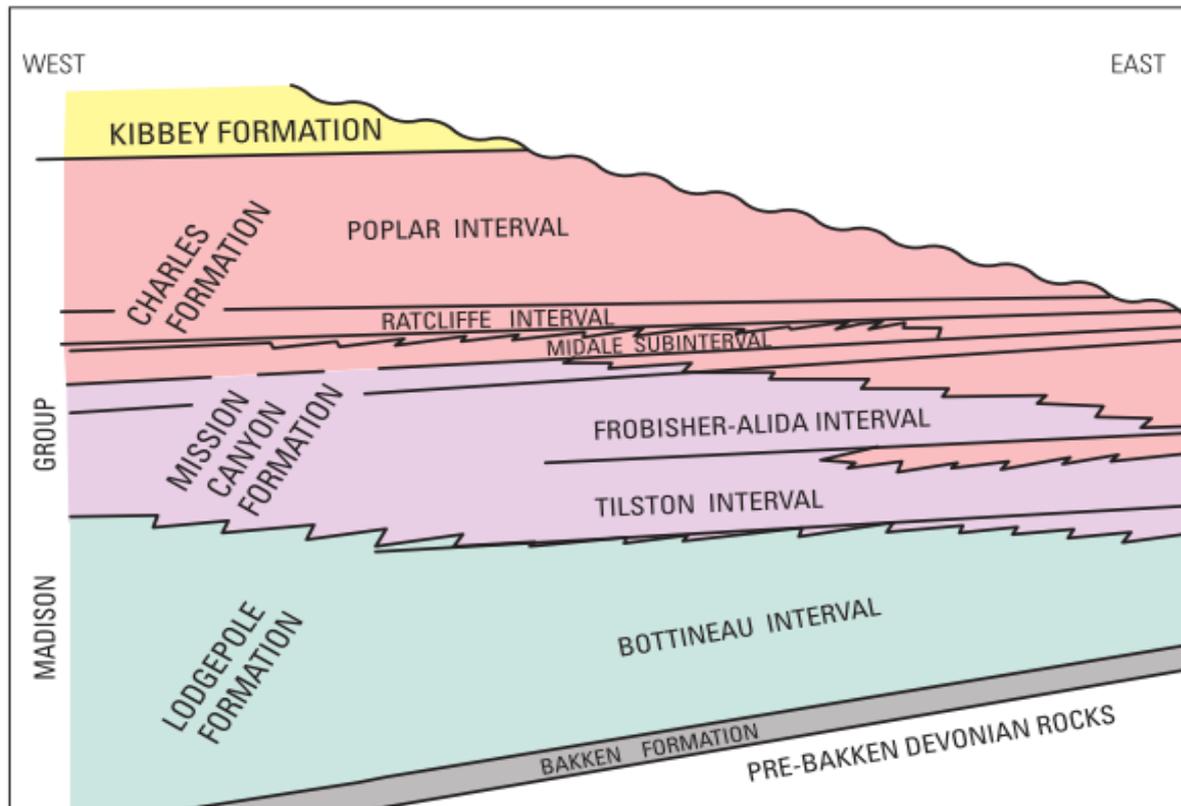

Figure 3.4. West-to east cross section showing formations and informal intervals of the Madison Group. From (Lindsay, 1988). Modified (Gaswirth et al., 2010).

These intervals were meant to indicate the basinward shift to the west in a series of rapid transgression and slow, episodic progradation throughout the basin during the Mississippian period (Lindsay, 1988). However, these intervals and repeated progradational regressive cycles within Mission Canyon Formation was later subdivided into smaller stratigraphic subintervals (Fig. 3.5). Originally defined as consisting of four sub-sections across all of the Eastern Flank, but as the oil industry started working systematically in the basin in the 1960s the formation was being redefined as series of 12 units based on discontinuities expressed as marker beds on well logs (Petty, 1996).

Each subinterval within the Mission Canyon Formation was described to be capped by evaporites (anhydrite) and contains potential reservoirs of dolomitized lime mudstone and wackestone, or lime grainstone, often deposited in coastal settings (Kerr Jr, 1988). The convention was based on the nearest town or village to where the production was ongoing. The Bluell unit at Renville County is overlain by a regional marker bed known as the "State A

marker" a porous regional dolomite marker bed that forms the uppermost unit within the underlying Frobisher Beds (Petty, 1988).
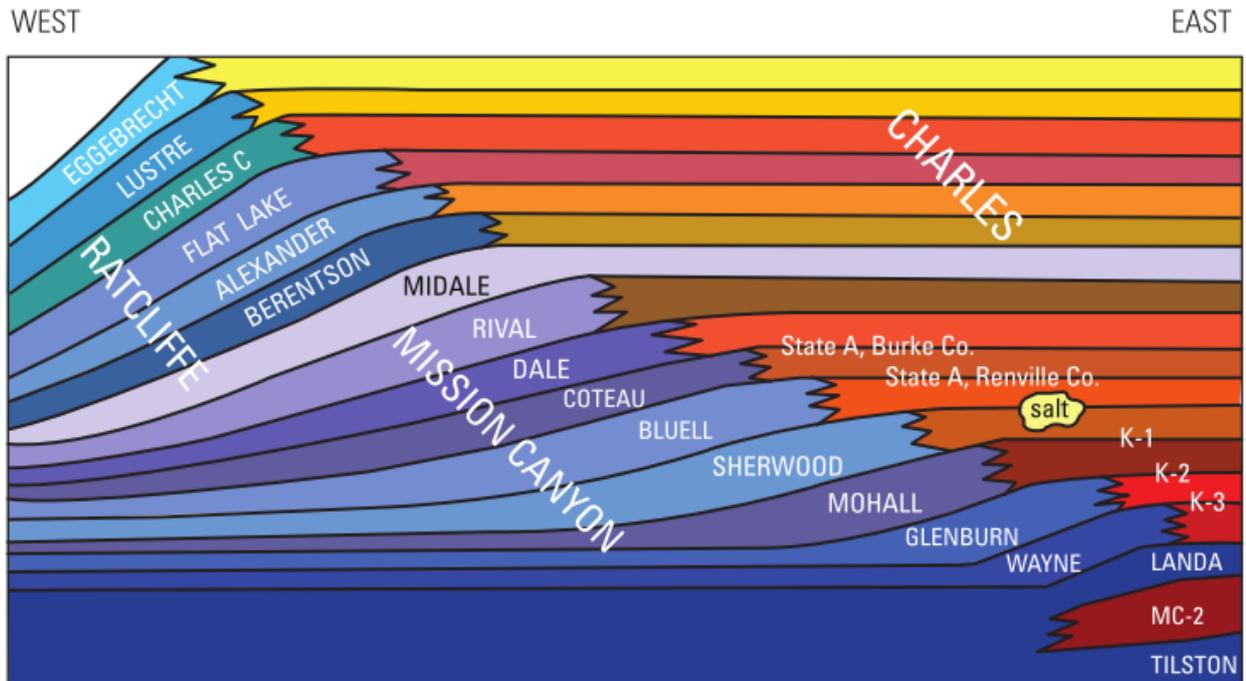

Figure 3.5. West-to-east cross section of the prograding, regressive sequences of the Mission Canyon and Charles Formation. Each unit represents a basinward progradational system. Units with red, orange and yellow shading corresponds to evaporites and blue, purple shading corresponds to carbonates, limestone and dolomites. From (Harris et al., 1966), (Hendricks, 1988), (Gaswirth et al., 2010).

Background from previous work at the Eastern Flank, North Dakota

Recent work at the eastern flank in Williston Basin was made by Dr. E.I.H Siggerud during the years 2009-2014 within the Mission Canyon in Renville County, North Dakota (Fig. 3.6) (Siggerud, 2014). One segment of the work summarises an overall discussion of the geological setting, revised stratigraphy and the depositional understanding for the Mission Canyon Formation at the Eastern Flank, undertaking a better understanding of the sediment distribution and the control of porosity as a consequence of the depositional system within the formation for further exploration in Renville County.

The previous work assembled a detailed well database within the Renville County from the public well database of the North Dakota Oil and Gas Division and was used together with the general stratigraphy from the area, to qualify a better understanding of the stratigraphy (Fig. 3.7). In addition, a list of wells with cores from the Mission Canyon Formation was created, which involved approximately 2100 meters of cores from 20 wells. These cores throughout the Mission Canyon Formation was selected to enable a better understanding of the depositional system and to create a more detailed stratigraphy within the formation.
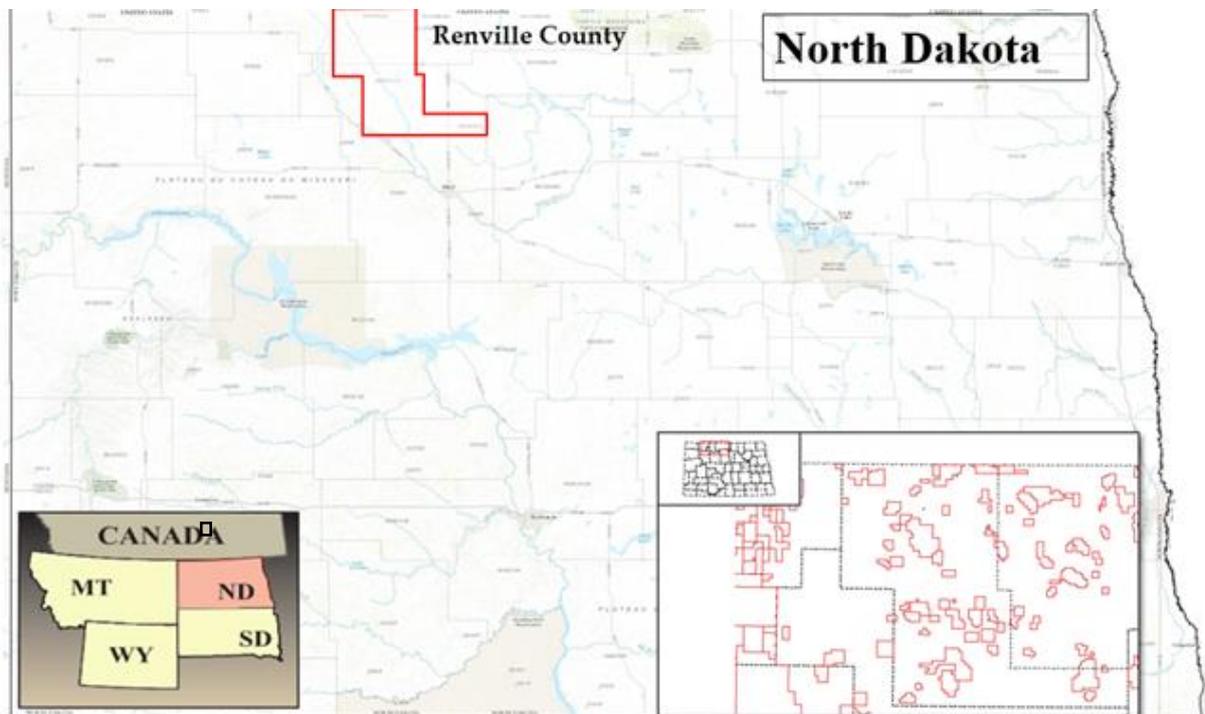
Figure 3.6. Map over North Dakota and Renville County at the Eastern Flank, Williston Basin

Era	System		Group	Formation	Main lithology	Depth (top)
	Quaternary				Fluvial gravel, glacial mudstones and sands	0
Cenozoic	Paleogene		Fort Union Group		Terrestrial mudstones, sandstones and coal beds	200
MESOZOIC	CRETACEOUS	LATE		Pierre Shale	Deep marine mudstones and some bentonites	1100
				Montana Group	Highly heterolithic, marine mudstone, shallow marine to terrestrial silt-sandstones & coal beds,	
			Colorado	Niobara	Deep Marine mudstones and Chalk	2100
				GreenHorn	Shallow marine shales and limestones	3100
		EARLY		Dakota	Terrestrial mudstone and sandstones	3300-3400
			Inyan Kara			
	JURASSIC			Morrison	Terrestrial mudstone and sandstones	
				Swift	Marine mudstone and sandstones	
				Rierdon	Marine mudstone & limestone	4300
				Piper	Highly heterolithic, marine shale grading into sandstone and gypsum	
				Nesson	Evaporates, shale and limestones (dolomitic)	
	TRIASSIC			Spearfish	Red mudstones and sandstones	4700+
PALEOZOIC	PERMIAN		Minnekahta/ Opeche		Missing section Reneville County	
	MISSISSIPPIAN		Big Snowy	Heath		
				Ottar		
				Kibbey		
			Madison	Charles	Anhydrite, dolomite, lime mudstone	5150
				Mission Canyon	Lime-mudstone, carbonate	5400-5600
				Lodgepole	Lime-mudstone, silisiclastic	
	DEVONIAN		Bakken		Dark deep marine mudstones	6500

Compiled by Dr. E.I.H. Siggerud, VP Exploration FRAM

---- Major unconformities
—— Condensed section

Figure 3.7. Constructed stratigraphy at the Eastern Flank in the Williston Basin. Note that the formations above the Mission Canyon Formation are missing in this area, when compared to the general stratigraphy for the Williston Basin. From (Siggerud, 2014).

From the extensive core analysis, it enabled a more precise definition of the depositional units that make up the Mission Canyon Formation (Fig. 3.8), it became clear that a better definition of the different "intervals" and 'subintervals' previously described by old authors within the Mission Canyon Formation was necessary. Especially to understand the sediment distribution and the control of porosity as a consequence of the depositional system within the formation (Siggerud, 2014). These previously described subintervals have been defined as members of the Mission Canyon Formation, the original name used in previous work across the Eastern Flank has been maintained to avoid confusion, but the difference in formal definition had implication on the identification of surfaces in going forward in the drilling of new wells (Siggerud, 2014). Subsequently, the former State A, which erroneously in the past have been referred to as a dolomite unit, is now used for a surface at the top of the Bluell Member.

Each sequence member at the eastern flank is described to consist of shallow marine to marginal marine carbonates to evaporites, consisting more or less of porous pack-grainstones, interbedded with wackestones, lime mudstones, occasionally dolomitized lime mudstone, and capped by anhydrite. With the exception of three sandy successions, with clasts of carbonate seen in figure 3.9.
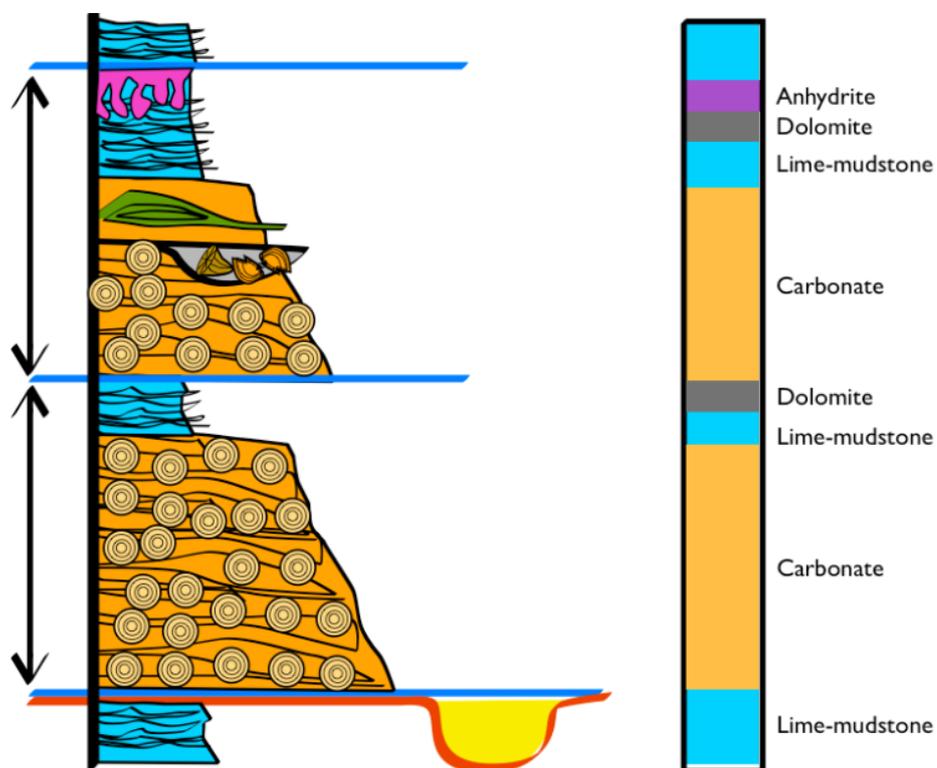
Figure 3.8. The general depositional lithology that make up the main building block (members) of the Mission Canyon Formation. The yellow trough represents the Kisby Sands described in previous figure 3.7. From (Siggerud, 2014).

Previously described within this chapter are not used when refereed to the different units seen in the Mission Canyon Formation, instead they are revised and defined as members within this thesis, but the with the same original name to avoid confusion as previously mentioned. This new and updated stratigraphy have been undertaken as a basis for this thesis and this is why the previously defined and very broad, interval "Frobisher-Alida" and "subintervals"

| Era	System	Group	Formation	Member	Main lithology	Thickness
PALEOZOIC	Mississippian	MADISON	Charles	Midale	Anhydrite, lime-mudstone, dolomite & carbonate	300±
			MISSION CANYON	Rival	Anhydrite, dolomite lime-mudstone	15
				Dale	Anhydrite, dolomite lime-mudstone	10
				Coteau	Anhydrite, dolomite lime-mudstone	10
					- - - - State A marker bed - - -	
				Bluell	Anhydrite, lime-mudstone, dolomite & carbonate	35
				Sherwood	Lime-mudstone & carbonate	60
				Kisby 1	Sandstone & carbonate clasts	0-90
				Mohall	Anhydrite, lime-mudstone, dolomite & carbonate	80
				Kisby 2	Sandstone & carbonate clasts	0-90
				Glenburn	Lime-mudstone, carbonate & silisiclastic mud- sandstone	100
				Wayne	Lime-mudstone, carbonate & silisiclastic mud- sandstone	70
				Landa	Lime-mudstone, carbonate & silisiclastic mud- sandstone	65
				Tilston	Lime-mudstone, carbonate & silisiclastic mud- sandstone	50
			Lodgepole		Lime-mudstone, carbonate & silisiclastic mud- sandstone	500±
	Devonian	Three Forks	Bakken		Dark grey/black coloured, organic risk mudstone, dolomite	

Figure 3.9. Stratigraphy within the Mission Canyon Formation consisting of different members showing main lithology and estimated thickness (displayed in metres) for different members at the Eastern Flank of the Williston Basin. From (Siggerud, 2014).

The main objective for this master thesis

The main objective for this thesis is organised partly as a continuation of previously described work made in Renville County, North Dakota. Within this particular area, the hydrocarbon production was primarily from the carbonate reservoirs made up exclusively of pack-grainstones, within two smaller members called Bluell and Sherwood within the Mission Canyon Formation (Fig. 3.2.1).

One of the major challenges within this area is the seemingly, random porosity within these carbonate reservoirs and that they are made up of complex, inhomogeneous and thin beds with irregular distribution of diagenetic cementation and porosity. These challenges with reservoir distribution and porosity development are widely known from previous work and a classic North Dakota oil field in this region, produces only 15-20% of the original-oil-in-place (NDGS, 2017). Previous studies within nearby areas also mentions that the key for further success and additional exploration will likely be within the detailed recognition and understanding of the relationship between facies distribution and the detailed recognition of the porosity development and diagenetic alterations within producing reservoirs (Petty, 1996).
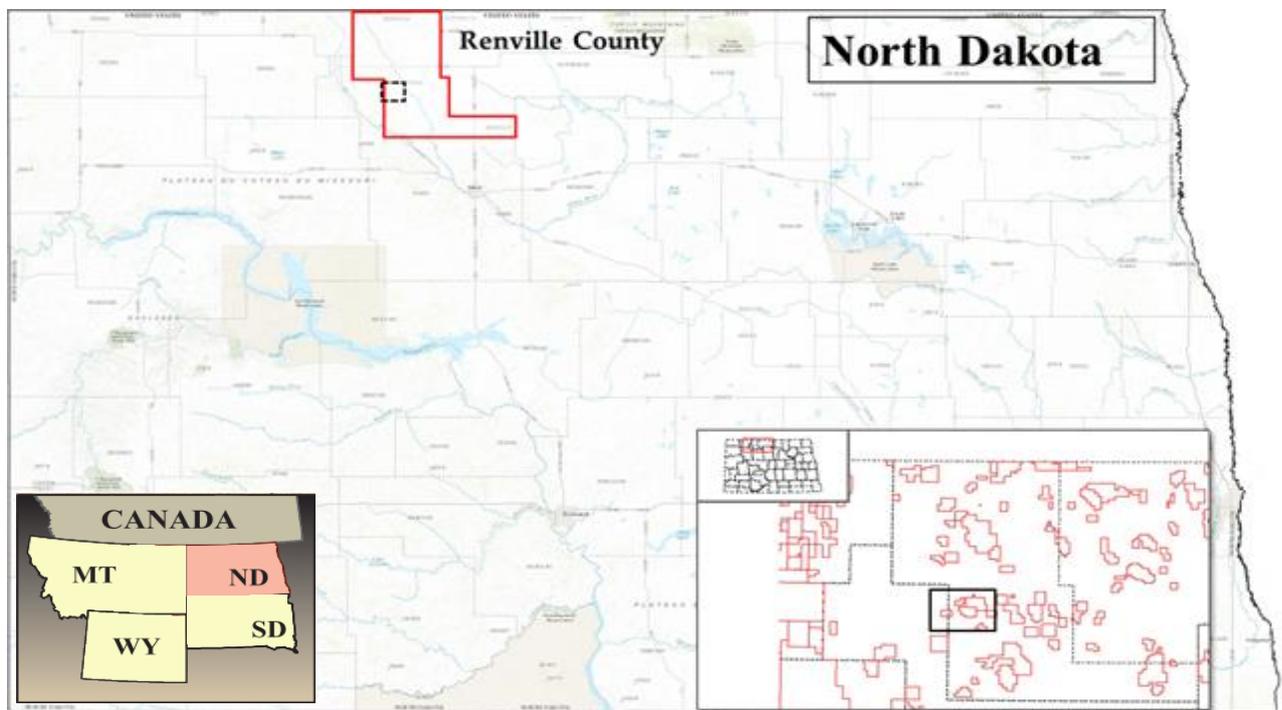
Figure 3.2.1 Map over North Dakota and Renville County. The small black box shows the study area within Renville County for this thesis, and can further be seen in detail in figure 14.

Therefore, the main objective for this thesis is to enable a better understanding of the facies within the depositional system for the Bluell and Sherwood Members, especially to understand the sediment distribution and the control of porosity as a consequence of the depositional system and create a logical understanding of observed porosity seen from cores. By using a more detailed and systematic method of facies description and interpretation on the relatively narrow stratigraphic, but still main producing, Bluell and Sherwood Members in the study area. The goal is to develop a better understanding of the seemingly random porosity, and find a relationship so that a logical prediction of the observed porosity in cores can be made by recognizing various producing and non-producing reservoirs by detailed facies interpretation, to see if a relationship actually can be observed between porosity and identified facies.

The main bullet points of this thesis is to; 1). Initial analysis, build database, organize and establish a new digitally logging template suited for presenting detailed interpretation of core data; 2). Logging systematically and digitally core analysis for picked wells, by using new template and core photographs; 3). With a statistical approach, review interpreted data statistically, by building facies interpretation for each well, describe facies and their distribution; 4). Develop a new depositional model for the Sherwood and Bluell Members within the study area, by using core results and facies stacking pattern to build an understanding of the depositional system; 5). Well correlation by building correlation panels from the facies stacking patterns to establish an overview over facies distribution and potential reservoirs in the area. 6). Find and describe potential reservoirs within Sherwood and Bluell Members and their diagenesis and porosity development; 7). Try to find a relationship and develop a better understanding of the observed porosity development and the relationship between different characteristics of each facies, and if porosity, degree of cementation and reservoir potential could possibly be facies controlled.

Location of the study area

The study area was picked out by selecting seven wells in an east to west direction that is roughly 8.5 km between the eastern most well (Laura Funke 4) within South Greene field to the western most well (Nailor Trust 1), near the Norma field (Fig. 3.2.2). The South Greene field contains five wells, where two wells were selected (Laura Funke 4 and Funke 1), with a distance of 600 meter apart. Between the wells Funke 1 and Donald Peterson 3-27, the distance is roughly 3.7 km. The Smith field contains 29 wells and three wells were selected (Donald Peterson 3-27, Siebert 1 and Epex-Weber 28-9). The distance between Donald

Peterson 3-27 and Siebert 1 is 820 meters and from Siebert 1 to Epex-Weber 28-9, the distance is 630 meters. Between the wells Epex-Weber 28-9 and Nailor Trust 1, the distance is roughly 2.95 km. Norma field contains 18 wells and the nearby well, Schlak 2, which counts as a part of the field. Between the well, Nailor Trust 1 and Schlak 2, the distance is roughly 1.25 km.
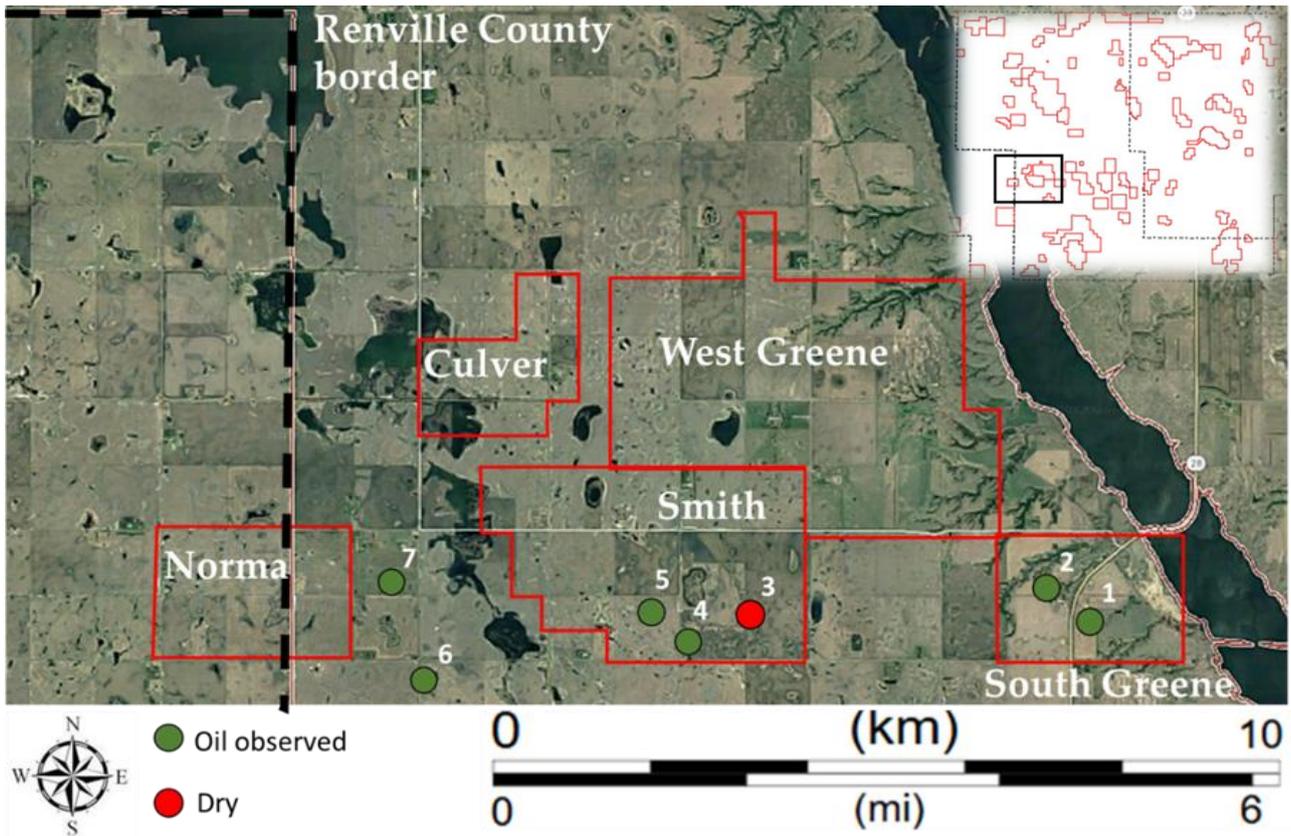

*Figure 3.2.2 Map of the study area showing nearby oil fields and the seven wells selected. The wells are: **1)** Laura Funke 4, **2)** Funke 1, **3)** Donald Peterson 3-27, **4)** Siebert 1, **5)** Epex-Weber 28-9, **6)** Nailor Trust 1, **7)** Schlak 2.*

CHAPTER 4 DATA AND METHODOLOGY

The first phase involved building a database from the public well database of North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division (NDOGD, 2017). Seven wells (Table 4.1) were selected from three fields within Renville County; South Greene Smith and Norma respectively (Fig. 3.2.2). Appointed wells penetrate the Bluell, Sherwood and Mohall Members within the Mission Canyon Formation, with the total core coverage of 188 meters, taken from the Bluell and upper Sherwood Members. Overview information regarding selected wells, including available information about well files, production data, core data and of electronic LAS files logs are shown in table 4.1.

Table 4.1 Overview over the database made, which includes available information about each particular well within the study area. Depth have been recorded in feet and later converted to meters. Mainly since The United States uses the international foot in preference to the metric system. Status: AB; abandoned, IA; inactive, P&A; plugged and abandoned and prod; producing.

No.	Location	No database	Well name	Core type	LAS logs	Production data	Type hydro-carbon	Status
1	South Greene	21720	Laura Funke 4	Large slab	NO	Not available	Oil	AB
2	South Greene	17739	Funke 1	Large slab	NO	available	Oil	IA
3	Smith	11957	Donald peterson 3-27	Large slab	NO	Not available	Dry	P&A
4	Smith	12758	Siebert 1	Large slab	YES	available	Oil	P&A
5	Smith	12640	Epex weber 28-9	Large slab	NO	available	Oil	Prod
6	Wildcat	19474	Nailor trust 1	Large slab	NO	available	Oil	P&A
7	Norma	19783	Schlak 2	Core photos	NO	Not available	Oil	IA

No.	Well name	Core depth (feet)	Core depth (m)	Core length (m)	IP reported	IP 1st month	Cumulative oil	Cumulative water	Years on production
1	Laura Funke 4	5189-5333	1581,6-1625,5	40.8	?	?	?	?	?
2	Funke 1	5230-5412	1594,1-1649,6	55.5	105	?	20449	201534	5
3	Donald peterson 3-27	5520-5580	1682,5-1700,8	18.3	?	?	?	?	?
4	Siebert 1	5494-5585	1674,6-1702,3	27.7	107	89	14212	36985	4
5	Epex weber 28-9	5480-5542	1670,3-1689,2	18.9	275	234	176934	247186	27
6	Nailor trust 1	5600-5628	1706,9-1715,4	8.5	12	?	?	?	?
7	Schlak 2	5585-5644	1702,3-1720,3	18.0	?	?	?	?	?

187.8

No.	Well name	Stratigraphy from well logs Bluell (feet)	Stratigraphy from well logs Bluell (m)	Stratigraphy from well logs Sherwood (feet)	Stratigraphy from well logs Sherwood (m)	Stratigraphy from well logs Mohall (feet)	Stratigraphy from well logs Mohall (m)	Thickness Bluell (m)	Thickness Sherwood (m)
1	Laura Funke 4	5207.0	1587.1	5281.0	1609.6	5394.0	1644.1	22.6	34.4
2	Funke 1	5228.0	1593.5	5280.0	1609.3	5387.0	1642.0	15.8	32.6
3	Donald peterson 3-27	5480.0	1670.3	5534.0	1686.8	5600.0	1706.9	16.5	20.1
4	Siebert 1	5496.0	1675.2	5540.0	1688.6	5656.0	1723.9	13.4	35.4
5	Epex weber 28-9	5487.0	1672.4	5538.0	1688.0	5600.0	1706.9	15.5	?
6	Nailor trust 1	5592.0	1704.4	5627.0	1715.1	5681.0	1731.6	10.7	16.5
7	Schlak 2	5593.0	1704.7	5618.0	1712.4	5687.0	1733.4	7.6	21.0
								102.1	160.0

4 DATA AND METHODOLOGY

Methodology and data management

The method used during the interpretation of available core data was the usage of a more systematic way of displaying digitally detailed core to core and facies analyses from core photos from selected wells. Facies are lithologic suites that represent sediments and precipitates deposits in similar environments and the facies analyses was focused on the relatively narrow, but main producing Bluell and Sherwood Members (Table 4.1).

NDOGD have a continuous core photography program, which are published on their website (NDOGD, 2017). 744 core photographs for all the seven wells was available and forms the basis for this thesis. The benefit from this extensive and very high-quality core photographs review program, was the ability to recognize the interpretation of depositional facies, lithology, cementation, grain size and sorting. Including to some degree, visual porosity and oil saturation. Oil stains could be recognized to some extent from the mark of stain colouring on the cores and with the help of ultra violet light photographs, when it was available.

To be able to create a better detailed definition and interpretation of the total 188 meters of core from the Bluell and upper Sherwood Members, a more systematic way of digitally detailed core to core facies analyses was used. The approach was used to record sedimentary details from the core photographs and was based on a methodology established by Dr. E.I.H Siggerud (Siggerud, 2014). His similar method was applied, but a new and updated logging spreadsheet was created in Excel to fit the workflow needed for the detailed description of these particular core photographs. The digital template enabled recording of observations in a very systematically matter, where core depth, depositional facies, lithology, dominated fabric, cementation, visible porosity (moldic to vuggy), grain size, sorting, sedimentary structures and oil saturation was recorded. The digital template is further described and discussed in chapter 5.

The sedimentary textures recorded, were defined using an updated version of the classification of Dunham (Dunham, 1962), the classification is a way of specifying the textural components of carbonate sediments dependent on texture recognizable and the content of lime mud ranging from lime mudstone to grainstone. The Dunham scheme is useful for hand samples since it is based on texture and not on the grains in the sample (Fig. 4.1).

Figure 4.1. Classification system for carbonate rocks proposed by Dunham and used to define the various textures observed within the core photographs. Modified from Dunham 1962.

The classification of visible and secondary enhanced-solution porosity that was large enough to be observed through the core photographs, was recorded as either visible moldic to vuggy porosity. With a scale ranging between poor, intermediate, well, and very well. Moldic porosity (Fig. 4.2) is a type of secondary porosity, created through the dissolution of a pre-existing constituent of a rock, such as a shell, rock fragment or grain, which the pore space preserves the shape, or mold, of the dissolved material (Lucia, 2007). Vuggy porosity (Fig. 4.2) is generated by dissolution of larger features in carbonate rocks, leaving large holes or vugs, which makes vuggy porosity non-fabric selective (Lucia, 2007). The interparticle porosity inside the rock can't be observed through core photographs alone, but it always exists and is controlled by particle size and sorting, and by the volume of interparticle cement and the interparticle porosity will be reduced in proportion to the volume of cement (Lucia, 2007).

The cementation grade defined for each facies, was recorded with a scale ranging between low, intermediate and highly cemented. E.g. where a core photograph section was observed with open moldic to vuggy porosity with little evidence of cementation inside or around the rock, the cementation grade was set as "low". In comparison to when a rock with observed moldic to vuggy porosity was completely infilled with cement or the whole structure of the rock, then the cementation grade was set as "highly". A visualization of the approach can be viewed in figure 4.2.
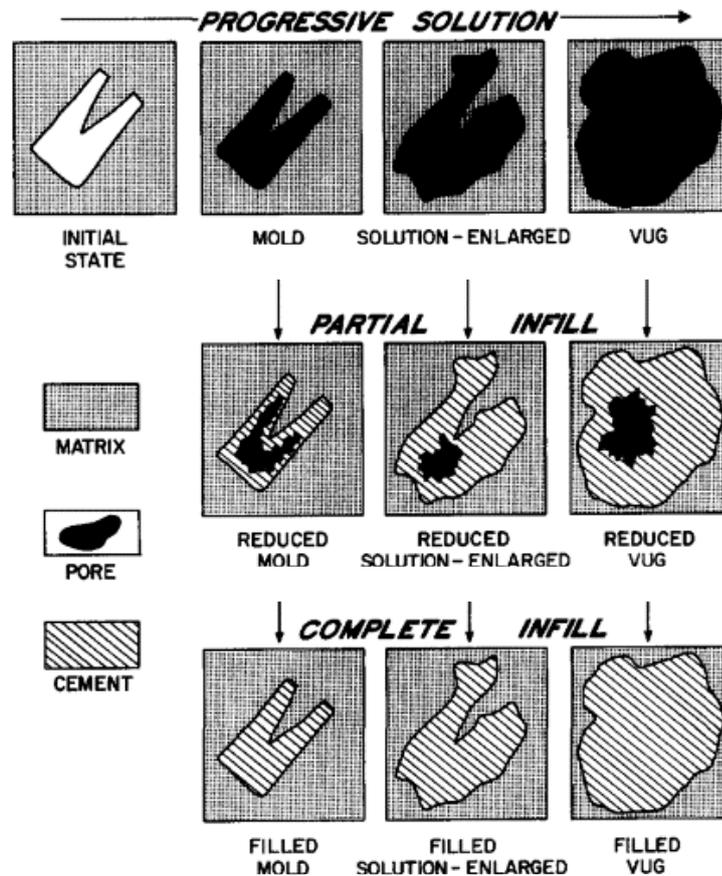
Figure 4.2. An example for visualising the definition between moldic to vuggy porosity and the concept of the "cementation grading" used during the observation of the core photographs. Where the first initial state can be compared to the "low" grade, and the last state can be compared to the "highly" grade when the rock was completely cemented.

Grain size classification for the digital template was recorded with a scale ranging between very fine to very coarse grained. The recognition was made to fit the observation made for core photographs, with a similarity to the existing siliciclastic grain size, classification charts (Table 4.2). Grain size, refers to the diameter of individual grains of sediment, or the lithified particles in rocks (Lucia, 1995). Granular material can range from very small particles through

Table 4.2 Grain size classification used for digital template, during the interpretation of the core photographs.

Description	Size in mm	Recognition
Very Fine Grained	<0,06	Individual grains cannot be seen
Fine Grained	0,06 - 0,2	Just visible as individual grains when zoomed in (400 %) on the core photographs
Medium Grained	0,2 – 0,6	Grains clearly visible when zooming in and just visible to the naked eye
Coarse Grained	0,6 – 2,0	Grains clearly visible to naked eye
Very Coarse Grained	> 2,0 -	Grains measureable

clay, silt, sand, gravel, and cobbles, to boulders. However, the grade scales for clastic rock are not best suitable for carbonate rock, mainly due to the names used within the scale units, which imply the clastic origin of the rock. Nevertheless, carbonate grains can be described as "of clay size," "of silt size," or "of sand dimension," and so forth, which has been used during the observation.

The degree of sorting was recorded with a scale ranging between very poorly, poorly, intermediate, well and very well sorted. Sorting describes the distribution of grain size of sediments and is a measure of how closely the grains in a sediment approach being one size (Lucia, 1995). In very well sorted sediments, the grains are all about the same size. In poorly sorted sediments the grains have a wide range of sizes (Lucia, 1995). By describing the sorting observed through the core photographs by using the terms -very poorly sorted, poorly sorted, moderately sorted, well sorted and very well sorted, it quantitatively describes the amount of variance seen in particle sizes (Fig. 4.3). The degree of sorting can indicate the energy, rate, and/or duration of deposition, as well as the transport processes as waves, storms, rivers, etc. Well sorted sediments tend to have greater porosity, while poorly sorted rocks have low porosity, because of the lack of grains, small enough to fill its pores (Lucia, 1995).

Figure 4.3. Visualizing the degree of the five different sub-categories used through the core photographs.

CHAPTER 5   THE USAGE OF A DIGITAL TEMPLATE

By grounding the workflow and the core results for every detailed core description and interpretation made in a digital template, it allowed for a more systematic analysis well by well on a small scale. By allowing each recordings and observations made throughout each core photograph to be eventually organized into facies, these different facies interpretations are described in chapter 6.

The digital template enabled recordings of observations in a very systematically matter, where core depth, depositional facies, lithology, dominated fabric, cementation, visible porosity (moldic to vuggy), grain size, sorting, sedimentary structures and oil saturation was recorded. The depth was recorded in feet and inches, mainly because The United States uses the international foot in preference to the metric system on all well files and core photograph available. However, the feet and inches was later converted when needed with the help of the conversion tool within the digital template. An overview and the progressive workflow can be observed within the figures 5.1, 5.2 and 5.3.

The management and organisation of the data for each particular well that was stored within a digital template, provided a good summary and overview for each observation made in the wells. By doing it this way, it allowed for a faster registration process, together with the combination of easy access and alternation of new or pre-existing data. Furthermore, by storing everything as digital data, it enabled the usage of digital stacking patterns and allowed for further loading of data into the digital program, Tigress. This program was used to visualize all the digital data, such as sorting, porosity and oil staining, together with stacking patterns and well logs, which is further discussed in chapter 8.

Subsequently, the systematic approach during the interpretation part of the core photographs were although first made by making a more qualitative observation and interpretation, which is still based on the authors understanding of the cores. However, composed with the new advantage of using an additional quantitative approach, by allowing the digital template's ability and different methods within the program to additionally analyse the data. By the help of visualizing, sorting and dividing the data in a more quantitative way, which can be observed in figure 5.4.

The aim of using an additional quantitative approach with the use of the digital template was to primarily utilize a better approach of better recognition and awareness for finding a possible relationship between each qualitative observation made. Subsequently to illustrate and understand the relationship between facies and reservoir development that alternates between

these producing and non-producing reservoirs, by recognizing various and detailed facies, together with their characteristics (e.g. sorting, grain-size) and their distribution. Including porosity development and the degree of cementation to see if a relationship actually could be observed.

Figure 5.1. An example from the well Schlak 2, one of the seven wells where the digital template was used. This is only a visual overview to show how extensive these digital templates could be and how it was used to record observed details from the core photographs. A detailed and more clarifying example within the upper part of this spreadsheet can be viewed in figure 5.2.

36

Depth	Anhy drite	Mud stone	Lime mud	Algal	Wacke stone	Pack stone	Grain stone	Dolo mitic	Crystal line	Facies	Oil stain	Dominant fabric (50-100%)
5585										5585 (TOP)		
5585.04	4 in								x	A 2		anhydrite and lime
5585.06			2 in						x	LM		lime mud
5586.05	11 in								x	A 2		anhydrite and lime
5587			7 in						x	LM		lime mud
5587.07				7 in						AL 1		algae and lime mud
5588.10			15 in						x	LM		lime mud
5590				2 in						AL 1		algae and lime mud
5590.11								11 in		D		dolomite/li me mud
5591.04	5 in								x	A 2		anhydrite
5592.08				16 in						AL 1		algae and lime mud
5593										Bluell		
5594.08			24 in						x	LM		lime mud
5594.11					3 in					W-P		wackeston e
5597.03			28 in						x	LM		lime mud
5598.02											OIL	packstone
5599						31 in				P 1	OIL	packstone
5599.10											OIL	packstone
5600.05												wackeston e
5601.06					41 in					W		wackeston e
5603.03												wackeston e
5603.06						24 in				P 1		packstone

Figure 5.2. A clarifying example within the upper and left part of the digital template shown in figure 5.1. The different code letters (e.g. A1, P1, W, etc.) are the terminology that was used within the digital templates to differentiate observed facies from each other. The digital template left part enabled recording of observations in a very systematically matter, including core depth, sedimentary textures, dominated fabric, oil staining, and facies, together with every bed thickness. Depth during the workflow was first recorded in feet and inches and later converted to metres when needed.

Cemented	Moldic	Vuggy	Grain-size	Sorting	Sedimentary structures	Others	Comments/interpretation	Facies
								5585 (TOP)
highly							creme white to light grey anhydrite, interbedded with lime mud	A 2
highly					massive		darker grey massive lime mud	LM
highly							light grey to darker grey lime mud with interbedded anhydrite nodules.	A 2
highly							light grey to darker grey lime mud	LM
highly			very fine to medium	moderately sorted	chaotic		light brown to light grey algae and lime mud. Few visable grains. Side of algae build ups?	AL 1
highly					planar laminae		light brown to light grey lime mud. Few visable grains	LM
highly			very fine to medium	moderately sorted	chaotic		light brown to light grey algae and lime mud. Few visable grains. Side of algae build ups?	AL 1
highly			very fine to medium	very well sorted			light grey to grey dolomite/lime mud.	D
highly							creme white to light grey massive anhydrite nodule, interbedded with lime mud	A 2
highly			very fine to medium	moderately sorted	chaotic		light brown to light grey algae and lime mud. Few visable grains. Side of algae build ups?	AL 1
							According to logs	Bluell
highly					massive		white to light grey lime mud. Few visable grains and visable anhydrite cementation	LM
highly			fine to very	very poorly sorted			grey to darker grey wackestone with cemented nodules/fragments.	W-P
highly					massive		white to light grey lime mud. Few visable grains	LM
low	well	intermediate	medium to very	well sorted		OIL	light grey to grey packstone with open moldic/vugs with brown oils saturation.	P 1
intermediate		intermediate	medium to very	moderately sorted		OIL	light grey to grey packstone with brown oil stains	P 1
low	intermediate	well	medium to very	well sorted		OIL	light grey to grey packstone with open moldic/vugs with brown oils saturation. Vertical	P 1
highly			fine to very	moderately sorted		coarsening	light grey to light brown wacekestone. Highly cemented. Stylolitic. Coarsening upwards	W
highly			fine to very	moderately sorted			light grey to light brown wacekestone. Highly cemented	W
highly			fine to very	moderately sorted			white to light grey wackestone. Big cemented nodules.	W
intermediate	poor		medium to coarse	well sorted			grey to brown packstone.	P 1

Figure 5.3. A detailed and more clarifying example within the upper and right part of the digital template shown in figure 5.1. The different code letters (e.g. A1, P1, W etc.) are the terminology that was used within the digital templates to differentiate observed facies from each other. The digital template right part enabled recording for further observations regarding cementation, moldic to vuggy porosity, grain-size, sorting, sedimentary structures, and together with general comments and interpretation thoughts during the workflow.

Figure 5.4. An example showing the usage of the digital template to make a better observation and visualization between facies and observed characteristics within the core photographs during the description and interpretation phase. The figure shows the usage and combination of the "sorting ability" and the ability to hide and only display the relevant data needed for the particular occasion.

5 THE USAGE OF A DIGITAL TEMPLATE

CHAPTER 6   FACIES DESCRIPTION & INTERPRETATION

This chapter describes the results of core photograph analysis from the digital templates used for the seven wells, included in this project (Table 4.1). The detailed core analysis focus on the Bluell and upper Sherwood Members and a total of approximately 190 m (616 feet) has been reviewed and described in inches (1 inch = 2.54 cm). Mainly, since The United States uses the international foot in preference to the metric system on all well files and every core photograph. By using the workflow described within the methodology in chapter 4, together with the systematic analysis from the digital template in chapter 5. The core interpretation workflow revealed 11 identified facies throughout the seven core sections within the seven wells, these are;

1. Massive, anhydrite

2. Nodular anhydrite

3. Algal mats

4. (D & LM): Dolomitic lime mudstone and lime mudstone

5. Siliciclastic, massive to planar laminated mudstone

6. Intraclastic wackestone-packstone

7. Algal Mounds-Stromatolites

8. Cemented peloidal packstone

9. Oolitic-peloidal packstone

10. Oolitic-peloidal grainstone

11. Bioturbated, skeletal wackestone

A summary for each facies can be observed in table 6.1. The black scale box in each core photograph defines the inch scale bar that was used for each image in every core photograph, due to the international foot system used in The United States, in preference to the metric system

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Table 6.1. Summary of the 11 facies that was observed throughout the seven wells in the study area.

Facies	Name	Description	Bed thickness	Sedimentary structures	Occurrence	Interpretation
1	Massive anhydrite	Massive anhydrite, white to grey, translucent, light blue colour. Primarily massive texture minor amounts of dolomite strings and tiny patches (>10%) of mixed dolomitic lime mudstone	25-90 cm. Max (160)	None	(5 of 7) wells. Bluell (4/5) Sherwood (2/5)	Supratidal zone, sabkha environment
2	Nodular anhydrite	White to grey, translucent nodular anhydrite. Up to 50-80 % consist of anhydrite nodules between thin sections or patches of interbedded laminae of dolomitic and lime mudstone	10-40 cm. Max (55)	None	(7 of 7) wells. Bluell (7/7) Sherwood (3/7)	Lower part of the supratidal zone. Evaporitic ponds
3	Algal mats	Poorly sorted intraclasts, dark brown fragments and few rounded grains with a "broken" to more "chaotic horizontal lamination, described as flat laminated algal mats	20-90 cm. Max (170)	"Broken" to more "chaotic" horizontal lamination	(6 of 7) wells. Bluell (5/7) Sherwood (3/7)	Uppermost intertidal zone, shallow algal-marsh and tidal flat setting
4 D / 4 LM	Dolomitic lime mudstone and lime mudstone	Tanned light grey to darker grey & light brown colored dolomitic lime mudstone and lime mudstone. Bioturbated, together with a few skeletal fragments, peloidal grains and coral fragments, generally lacks normal marine fauna	5-100 cm. Max (230)	Bioturbated, massive & planar lamination	(7 of 7) wells. Bluell (7/7) Sherwood (7/7)	Lowermost to uppermost intertidal zone. Broad tidal flat setting
5	Siliciclastic massive to planar laminated mudstone	Very fine-grained, darker grey siliciclastic mudstone with few visible grains and fragments	2-20 cm	Massive & planar lamination	(7 of 7) wells. Bluell (6/7) Sherwood (3/7)	Suspended sediment fallout or storm events
6	Intraclastic wackestone - packstone	Mixed composition of very-poorly to poorly sorted, angular to rounded grains & skeletal fragments, mixed with some intraclasts and pieces of algal fragments, floating in a lime mudstone matrix	10-75 cm	chaotic and eroded structure with sharp contacts	(7 of 7) wells. Bluell (6/7) Sherwood (5/7)	Lag deposits incised by intertidal channels in the intertidal zone
7	Algal Mounds-stromatolites	Poorly sorted but with larger pieces of algal fragments and intraclasts and higher degree of well-sorted peloids and oolitic grains trapped. Lacks the horizontal chaotic lamination observed in facies 3	15-100 cm. Max (100)	chaotic and eroded structure	(4 of 7) wells. Bluell (2/7) Sherwood (2/7)	Shallow Subtidal & lowermost intertidal zone
8	Cemented peloidal packstone	Intermediate to well sorted packstone. Grain types primarily include peloids, intraclasts, pisoids, ooids and minor skeletal fragments. Observed moldic & vuggy porosity, but highly cemented. No observed oil stains	15-25 cm. 65-90 cm. Max (130)	Planar, low angle & wavy laminae	(7 of 7) wells. Bluell (6/7) Sherwood (4/7)	Subtidal, low relief shoals
9	Oolitic-peloidal packstone	Well to very well sorted packstone. Grain types primarily include ooids, peloids, intraclasts, pisoids and minor skeletal fragments. Open solution-enhanced moldic and vuggy porosity with low cementation grade. Observed oil stains	40-75 cm. Max (155)	Planar, low angle & wavy laminae	(6 of 7) wells. Bluell (6/7) Sherwood (4/7)	Subtidal, low relief shoals
10	Oolitic-peloidal grainstone	Well sorted nature with ooids, peloids and pisoids grainstone without lime mud laminae. Developed solution-enhanced moldic & vuggy porosity, commonly low cementation grade. Observed oil stains	20-75 cm. Max (130)	Cross-bedding and wavy bedding	(5of 7) wells. Bluell (5/7) Sherwood (3/7)	Subtidal, low relief shoals
11	Bioturbateds keletal wackestone	Tanned, light grey to brown color lime mudstone with few gravel, skeletal fragments and occasionally a few intraclasts. Extensive bioturbation and burrow-mottled appearance, with no clear traces	40-100 cm. Max (130)	Extensive bioturbation	(7 of 7) wells. Bluell (6/7) Sherwood (5/7)	Subtidal, open marine, low to moderate energy

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6 FACIES DESCRIPTION & INTERPRETATION

Facies 1 description: Massive, anhydrite

Facies 1 consists of massive anhydrite, dominated by white to grey, translucent, light blue colour. Primarily observed with the massive texture, together with occurrence of minor amounts of dolomite strings and tiny patches (>10%) of mixed lime mud and dolomite (Fig. 6.1). No observable sedimentary structures can be seen within Facies 1 and the thickness range between 25 to 90 cm, with a maximum thickness of 160 cm (Laura Funke 4). Facies 1 bed boundaries occur predominantly with nodular anhydrite (Facies 2) and dolomitic lime mudstone facies (Facies 4).

Facies 1 was observed in five out of seven wells and according to the well logs that represents the bed tops for Bluell and Sherwood Members, facies 1 was observed in both members throughout the study area. Although, facies 1 was only observed near the top of the Bluell Member for the wells; Siebert 1, Epex Weber 28-9 and Nailor Trust 1. The well Donald Peterson 3-27 only had observed facies 1 in the Sherwood Member. The well, Laura Funke 4, furthest to the east had observed facies 1 in both members. Facies 1 was not observed in the wells, Funke 1 and Schlak 2. The distribution of facies 1, accordingly to what member it was observed in, can be further observed through the stacking patterns in chapter 7.
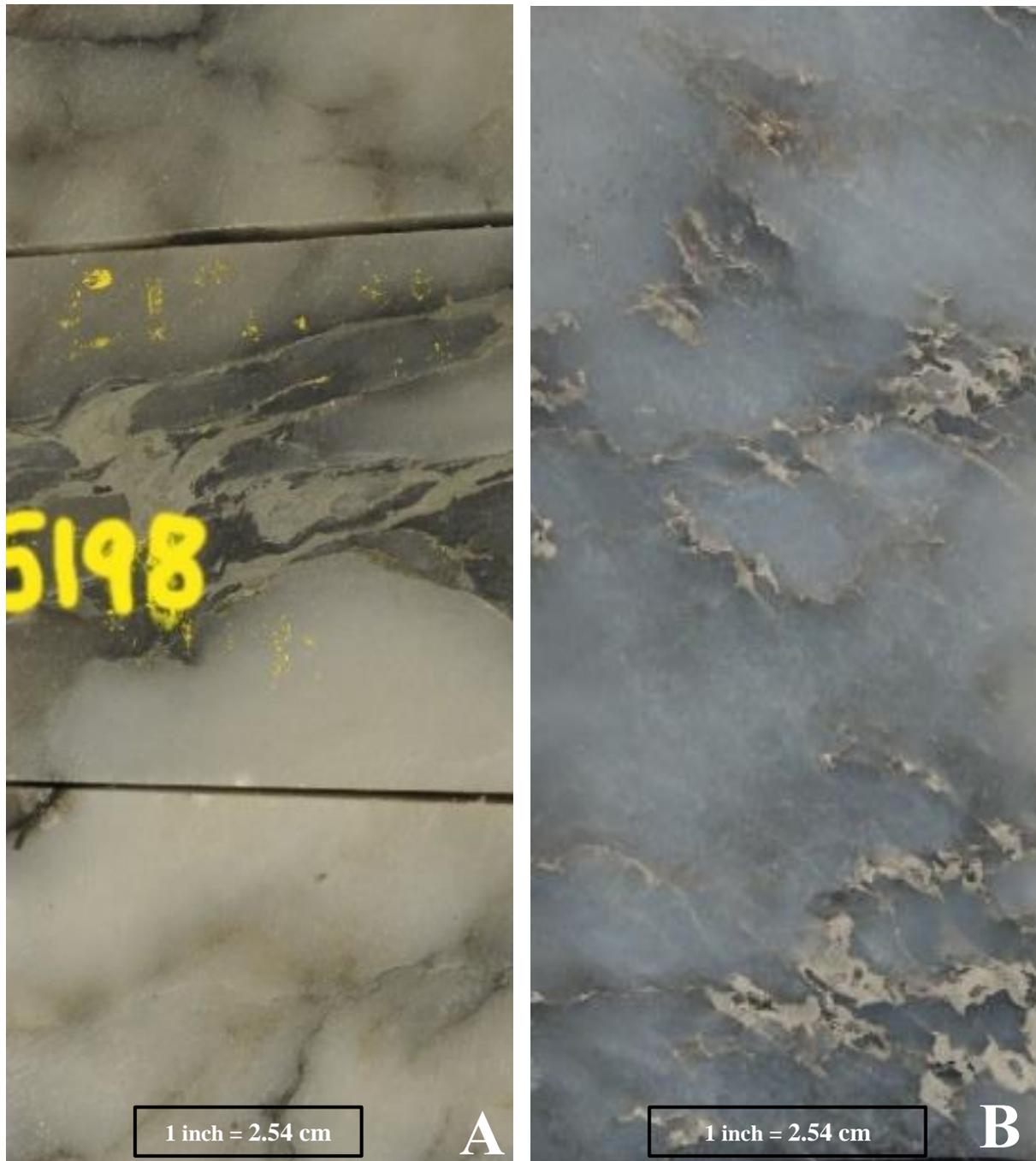
*Figure 6.1. **A).** Core slab from Laura Funke 4. Depth 1584 m (5198 feet). Cream white massive anhydrite with tiny patches of lime mud and dark grey dolomite strings. **B).** Core slab from Epex Weber 28-9. Depth 1672 m (5485 feet). Translucent, light blue massive anhydrite (Facies 1) with tiny patches of dolomitic lime mudstone.*

6 FACIES DESCRIPTION & INTERPRETATION

Interpretation

The massive anhydrite that make up facies 1, is a major component in sedimentary evaporite deposits, commonly formed by dehydration of gypsum in arid regions (Schreiber and Tabakh, 2000). Based on the massive anhydrite texture and similarities to modern analogues, e.g. northern coast of Qatar and Abu Dhabi coast of the Persian Gulf (Qing and Nimegeers, 2008), this facies is interpreted to represent a supratidal regime and sabkha environment above the shoreline (Fig 6.2).

Schreiber and Tabakh, (2000) describe sabkhas that forms along arid coastlines and salt marshes, characterized by evaporite-carbonate deposits that accumulate along a generally regressive shoreline with prograding and shoaling-upward sequences. These sabkha accumulations with anhydrite are commonly thin sequences of 30 cm to 1-2 m, and repeated sequences are not uncommon (Schreiber and Tabakh, 2000). These observed anhydrite beds are also typically known and used as the top markers for old well logs to distinguish the different members within the Mission Canyon Formation and has been described by previous authors over the years as evaporite deposits that formed most landward on a broad, low angle ramp, widely known for the Mission Canyon Formation, with a mixed sabkha/salina setting (Lindsay, 1988, Petty, 1996).
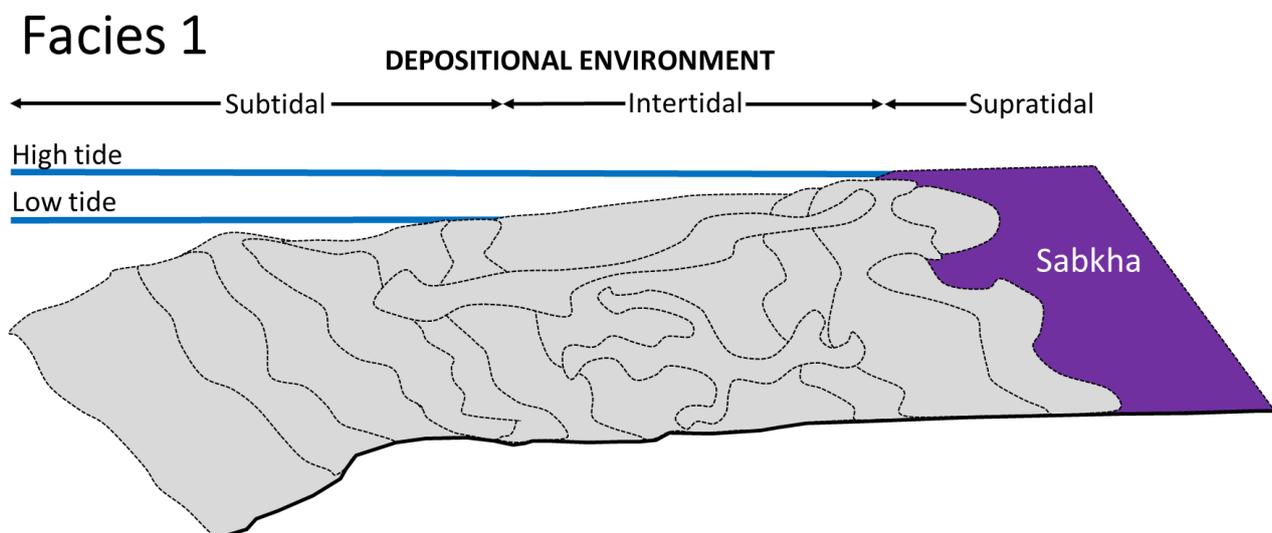
Figure 6.2. Depositional model with massive anhydrite (Facies 1) that represent the most landward, supratidal zone and sabkha environment within arid regions.

6 FACIES DESCRIPTION & INTERPRETATION

Facies 2 description: Nodular anhydrite

Facies 2 consists of white to grey, translucent nodular anhydrite with a muddy matrix of light grey, to darker grey, dolomitic lime mudstone and less commonly lime mudstone.
(Fig. 6.3). This facies is commonly observed with nodules that varies between 2 to 5 cm in diameter and up to 50-80 percent of this facies may consist of anhydrite nodules and they occur commonly between thin beds or patches of interbedded laminae of dolomitic lime mudstone.

No sedimentary structures were observed within the nodules or the muddy laminae and the thickness range between 10 to 40 cm, normally with a shifting variation in thickness. The maximum thickness was 55 cm, which was observed in the well Nailor Trust 1.

Facies 2 bed boundaries occur commonly with shifting alternations between dolomitic lime mudstone and lime mudstone (Facies 4), occasionally with observed algal fragments interbedded within lime mudstone (Facies 3), and less commonly with intraclastic wackstone-packstone (Facies 6). Facies 3 and 4 can commonly be observed to grade upwards into the nodular anhydrite, typically, with visible and sharp lower contacts.

Facies 2 was observed within all seven wells throughout the cores and according to the well logs representing the top of Bluell and Sherwood Member, the eastern most wells, Laura Funke 4, Funke 1 and Donald Peterson 3-27 had observed facies 2 within both members.
Facies 2 was only observed within the upper part of the Bluell Member within the wells, Siebert 1, Epex Weber 28-9, Nailor Trust 1 and Schlak 2. The distribution of facies 2, accordingly to what member it was observed in, can be further observed through the stacking patterns in chapter 7.
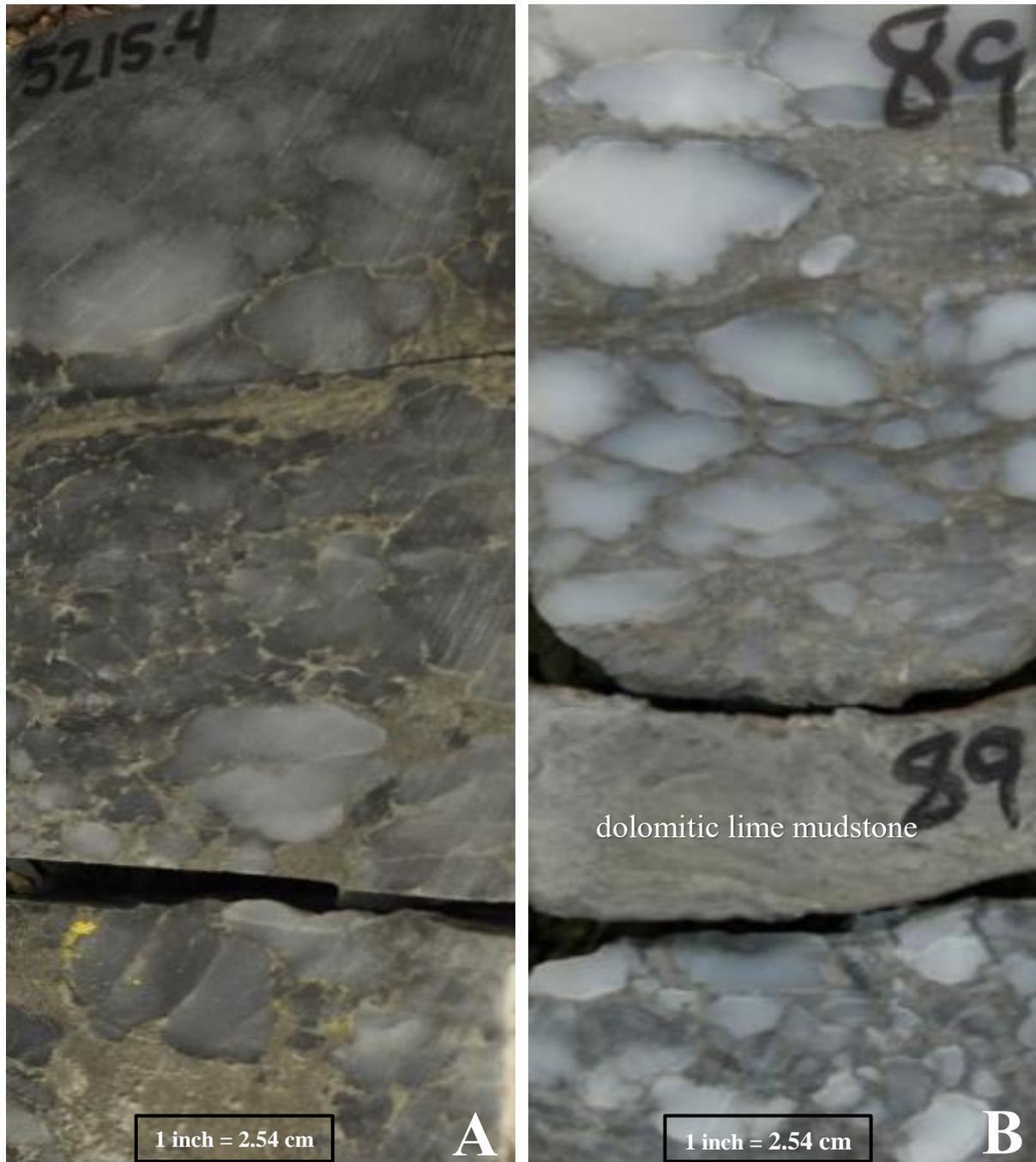
*Figure 6.3. **A)**. Core slabs from Laura Funke 4. Depth 1590 m (5216 feet). Cream white to grey nodular anhydrite grading into the massive anhydrite at the top (Facies 1). **B)**. Core slab from Epex Weber 28-9. Depth 1673 m (5490 feet). Nodular anhydrite (Facies 2) interbedded with dolomitic lime mudstone (Facies 4).*

Interpretation

Facies 2 is interpreted to be deposited near the boundary between the uppermost reaches of the intertidal flat zone, and the lower part of the supratidal zone (Fig. 6.4). The nodular anhydrite observed in facies 2, possibly formed subaqueously in evaporitic ponds, due to the observed cyclical nature and interbedded variation with massive anhydrite (Facies 1) and dolomitic lime mudstone (Facies 4). This possibly reflect episodic wash overs and flooding and shallowing near the lower part of the supratidal environment, thus the cause behind these evaporitic ponds and the subaqueously formed nodular anhydrite. Hendricks (1987) and Warren & Kendall (1985) described similar nodular anhydrite beds and suggested that these beds initially are deposits of gypsum under subaqueous conditions in shallow hypersaline lakes and costal ponds, based on the vertically-elongated morphology of the nodular anhydrite (Warren and Kendall, 1985, Hendricks et al., 1987). Their description proves strong resemblance to the nodular anhydrite observed in facies 2.
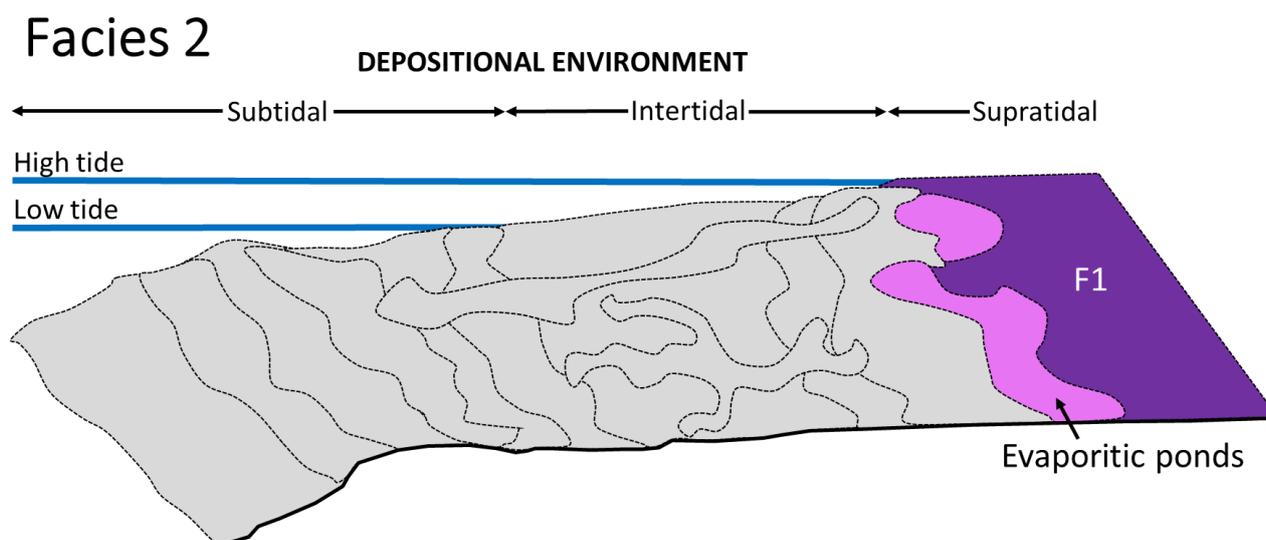
Figure 6.4. Continuation of the depositional model with nodular anhydrite (Facies 2) that represents the boundary between the uppermost reaches of the intertidal flat zone, and the supratidal zone. Facies 2 was possibly formed subaqueously in evaporitic ponds near the lower part of the supratidal environment.

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Facies 3 description: Algal mats

Facies 3 consists of poorly sorted intraclasts, dark brown fragments and few rounded grains with a laminated, although "broken" to more "chaotic horizontal lamination. These dark brown fragments are described as algal fragments, mixed within dolomitic lime mudstone and lime mudstone, which occur with debris of grains that are trapped within these laminated algal mats (Fig. 6.5). In Facies 3, different types of observable algal fragments and horizontal laminae are described as flat laminated algal mats and no other sedimentary structures, except the "broken" to more "chaotic" horizontal lamination was observed.

The thickness alternates between 20 to 90 cm and within one particular well (Funke 1), thickness for two observed algal mats beds, reached 170 cm and 165 cm, only separated with 15 cm lime mudstone (Facies 4), together, reaching a thickness over three metres within the upper Sherwood Member.

Facies 3 bed boundaries is commonly observed with nodular anhydrite (Facies 2), dolomitic lime mudstone (Facies 4) and intraclastic wackestone-packstone (Facies 6). Facies 3 was commonly observed to progressively grade upwards into patches of dolomitic lime mudstone with nodular anhydrite (Facies 2).

Facies 3 were observed in six out of the seven wells, except Nailor Trust 1 and according to the well logs representing the top of the Bluell and Sherwood Member, the well furthest to the east (Laura Funke 4) had facies 3 at the top of Bluell Member and 10 metres below the top of Sherwood. For Funke 1, facies 3 was only observed 10 metres below the top of the Sherwood Member. The well Donald Peterson 3-27, had facies 3 observed in Sherwood Member. Facies 3 was observed in the well Siebert 1, within the lower part of the Bluell Member, near the top of Sherwood. Epex Weber 28-9 had observed facies 3 near the top of Bluell Member. The well furthest to the west (Schlak 2) had observed facies 3 at and above the Bluell top. The distribution of facies 3, accordingly to what member it was observed in, can further be observed through the stacking patterns in chapter 7.
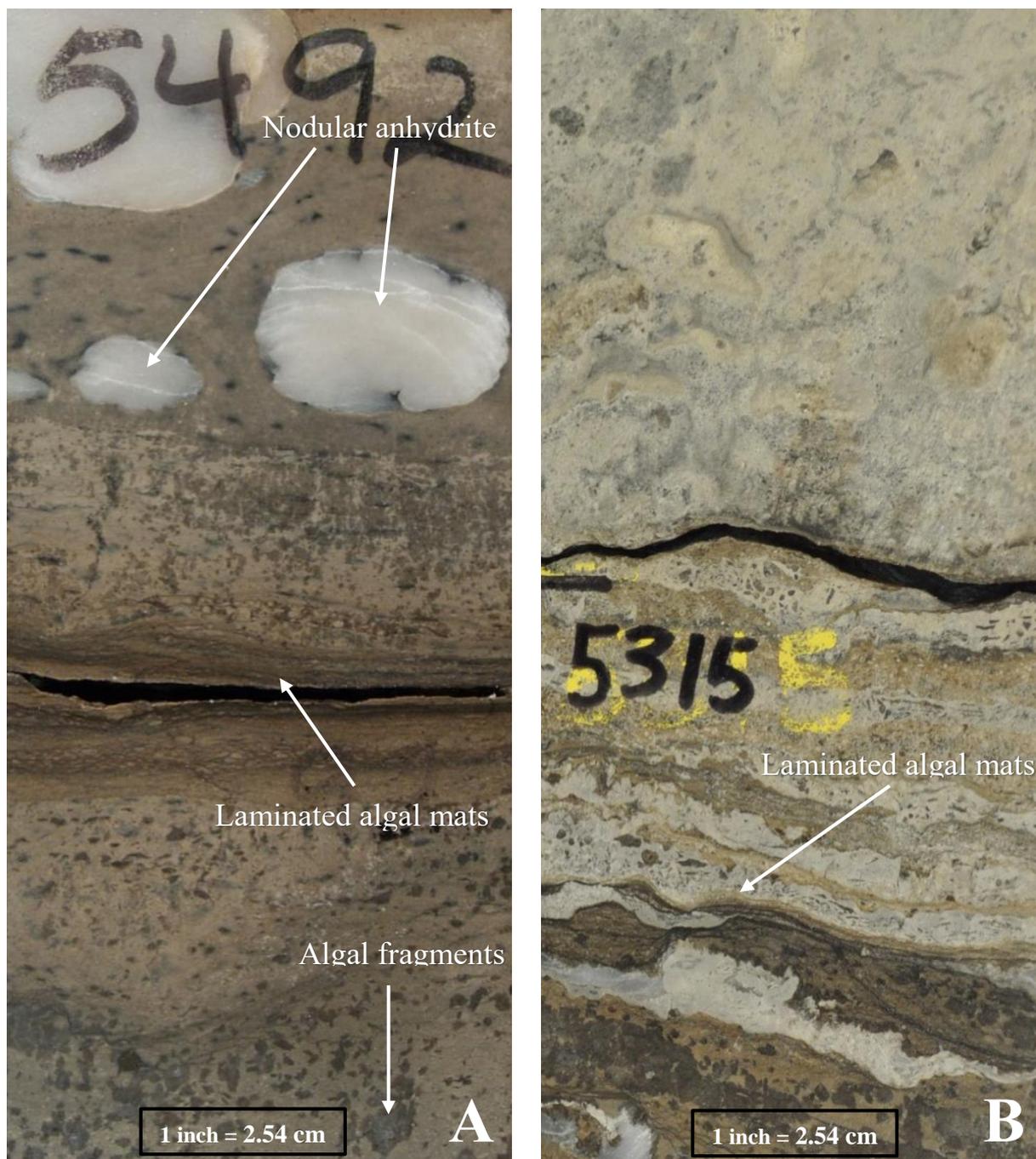
Figure 6.5. ***A).*** *Core slab from Epex Weber 28-9. Depth 1674 m (5493 feet). Dark brown algal fragments within lime mudstone matrix with laminated brown algal mats. Grading into nodular anhydrite (Facies 2)* ***B).*** *Core slab from Laura Funke 4. Depth 1620 m (5315 feet). White to light brown "broken" laminae of algal mats and pieces of algal fragments.*

Interpretation

Facies 3 types of observable fragments, together with the textures of laminated, although "broken" to more "chaotic horizontal lamination is typical for flat laminated algal mats, which forms on the uppermost reaches of the intertidal zone, possibly in a shallow algal-marsh and tidal flat setting (Fig. 6.6).

These interpreted algal mats are one of many types of microbial mats that can be formed within the upper intertidal zone within similar environments as the one for the Mission Canyon Formation. They include brown, green and red algae that are relatively large filamentous forms and locally, are sufficiently abundant to be important sediment stabilizers in marine and non-marine carbonate environments (Riding, 2000). Algal mats trap micritic sediment, and where they are thick, these algal mats may also trap sand, coarser grains and stabilize sediment (Riding, 2000). Qing and Nimegeers, (2008) described similar algal packstones and microbial mats facies to be interpreted as either shallow algal-marsh/lagoon and tidal flat settings in an area in southeastern Saskatchewan, Canada within the Midale Member (Fig. 3.7)

However, facies 3 observed within the present study area seems to have a higher quantity of broken algal fragments, intraclasts and bands of well-sorted peloid debris, trapped within the algal mats. This may suggest events of episodic, and slightly more agitated energy conditions, together with intertidal channels or probable storm events, involving erosion and transport of sediments on a broad and open tidal flat setting.
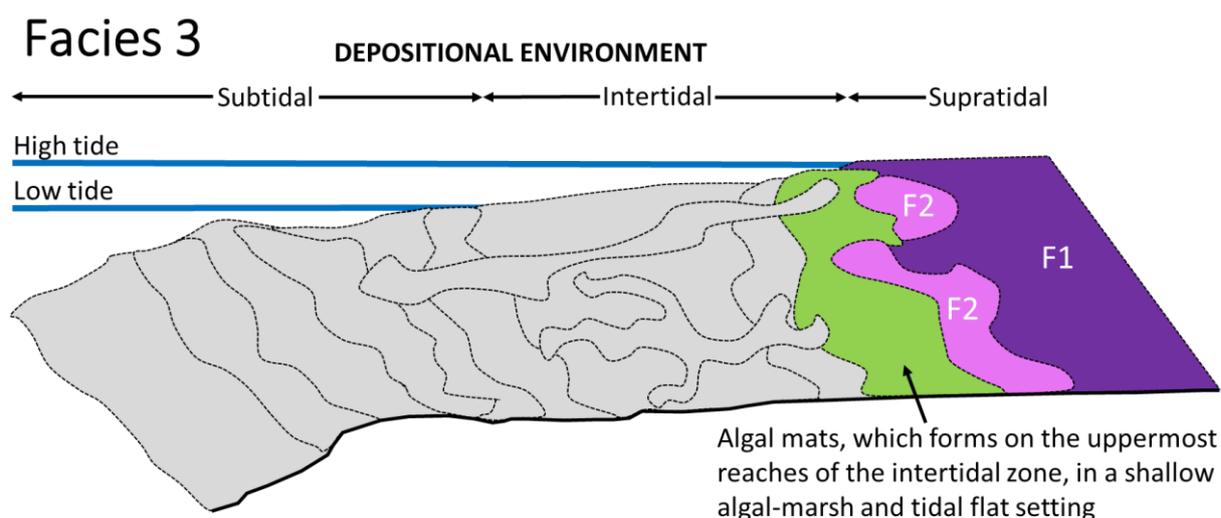
Figure 6.6. Continuation of the depositional model with algal mats (Facies 3) that represents the uppermost reaches of the intertidal zone, possibly in a shallow and open algal-marsh and tidal flat setting.

6 FACIES DESCRIPTION & INTERPRETATION

Facies 4 description: (D & LM) Dolomitic lime mudstone and lime mudstone

Facies 4 consists of tanned light grey to darker grey and light brown colored, dolomitic lime mudstone and lime mudstone. This facies generally lacks normal marine fauna and commonly have a massive and bioturbated texture, occasionally with visible irregular to more planar laminated sedimentary structures. Few skeletal fragments, peloidal grains and very few coral fragments are observed (Fig. 6.7). The thickness of this facies varies from a few centimetres to more than one meter. The maximum thickness is 2.3 meters in one particular bed, observed in the well, Donald Peterson 3-27. This particular well had extensive thickness of observed lime mudstone, which can be observed through the stacking pattern (Fig. 7.3). Facies 4 is primarily observed interbedded with algal mats (Facies 3), nodular anhydrite (Facies 2) and intraclastic wackstone-packstone (Facies 6), and less commonly with the subtidal facies as oolitic/peloid packstones (Facies 8 & 10) and bioturbated, skeletal wackestone (Facies 11). Facies 4 is common and abundant facies observed repeatedly throughout the entire stratigraphic section in all seven wells, and occurs according to the well logs, representing the top of the Bluell and Sherwood Member in both Members in all seven wells.
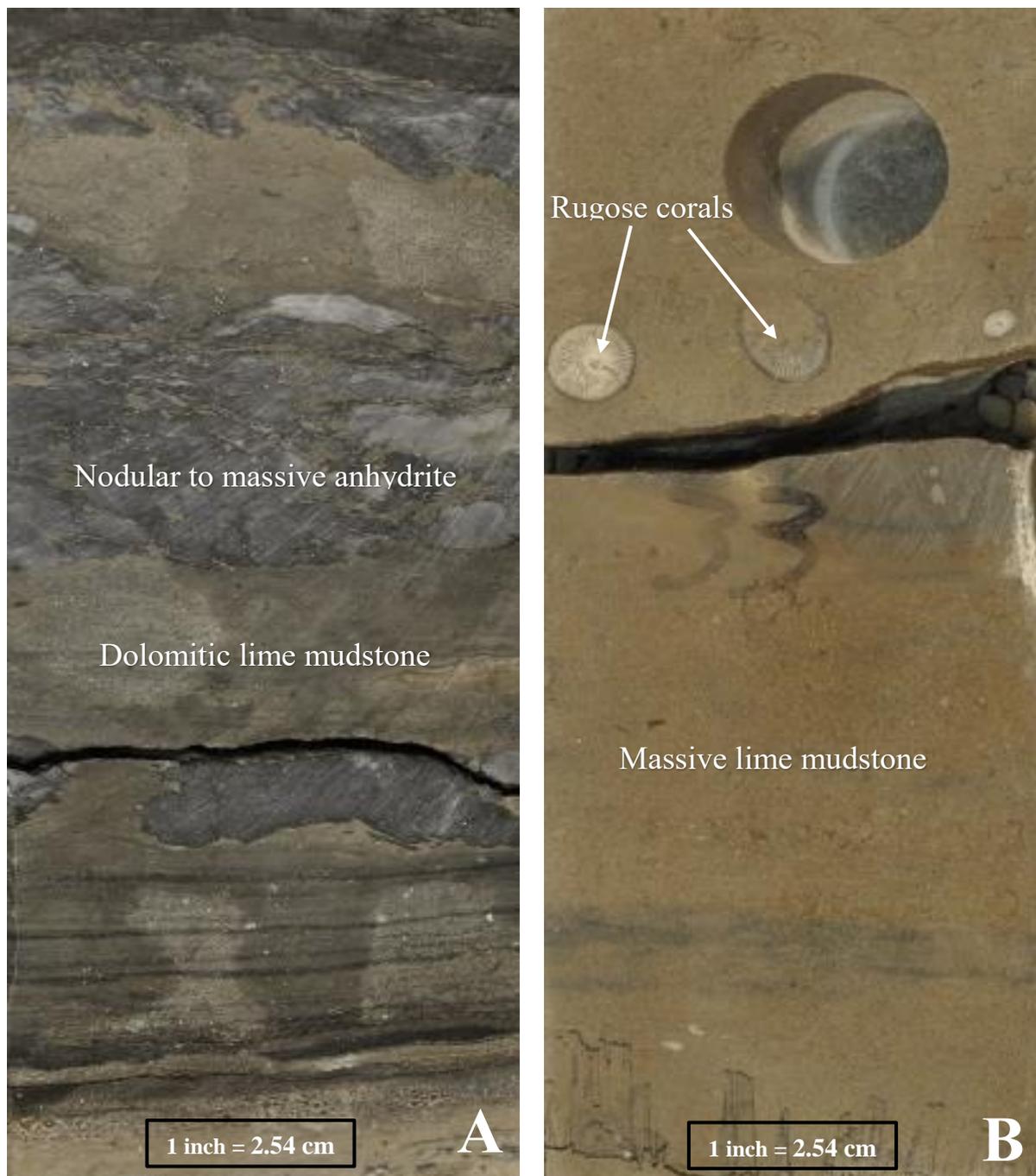
*Figure 6.7. **A).** Core slab from Siebert 1. Depth 1675 m (5496 feet). Shows the close interbedded association and fast variety of different facies with sharp contacts. Where facies 4 alternates between dolomitic lime mudstone (Facies 4) and nodular to massive anhydrite (Facies 1 & 2). **B).** Core slab from Donald Peterson 3-27. Depth 1686 m (5533 feet). Grey to light brown lime mudstone (Facies 4) with small black planar laminae of siliciclastic mudstone (Facies 5). Two intact rugose corals can be observed in the upper top with a few visible skeletal fragments.*

6 FACIES DESCRIPTION & INTERPRETATION

Interpretation

Working with core photographs alone and restricted well log data can make it hard to distinguish dolomitic and non-dolomitic mudstone facies apart, due the obvious similarity in both colour and texture, hence the name and description of facies 4. Consequently, similar visible textures based on color and fabric have been correlated against log data. However, where textures nor log data couldn't aid in the process to point out dolomitization, the description and interpretation was set as lime mudstone. Furthermore, the dolomitic lime mudstone based on core results, appear mainly to occur in association with lime mudstone.

Facies 4 was interpreted to represent shallow water conditions between the lowermost and uppermost intertidal flat environment (Fig. 6.8). Dolomitic lime mudstone is observed within uppermost reaches of intertidal flats, interbedded and associated with uppermost intertidal facies (Facies 1, 2 & 3). Similar analogues for this facies are the thin dolomitic layering and massive dolomitic lime mudstone facies with geometries, also linked to tidal-flat facies, deposited on a very broad shallow carbonate shelf within the upper Ordovician Red River Formation reservoirs in the Williston Basin (Lucia, 2007). Alternatively, Qing and Nimegeers (2008) described a similar alternation of dolomitic lime mudstone facies that suggest supratidal, evaporitic mud flats, with frequent wash overs events in the Midale Member (Mission Canyon Formation) in the Southeastern Saskatchewan, Canada.

The non-dolomitic lime mudstone in this study is abundant throughout large parts of the intertidal flat with observed planar laminae and thin wavy bedding, observed coral fragments and few visible grains, reflecting a more open and broad intertidal flat environment, possibly further seaward from the uppermost tidal flat with dolomitic lime mudstone. The observed interbedded alternations of thin centimetre lime mudstone beds within and between the deeper, subtidal facies as packstone-grainstone (Facies 8, 9 & 10), possibly reflects small subtle changes of relative sea level that occurred due to the very gently-dipping ramp environment that is widely known for the Mission Canyon Formation.

Facies 4
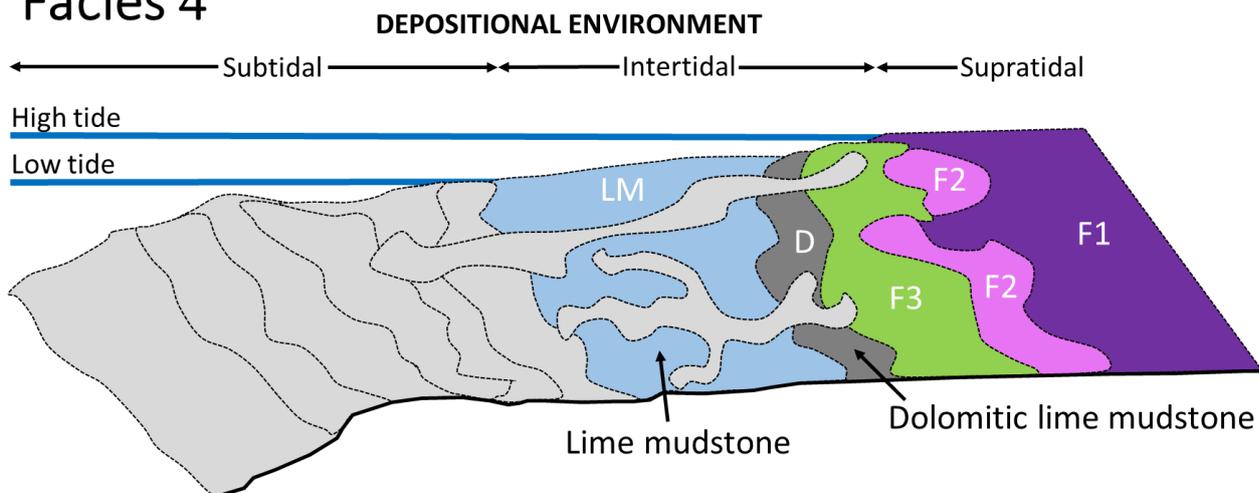
Figure 6.8. Continuation of the depositional model with dolomitic lime mudstone (D) and lime mudstone (LM) (Facies 4). The dolomitic lime mudstone is commonly observed within the uppermost intertidal zone and non-dolomitic lime mudstone is abundant and observed scattered over the open and broad intertidal zone.

Facies 5 description: Siliciclastic massive to planar laminated mudstone

This facies consists of very fine-grained, darker grey siliciclastic mudstone with only few visible grains and fragments (Fig. 6.9). Facies 5 is massive with a few planar laminated thin bed intervals and bed thickness range from 2 to 20 cm. Facies 5 are observed in all seven wells, within the Bluell and Sherwood Members and occur commonly as very thin massive or planar laminated beds, interbedded randomly between all other 10 facies with sharp contacts.

Figure 6.9. ***A).*** *Core slab from Laura Funke 4. Depth 1602,5 m (5257,5 feet). Light tan lime mud (Facies 4) with a massive structure and with an upper sharp contact into darker grey massive siliciclastic mudstone (Facies 5).* ***B).*** *Core slab from Donald Peterson 3-27. Depth 1700 m (5578 feet). Light brown lime mud matrix with scattered darker brown algae fragments from algal mats (Facies 3). Grades into light grey siliciclastic mudstone (Facies 5) with a sharp contact and visible black planar laminated structures.*

6 FACIES DESCRIPTION & INTERPRETATION

Interpretation

Facies 5 is interpreted as very fine sediments of siliciclastic mudstone, possibly entering the carbonate-dominated environment through fluvial pathways, deposited as suspended sediment fallout from periodic low-energy tidal or fluvial currents within the intertidal flat. These particular cm-scale, thin beds observed throughout the wells, typically with horizontal and planar laminae may reflect this suspension sediment fallout. Alternatively, facies 5 can be from storms events, which transfer large amount of sediments from one facies to another, as facies 5 was observed with sharp and irregular contacts, separating lower strata. This can be typical evidence on erosion from storm reworking sediments.

Mount (1984) describes mixing of siliciclastic and carbonate sediments in shallow ramp environments that occur both from suspension of sediment fallout and from erosion due to storm processes of peritidal carbonates, where the source are from nearshore belts and tidal flat siliciclastic sediments (Mount, 1984). However, primarily the observed beds are just a few centimetres thick and observed more commonly with repetitive interbedded associations in previously described shallow facies. This suggests that the deposition is more likely from sediment suspension of episodic low energy currents, from periodic low-energy tidal or fluvial currents within the intertidal flat.

As facies 5 very thin beds are not very typical and hard to determine where to primarily find this facies in this particular carbonate-dominated environment, it was decided that facies 5 is not included in the depositional model and stacking patterns and is only interpreted as irregular and occasional sediment from suspended sediment fallout from periodic low-energy tidal or fluvial currents within the intertidal flat.

6 FACIES DESCRIPTION & INTERPRETATION

Facies 6 description: Intraclastic wackestone-packstone

This facies consists of a mixed composition of very-poorly to poorly sorted, angular to rounded grains and skeletal fragments, mixed with intraclasts and pieces of algal fragments, which together is floating in a lime mudstone matrix (Fig. 6.2.1). No sedimentary structures can be observed and the thickness for facies 6 range between 10-50 cm, occasionally with a few beds reaching a thickness between 50-75 cm.

Facies 6 can be observed in all seven wells, reoccurring throughout both the Bluell and Sherwood Members. Primarily, the beds are thin and observed with sharp and irregular top and bottom boundaries that separate facies 6 from the frequently observed shallow related facies (Facies 2, 3 and 4). However, facies 6 can occasionally be observed with sharp bed boundaries with more seaward and subtidal facies, (Facies 7, 8, 9, 10 & 11). This part of the facies consists of a higher degree of rounded grains, mixed with mud intraclasts and skeletal fragments, compared to the more angular fragments and mud intraclasts texture, observed in the shallower and algal-rich facies (Facies 2, 3 & 4). The distribution of facies 6, accordingly to what member it was observed in, for each particular well can be further observed through the stacking patterns in chapter 7.

Figure 6.2.1. ***A).*** *Core slab from Siebert 1. Depth 1681 m (5514 feet). Light grey to brown intraclastic/peloid mixture. Grades into a thin bed with big rounded to angular grains with sharp contacts, indicating some sort of event of erosion and transport of reworked sediments.* ***B).*** *Core slab from Laura Funke 4. Depth 1623 m (5326 feet). Light tan intraclastic packstone with big pieces of lime mud intraclasts, peloid grains within a very poorly sorted and floating muddy texture.*

Interpretation

The poorly-sorted texture, and mixed composition of facies 6, which for the most part is made up by thin beds with sharp contacts to under- and overlaying beds. The sharp and irregular basal contact possibly was made due to subsequent and massive erosion, cutting through underlaying strata. This facies thus most likely represents lag deposits cross-cut by intertidal channels, developed from incised intertidal channels moving through the uppermost to the lowermost intertidal flat zone (Fig. 6.2.2) and possibly close to the subtidal zone, near the algal mounds, packstone and grainstone facies (Facies 7, 8, 9 & 10).

Alternatively, facies 6 could form due to episodic, high energy storm events, causing erosion and landward transport of coarser-grained sediments from packstone and grainstone shoals onto the more mud dominated intertidal flat areas. This could possibly be suggested from the beds that contains a higher degree of a rounded grain composition, containing higher degree of skeletal grains and peloids. Qing and Nimegeers (2008), described a similar intraclastic-pelodial packstone to wackestone facies, belonging to a back-barrier and wash-over environment, observed within the Midale Member in the Southeastern Saskatchewan, Canada.

However, due to the poorly-sorted texture, together with the mixed composition and wide diversity from angular intraclasts from lime mudstone and algal fragments to a more rounded grain composition, previously described and with the observation of sharp and irregular contacts to under- and overlaying beds. This facies, thus most likely represent lag deposits that are incised by intertidal channels, moving across the whole intertidal flat, from the uppermost and lowermost intertidal zone, and possibly close to the subtidal zone, near the algal mounds, packstone and grainstone facies (Facies 7, 8, 9 & 10).
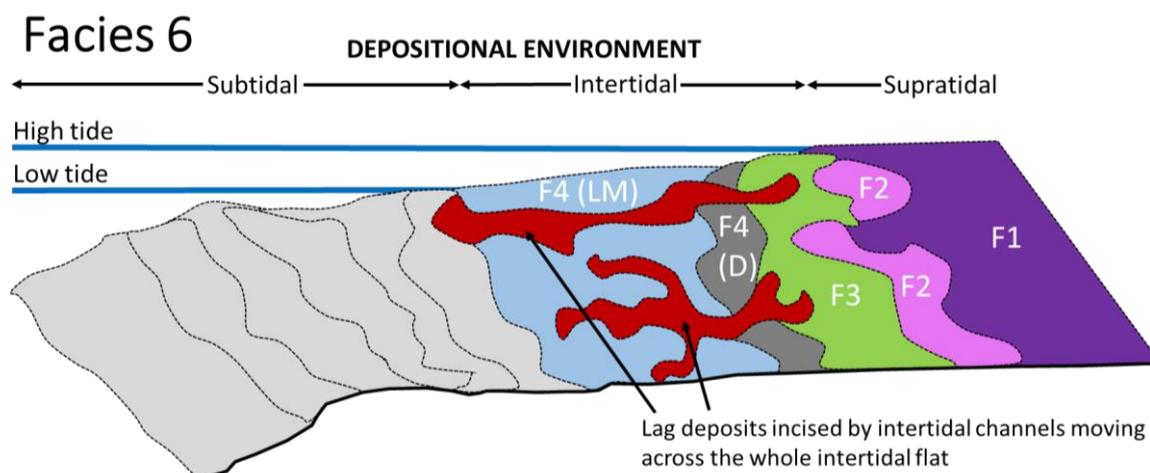
Figure 6.2.2. Continuation of the depositional model with the intraclastic wackestone-packstone (Facies 6) that represent lag deposits developed from incised intertidal channels. Moving through the uppermost to the lowermost intertidal flat zone and possibly near the subtidal zone.

6 FACIES DESCRIPTION & INTERPRETATION

Facies 7 description: Algal mounds - stromatolites

Facies 7 consists of a poorly sorted mixture of large, almost vertical algal fragments and intraclasts with visible and well sorted debris of peloids and oolitic grains, which are mixed with lime mudstone (Fig. 6.2.3). Facies 7 different types of observable algal fragments have similarities to facies 3 algal mats, but facies 7 have a higher degree of well sorted debris of peloids and oolitic grains, and the texture lacks the horizontal lamination observed within facies 3. Facies 7 is described as algal mounds from stromatolites and these algal mounds develop low-relief domes and columns in the subtidal zone, as the microbes slowly move upwards against the water surface to avoid being smothered by sediment deposited on them by water (Riding, 2000). No sedimentary structures are common due to chaotic structure and visible erosion. The observed thickness for facies 7, range between 20 to 100 cm. The bed boundaries observed are lime mudstone (Facies 4), intraclastic wackestone-packstone (Facies 6), packstone and grainstone (Facies 8, 9 & 10) and bioturbated, skeletal wackestone (Facies 11).

Facies 7 was observed in four out of the seven wells, with the exception of Donald Peterson 3-27, Nailor Trust 1 and Schlak 2. According to the well logs representing the top of the Bluell and Sherwood Member, the wells furthest to the east (Laura Funke 4 and Funke 1) had observed algal mounds within the Sherwood Member. (Siebert 1 and Epex-Weber 28-9 had observed algal mounds within the Bluell Member. The distribution of facies 7, accordingly to what member it was observed in, for each particular well can be further observed through the stacking patterns in chapter 7.
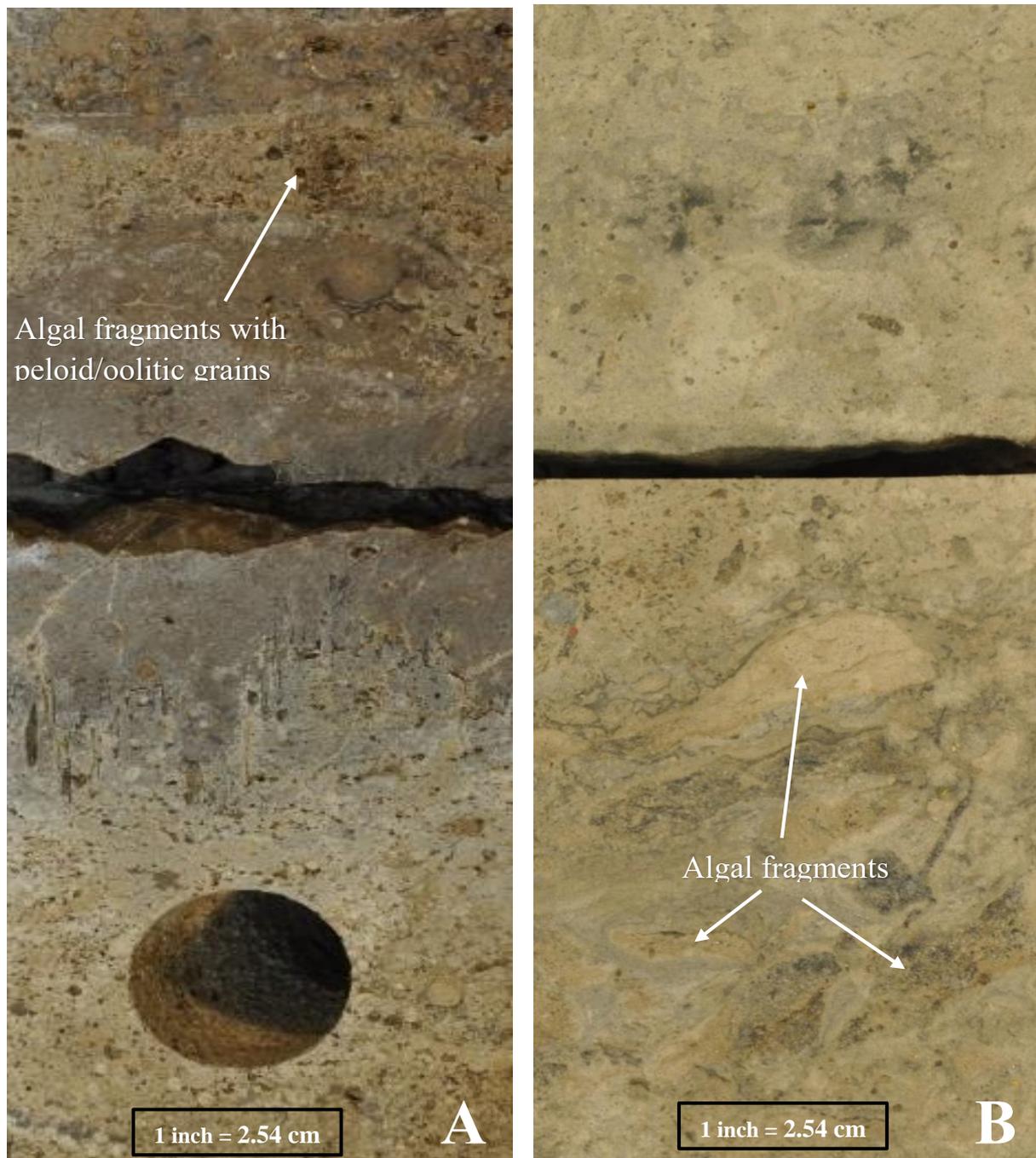
Figure 6.2.3. ***A).*** *Core slab from Siebert 1. Depth 1685.239m (5529 feet). Peloid to oolitic golden, brown grainstone (Facies 10) grading into the algal mounds (Facies 7) with well sorted visible grains, trapped within pieces of stromatolites.* ***B).*** *Core slab from Funke 1. Depth 1625,5 m (5333 feet). Chaotic muddy structure with pieces of algal mounds-stromatolites fragments.*

6 FACIES DESCRIPTION & INTERPRETATION

Interpretation

The diversity with more vertical and larger pieces of broken algal fragments and well sorted debris of peloid and oolitic grains in facies 7, is interpreted to be from algal mounds – stromatolites that develop low-relief domes and columns. They differ from facies 3, both in texture and structure because facies 7, lack the horizontal lamination observed within facies 3. Hence, the two different interpretations for the algal fragments, observed during the core interpretation phase. These interpreted mounds can be found further seaward, compared to facies 3 flat algal mats, which is near the shallow subtidal, close to the lowermost intertidal zone (Fig. 6.2.4).

These algal mounds – stromatolites slowly move upwards to the water surface to avoid being smothered by sediment, deposited from the shallow water surface on ramps that have uniform, gentle slopes that extend out into the adjacent basin (Riding, 2000). These stromatolites are prime examples of different layers of cyanobacteria and sediments developing into structures, such as domes and columns (Riding, 2000). Famous analogues of modern carbonate ramps include the Shark Bay, western Australia were modern analogues with old stromatolites can be observed. These are made up of coarse domes and columns with complex bacterial algae within the subtidal zone (Riding, 2000).
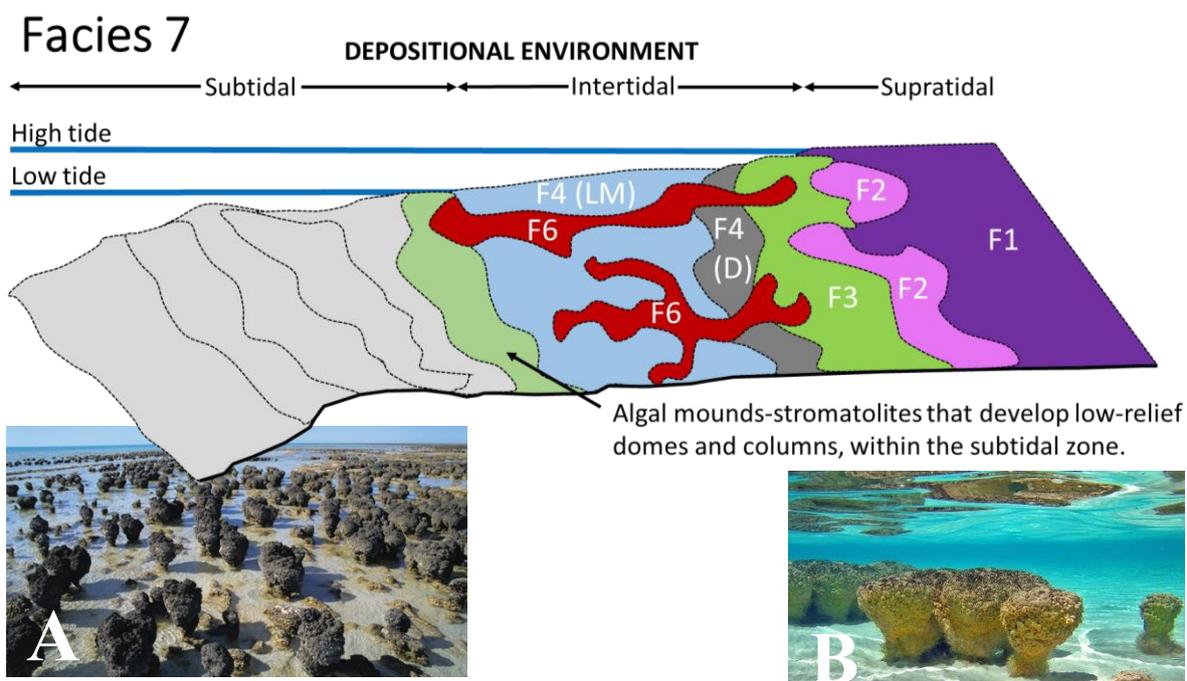
*Figure 6.2.4. Continuation of the depositional model with algal mounds-stromatolites (Facies 7). This facies represent stromatolites that develop domes and columns within the subtidal zone on ramps that have uniform, gentle slopes that extend out into the adjacent basin (Riding, 2000). The two images; **A)**. shows a modern analogue from old stromatolites formed in Hamelin pool, which can be viewed at Shark Bay, western Australia. **B).** Visualizes how stromatolites develop these low-relief domes and columns under water in the shallow subtidal zone.*

6 FACIES DESCRIPTION & INTERPRETATION

Facies 8 description: Cemented peloidal packstone

Facies 8 consists dominantly of intermediate sorted packstone with subordinate amounts of interbedded lime mudstone. Grain types primarily include peloids, intraclasts, pisoids, ooids and minor skeletal fragments (Fig. 6.2.5).

Few sedimentary structures are observed as planar stratification, low angle lamination and wavy laminae but typically, the sedimentary structures and grains within the facies were occasionally hard to distinguish, due to solution-enhanced moldic to vuggy porosity. The observed moldic to vuggy porosity in facies 8 was completely infilled and highly cemented and no oil stains was never observed together with facies 8.

The bed thickness for this facies has a wide alternation between 15 to 25 cm and 65 to 90 cm beds. The maximum thickness was observed in Schlak 2 with a thickness at 130 cm. Facies 8 bed boundaries was observed to have a close interaction with the well-sorted oolitic-peloidal packstone and grainstone beds (Facies 9 & 10) but was also observed with either intraclastic wackestone-packstone (Facies 6), algal mounds - stromatolites (Facies 7) and occasionally with skeletal, bioturbated wackestone (Facies 11).

Facies 8 was observed in all seven wells and according to the well logs representing the top of the Bluell and Sherwood Member, the wells, Laura Funke 4, Siebert 1 and Schlak 2, had facies 8 in the Bluell and Sherwood Members. Facies 8 in the wells Funke 1, and Epex Weber 28-9 was only observed in the Bluell Member. The well, Donald Peterson 3-27 only contained facies 8 in the Sherwood Member. The distribution of facies 8, accordingly to what member, can further be observed through the stacking patterns in chapter 7.
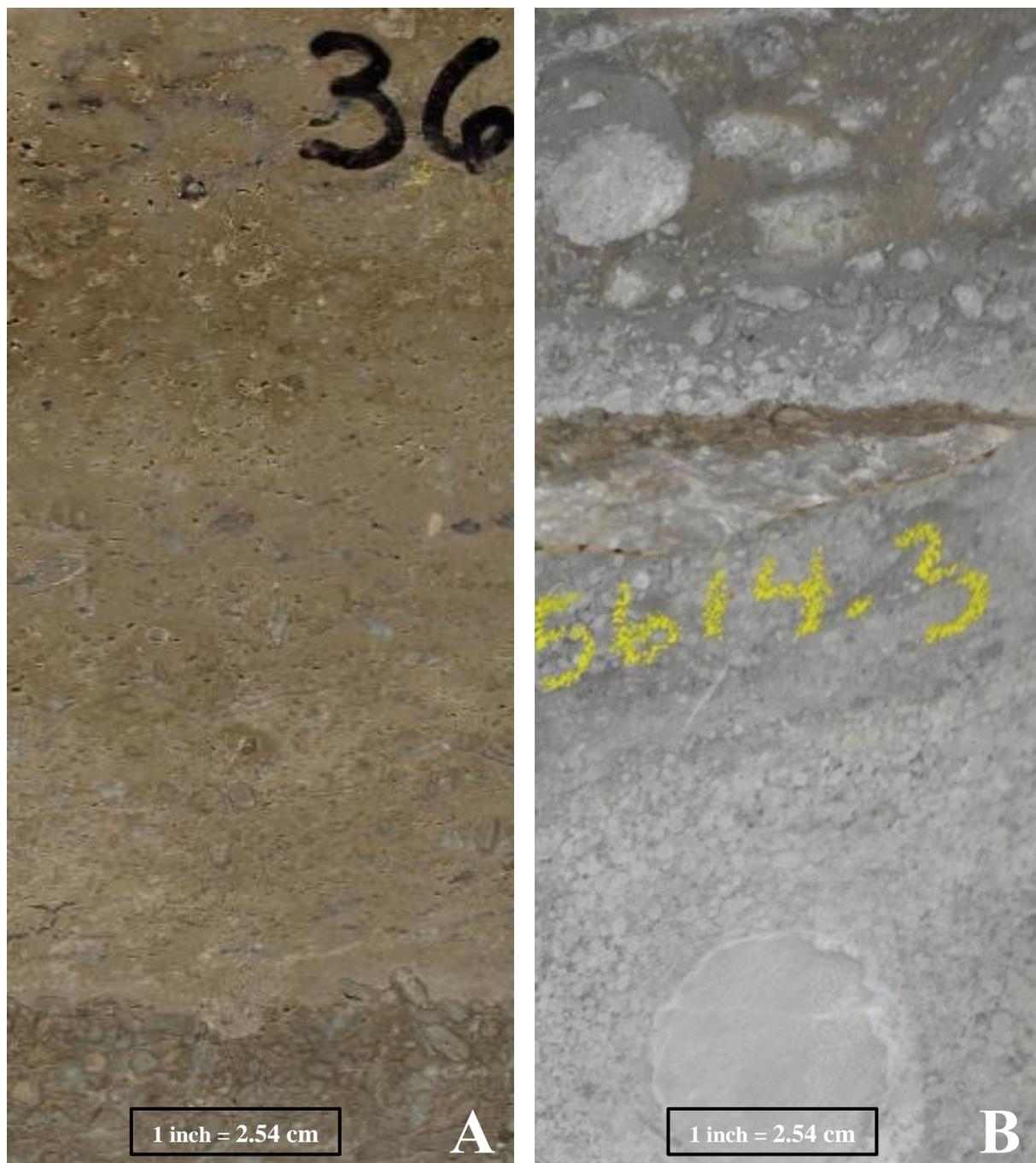
*Figure 6.2.5. **A)**. Core slab from Epex Weber 28-9. Depth 1688 m (5537 feet). Consisting of light brown cemented packstone (Facies 8) with trace of poor vuggy porosity, but note that it's completely infilled with cement. In the upper part, facies 8 starts to grade gradually into the more open packstone (Facies 9) with open moldic to vuggy porosity. **B)**. Core slab from Nailor Trust 1. Depth 1711 m (5615 feet). Light grey, cemented peloid packstone (Facies 8) with large calcite nodule in the lower part. Grading upwards into intraclastic wackstone-packstone with sharp and distinct contact (Facies 6).*

6 FACIES DESCRIPTION & INTERPRETATION

Facies 9 description: Oolitic-peloidal packstone

Facies 9 consists of well to very well sorted packstone, with subordinate amounts of interbedded lime mudstone and the grain types primarily include peloids, intraclasts, pisoids, ooids, and minor skeletal fragments (Fig. 6.2.6). Sedimentary structures were observed as planar stratification, low angle lamination and wavy to cross-bedding laminae. Typically, these sedimentary structures were uncommon and together with the grain composition in the cores photographs, it could sometimes be obscured, due to the dissolution and formation of solution-enhanced moldic to vuggy porosity. The observed moldic to vuggy porosity is primarily well developed, and open or just partly infilled with cement.

The bed thickness commonly ranges between 40 to 75 cm and the maximum thickness observed is 155 cm (Laura Funke 4). Facies 9 bed boundaries was observed to have a close interaction with the packstone and grainstone beds (Facies 8 & 10), but also with intraclastic wackestone-packstone (Facies 6), algal mounds-stromatolites (Facies7) and skeletal, bioturbated wackestone (Facies 11).

Facies 9 is observed with combined and interbedded alternation with the oolitic-peloidal grainstone (Facies 10), which can be observed in the wells, Laura Funke 4, Funke 1, Epex Weber 28-9, Siebert 1, and Schlak 2. The total thickness for these two facies can create beds up to over 2 to 3 meters. These types of combined beds commonly contain every observed oil staining in the wells. Every oil staining observed in six out of the seven wells (exception, Donald Peterson 3-27) was observed together within these two facies, which makes facies 9 and 10 possibly the best reservoirs in the study area.

Alone facies 10, the facies 9 can be observed in six out of seven wells, with the exception of Donald Peterson 3-27. The wells Laura Funke 4, Funke 1, Epex Weber 28-9, Siebert 1 and Schlak 2 have facies 9 stratigraphically in the lower and upper part of the cores within both Bluell and Sherwood Members. The well Nailor Trust 1 have facies 9 in the lower parts of the well within the Bluell Member. The distribution of facies 9, accordingly to what member it was observed in, can be further observed through the stacking patterns in chapter 7, together with observed oil staining.

*Figure 6.2.6. **A).** Core slab from Epex Weber 28-9. Depth 1679 m (5507 feet). Brown oolitic-peloid packstone with few skeletal fragments (Facies 9). Enhanced well to very well moldic to vuggy porosity with dark brown oil stains can be observed. **B).** Core slab from Laura Funke 4. Depth 1597 m. (5241 feet). Different type of a lighter grey, well sorted oolitic to peloid packstone (Facies 9) with a few mud laminae and visible enhanced solution moldic to vuggy porosity.*

6 FACIES DESCRIPTION & INTERPRETATION

Facies 10 description: Oolitic-peloidal grainstone

Facies 10 consists commonly of well to very well sorted grainstone with ooids, pisoids and peloids grains, together with a few cases of moderately sorted grainstone with minor quantities of skeletal debris and fragments (Fig. 6.2.7). Sedimentary structures were observed as low angle lamination and wavy to cross-bedding. Typically, these sedimentary structures were uncommon and together with the grain composition in the cores photographs, it could sometimes be obscured, due to the dissolution and formation of solution-enhanced moldic to vuggy porosity. The observed moldic to vuggy porosity is primarily well developed, and open or just partly infilled with cement, in a few cases, similar to facies 9

The thickness varies for facies 10 and occurs primarily as beds between 20 to 75 cm. The maximum thickness was observed within the well Siebert 1, as a 130-cm thick bed. Facies 10 is observed with combined and interbedded alternation with the oolitic-peloidal packstone (Facies 9), which can be observed in the wells, Laura Funke 4, Funke 1, Epex Weber 28-9, Siebert 1, and Schlak 2 in the stacking patterns in chapter 7. The total thickness for these two facies can create beds up to over 2 to 3 meters. These types of combined beds commonly contain every observed oil staining in the wells and all oil staining observed in six out of the seven wells (exception, Donald Peterson 3-27) was observed together within these two facies, which makes facies 10 and 9 possibly the best reservoirs in the study area. Facies 10, bed boundaries are primarily observed with intraclastic wackestone-packstone (Facies 6), cemented peloidal packstone, (Facies 8), oolitic and peloidal packstone (Facies 9) and bioturbated, skeletal wackestone (Facies 11).

Facies 10 can be observed in five out of seven wells, with the exception of Donald Peterson 3-27 and Nailor Trust 1. Within the wells Laura Funke 4, Siebert 1, Epex-Weber 28-9 and Schlak 2, facies 10 could primarily be observed in the Bluell Member and at the lower part of the cores in the Sherwood Member. Facies 10 in the well Funke 1, was observed within the mid and top core section in the Bluell Member. The distribution of facies 10, accordingly to what member it was observed in, can further be observed through the stacking patterns in chapter 7, together with observed oil staining.

*Figure 6.2.7. **A).** Core slab from Epex Weber 28-9. Depth 1687 m (5517 feet). Light grey, brown oolitic to pisolitic grainstone with darker brown oil stains and enhanced moldic to vuggy porosity. **B).** Core slab from Siebert 1. Depth 1696 m (5563 feet). Light brown grainstone with enhanced moldic to vuggy porosity. No visible textures of sedimentary structures and grain composition due to the dissolution.*

6 FACIES DESCRIPTION & INTERPRETATION

Interpretation (Facies 8, 9 & 10)

The grain composition, primarily well sorted nature, the majority of oolitic, peloid and pisolitic grain types, together with the lack of extensive thickness. All these characteristics, combined with observed sedimentary structures, such as low angle stratification, cross-bedding and wavy laminae and the distribution of beds, commonly within the decimetre, rather than metre scale. This suggests that facies 8, 9 and 10 were deposited as subtidal, low relief shoals that underwent earlier, extensive reworking and abrasion in a shallow, open marine within a higher energy and wave-dominated environment characterised by subtle shoaling and these thin subtidal shoals (Fig. 6.2.8). These 2-3 m shoals can't much likely support a back-barrier zone or lagoon environment, thus the described wide and open tidal flat setting in previous facies descriptions.

In comparison to similar analogues from Qing and Nimegeers (2008), which described a similar packstone and grainstone facies, but within a protective shoal-barrier environment observed within the Midale Member in the Southeastern Saskatchewan, Canada. These facies also include cross-bedding, planar stratification and laminations in beds that can reach a maximum thickness of about 6 meters, with similarities to the barrier-island of northern Andros Island, Bahamas (Qing and Nimegeers, 2008). But he mentioned this described thickness and protection from these shoal-barrier islands, allows a transition from a more high-energy shoaling environment to a lower-energy lagoon/back-barrier setting, where the sufficient and thick barrier island can create a back-barrier lagoon environment. Although, this will be further discussed in the discussion chapter 8 of the depositional environment.
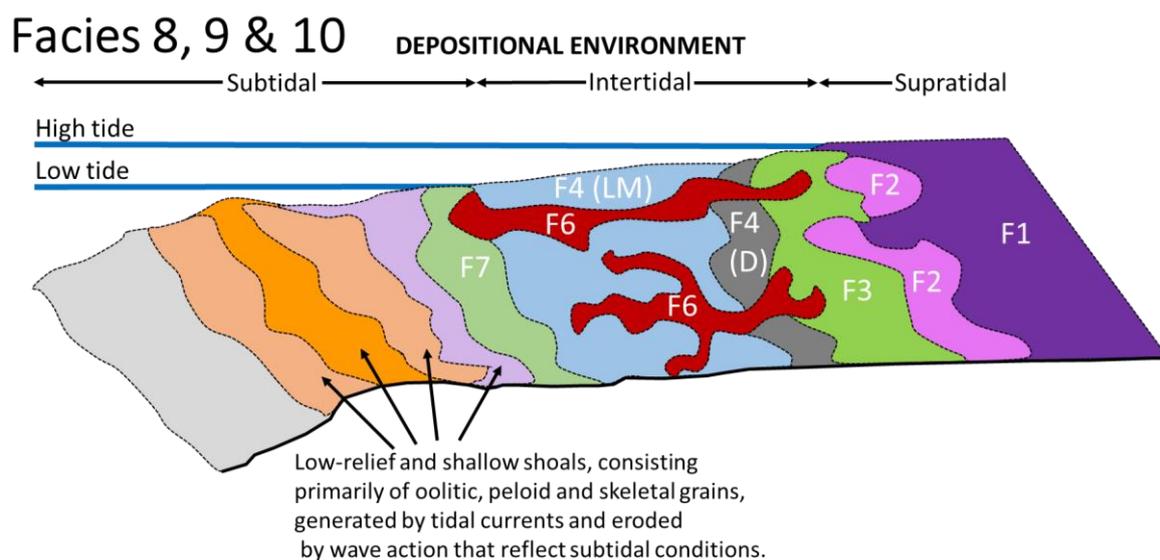
Figure 6.2.8. Continuation of the depositional model for facies 8, 9 & 10. These facies represent the shallow subtidal zone as low relief shoals that underwent earlier, extensive reworking and abrasion generated by tidal currents and eroded by wave action within an open and shallow marine environment.

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6 FACIES DESCRIPTION & INTERPRETATION

Facies 11 description: Bioturbated, skeletal wackestone

Facies 11 consist of tanned, light grey to brown colour of lime mudstone with few gravel, skeletal fragments and occasionally a few intraclasts (Fig. 6.2.9). The lack of clear sedimentary structures, possibly due to extensive bioturbation by a burrow-mottled appearance, with no clear traces and occasionally crinoids fragments was also observed in this facies. The thickness for facies 11 ranges commonly between 40-100 cm, but was occasionally observed to be only a few cm thick. The maximum thickness of 130 cm was observed in the well Siebert. Facies 11 bed boundaries were observed primarily with the subtidal pack-grainstone facies (Facies 8, 9 & 10) and occasionally with intraclastic wackestone-packstone (Facies 6) and algal mounds (Facies 7). Facies 11 was observed in all seven wells, throughout both the Bluell and Sherwood Members. The distribution of facies 11, accordingly to what member it was observed in, can further be observed through the stacking patterns in chapter 7.

*Figure 6.2.9. **A).** Core slab from Siebert 1. Depth 1699 m (5574 feet). Tan to light brown massive and bioturbated wackestone with a few dissolved skeletal fragments. **B).** Core slab from Donald Peterson 3-27. Depth 1689 m (5542 feet). Tan to light brown massive and bioturbated wackestone with a few dissolved skeletal fragments.*

Interpretation

Facies 11 was interpreted to be deposited in a subtidal, open marine in a predominantly low to moderate energy setting, which is characterized by the diverse skeletal assemblage and extensive bioturbated muddy, fine-grained matrix. Facies 11 is possibly formed further seaward from the packstone and grainstone facies (Facies 8, 9 & 10). Where the few skeletal grains and fragments have been carried out from the low-relief shoals during periodic higher energy or storm events (Fig.6.3.1).

Most of the skeletal assemblage have been dissolved within the facies and thus making it hard to identify these fragments. However, crinoids were observed in the well, Laura Funke 4 and extensive bioturbation is inferred by an overall burrow-mottled appearance, with no clearly visible traces. Usually the wide diversity of fossil and trace fossil assemblages are characteristic of a normal-marine subtidal setting in a predominantly low to moderate energy regime. Qing and Nimegeers (2008) describe a similar bioturbated fossiliferous wackestone facies in an open to semi restricted marine subtidal environment in the Midale member in Southeastern Saskatchewan, Canada. Although, his facies was described with a higher diversity of skeletal assemblage including crinoids, Syringapora and rugose corals, brachiopods and bivalves (Qing and Nimegeers, 2008).
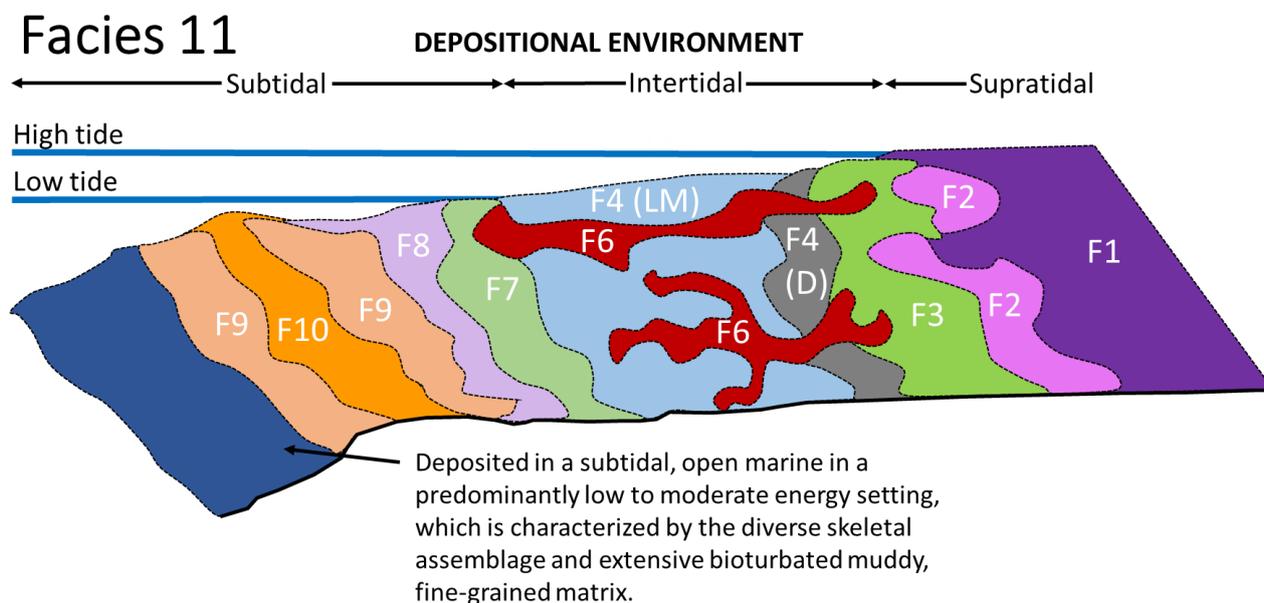
Figure 6.3.1. Continuation of the depositional model with facies 11. The wide diversity of fossil and trace fossil assemblages are characteristic of normal-marine subtidal settings in a predominantly low to moderate energy possibly formed further seaward from the packstone and grainstone (Facies 8, 9 & 10).

6 FACIES DESCRIPTION & INTERPRETATION

CHAPTER 7   FACIES STACKING PATTERNS

The digital core data stored within the digital templates was used to create seven digital stacking patterns, where each identified facies, including thickness was displayed, with the exception of siliciclastic mudstone (Facies 5), due to the irrelevance of this thin facies within this particular carbonate-dominated depositional environment.

The stacking patterns made for each particular well in the study area allowed the visualising of the facies distribution and their individual thickness within the depositional system, displayed through time. These seven stacking patterns can be observed in the next seven pages within figures 7.1. to 7.7. The distribution of each of the reservoirs with oil staining and the thickness that was determined from the core results can also be observed within the facies stacking patterns.

The seven stacking patterns allowed each of the involved facies throughout the wells to be displayed, representing if the depositional system moves landward or basinward through time, which is reflected in the occurrence of movement from deeper facies to more shallow facies. These so called regressive and transgressive events were set to reflect either upward shallowing and overall basinward progradation or the upward deepening and overall landward retrogradation for the depositional ramp system. They consist of a series of upward shallowing sequences bounded, at the base and top, of a regressive surface, which is the anhydrite and this marks the shallowest part in time within the depositional system (supratidal). Where the occurrence of later, and repeated deeper facies indicates this marine flooding surface and the marks the boundary to the next overlying unit with upward deepening of facies. As such, these are called depositional sequences, bounded at the base and top by marine flooding surfaces.

The depositional sequences are only set where sufficient core could display both shallowing and deepening of facies into a set depositional sequence and do not take into account the smallest facies variations seen in the stacking patterns because this is considered due to lateral (highly localised) facies variations rather than having a rather than having a significant stratigraphic importance. Instead the depositional sequences reflect the general significant stratigraphic importance of upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
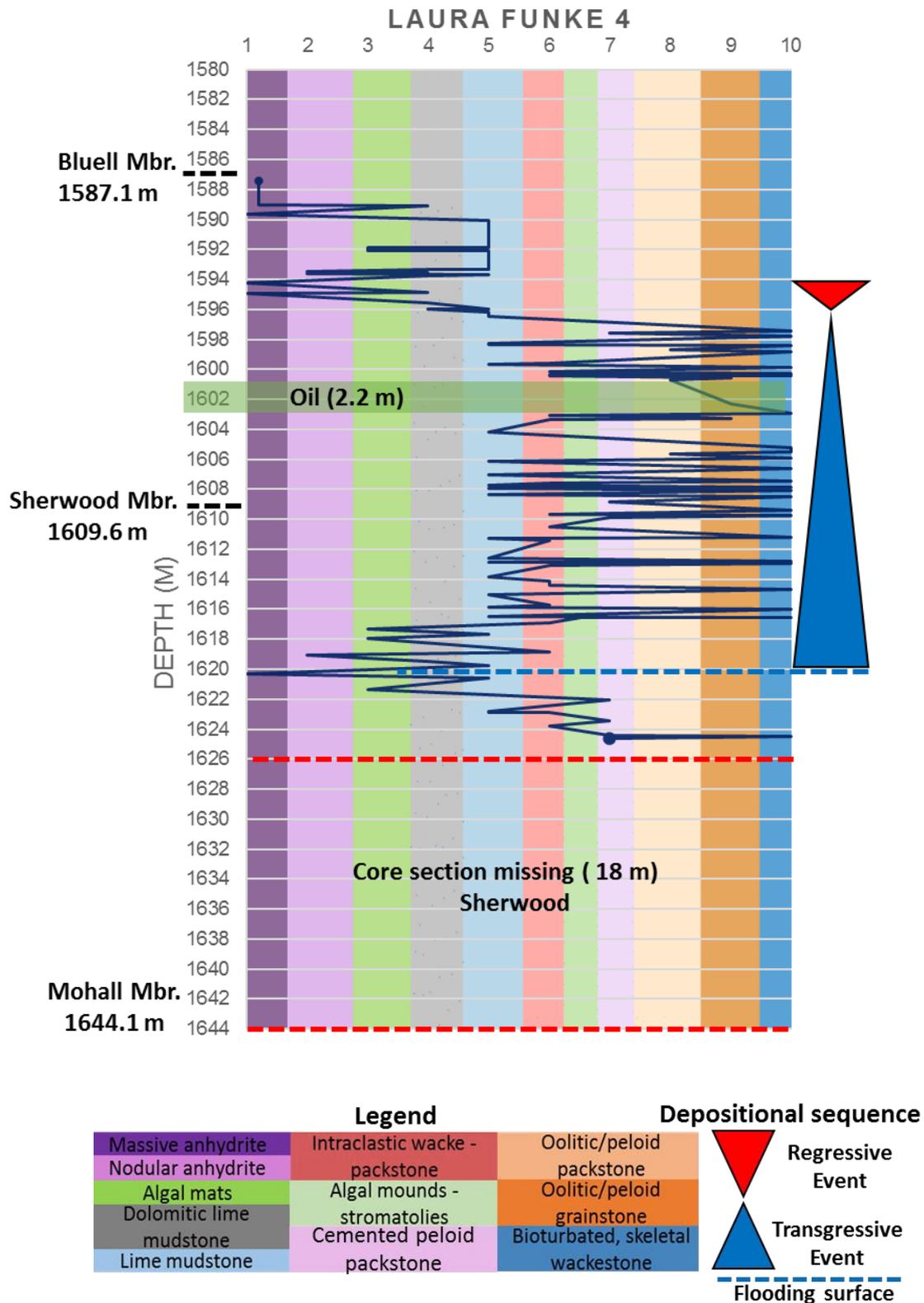
Figure 7.1. Stacking pattern for Laura Funke 4 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies. Note the whole depositional sequence in this well that reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
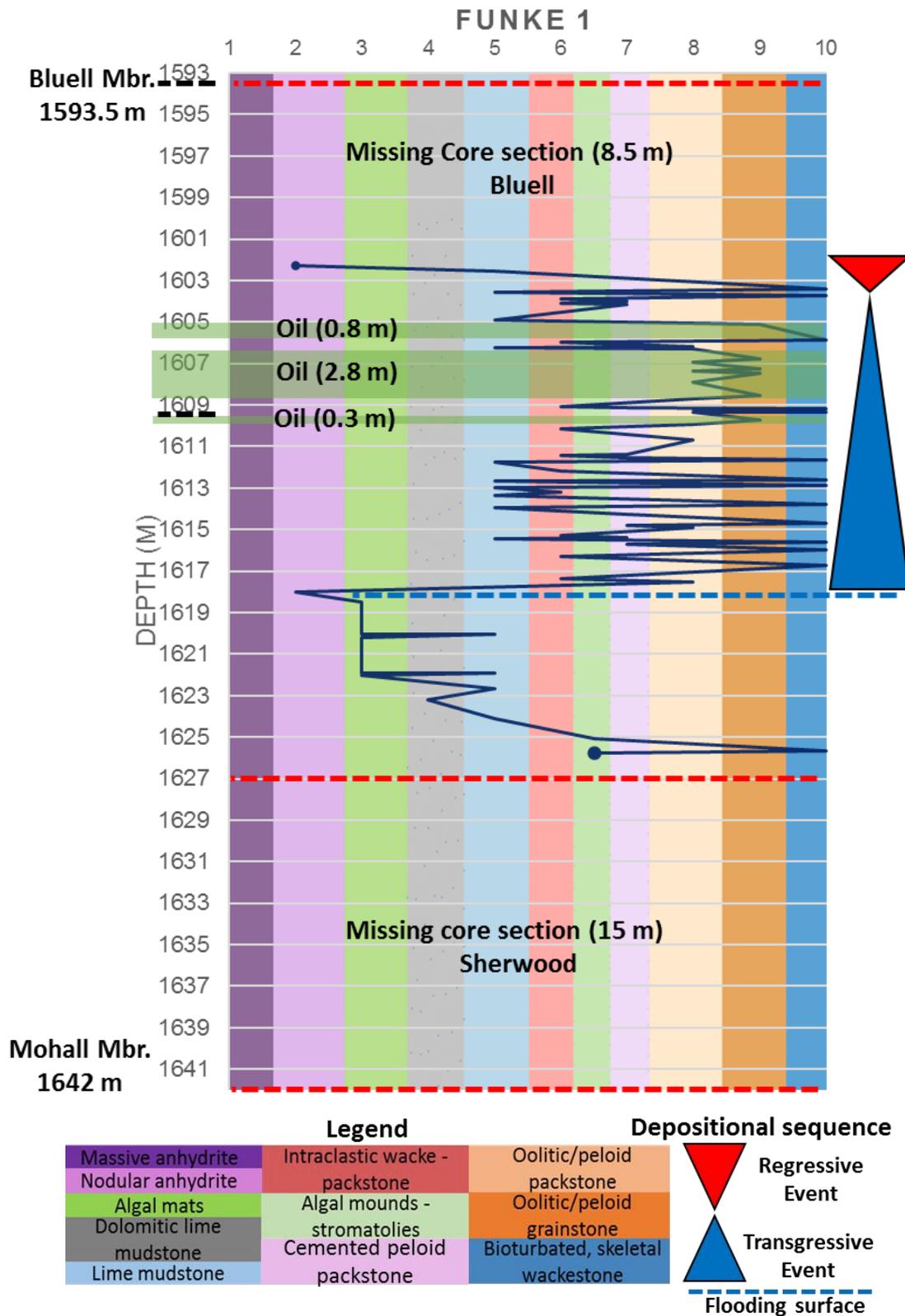
Figure 7.2. Stacking pattern for Funke 1 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies. Note the whole depositional sequence in this well that reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
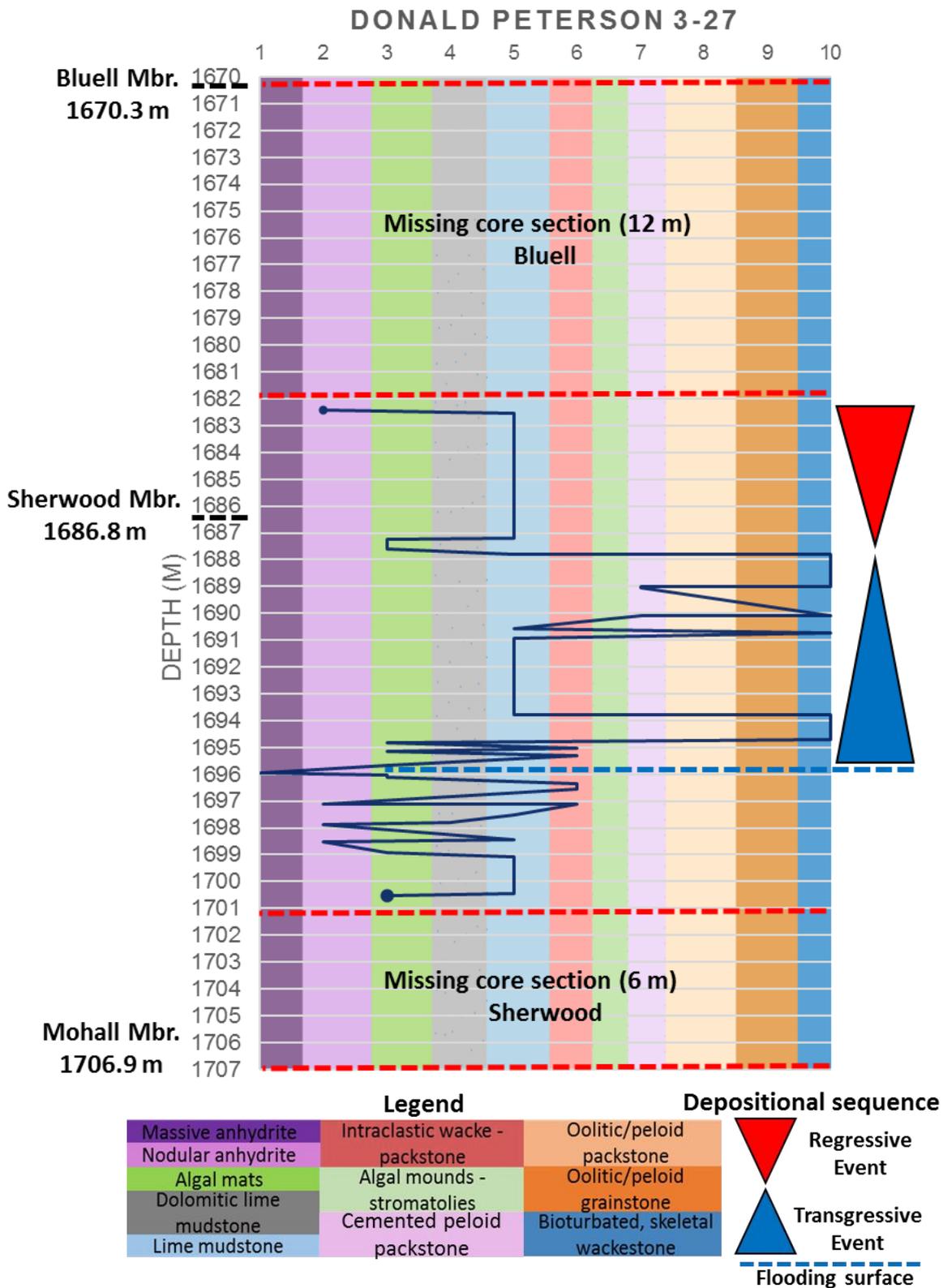
Figure 7.3. Stacking pattern for Donald-Peterson 3-27 with well log top markers for Mohall, Sherwood and Bluell Members. Note no observed oil and no packstone/grainstone reservoir facies with much thicker facies beds, compared to the other wells. Note the whole depositional sequence in this well that reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
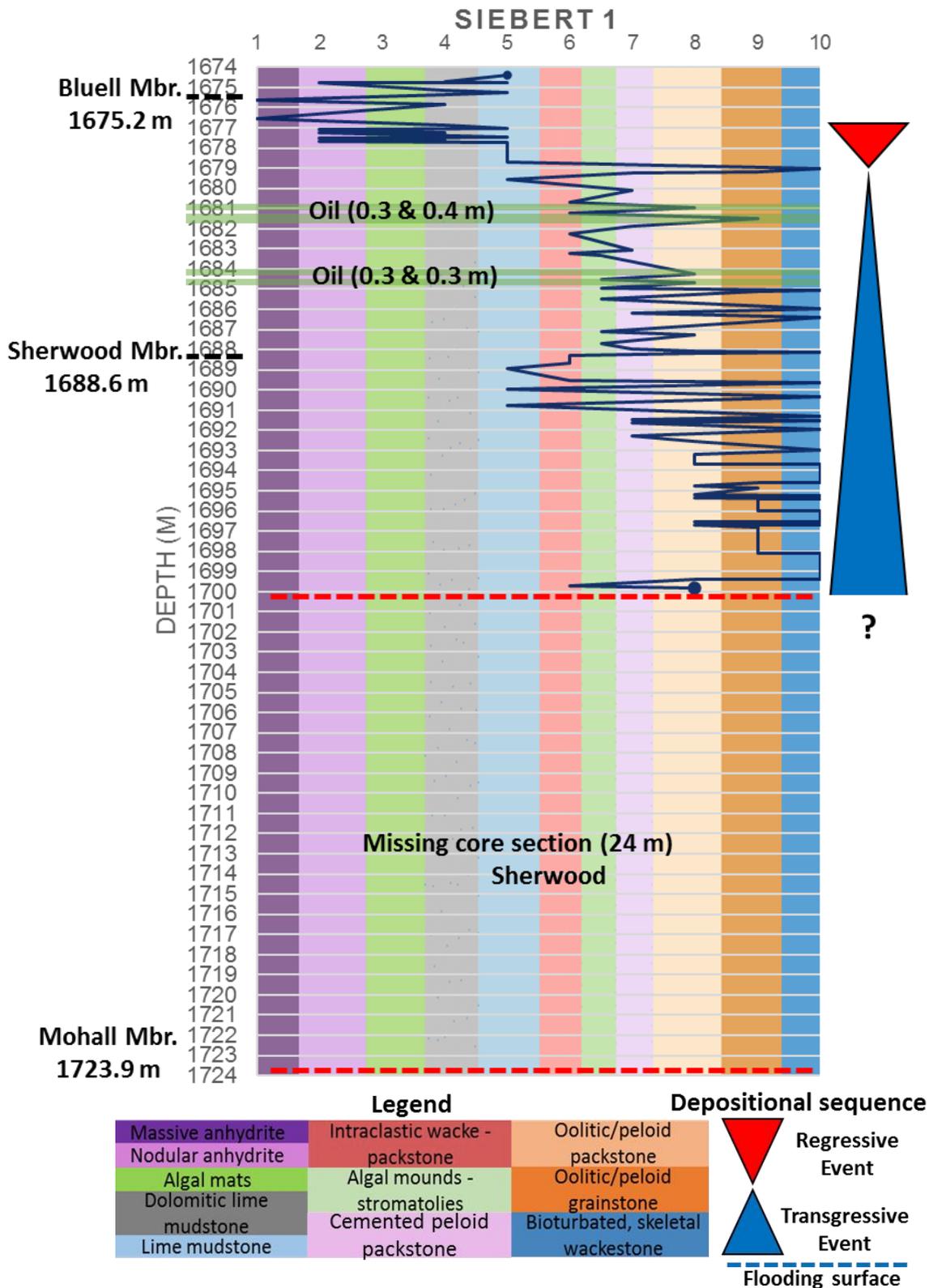
Figure 7.4. Stacking pattern for Siebert 1 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies. Note that the depositional sequence is not from the shallowest part in time for the system, due lack of sufficient core material. Still the depositional sequences reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
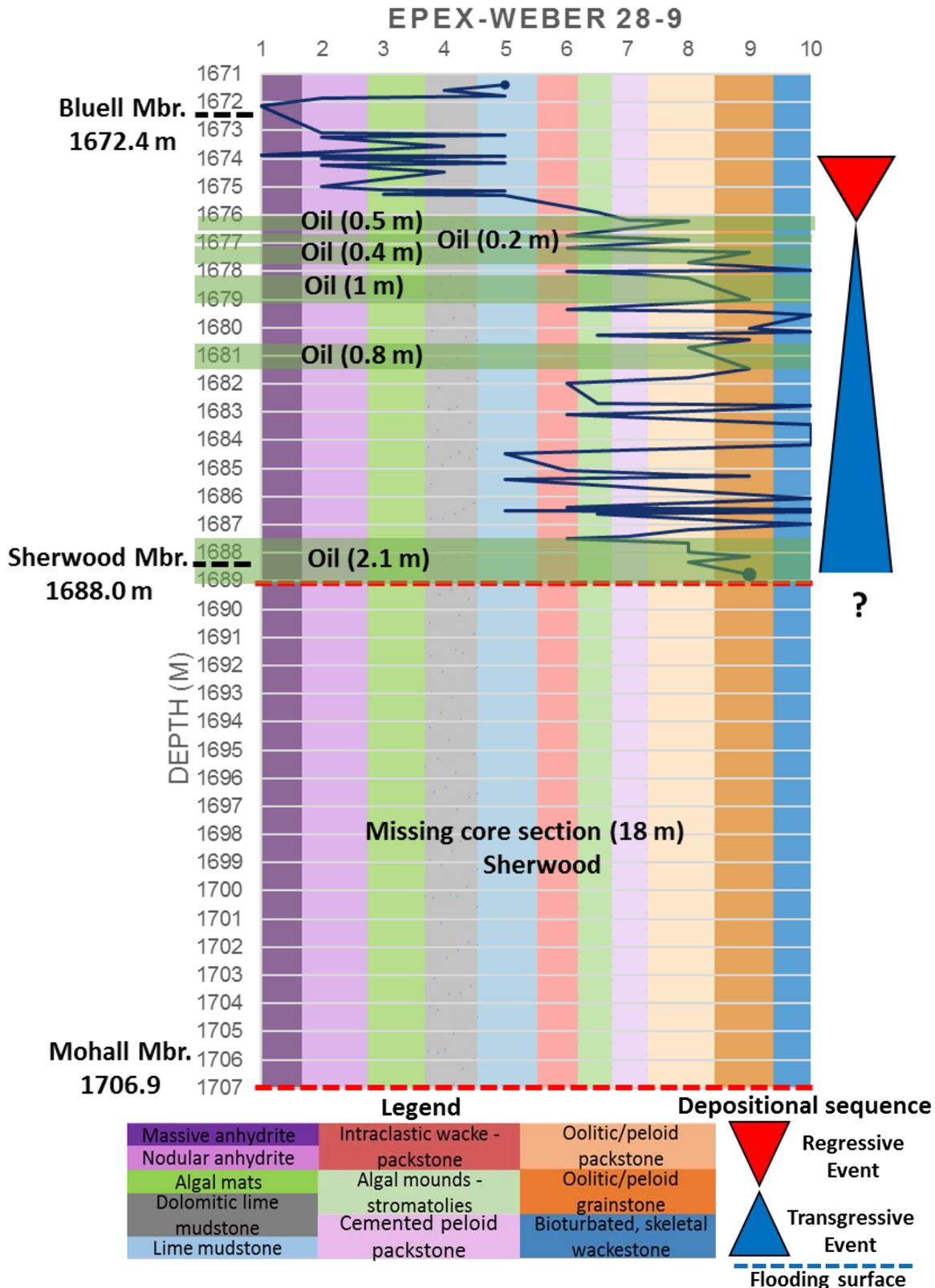
Figure 7.5. Stacking pattern for Epex-Weber 28-9 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies. Note that this particular well has the most extensive reservoir. Note that the depositional sequence is not from the shallowest part in time for the system, due lack of sufficient core material. Still the depositional sequences reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
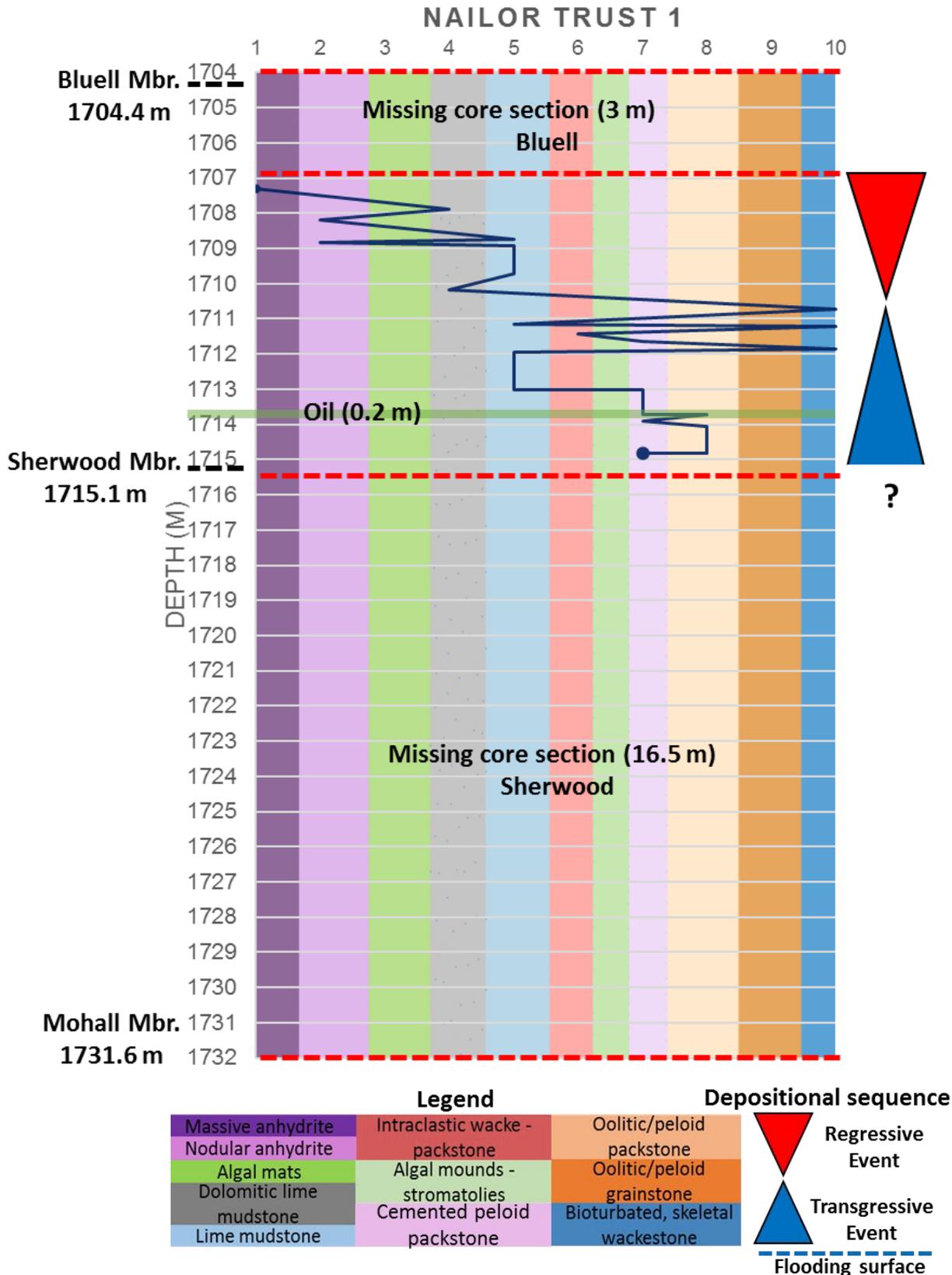
Figure 7.6. Stacking pattern for Nailor Trust 1 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies Note that the depositional sequence is not from the shallowest part in time for the system, due lack of sufficient core material. Still the depositional sequences reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.
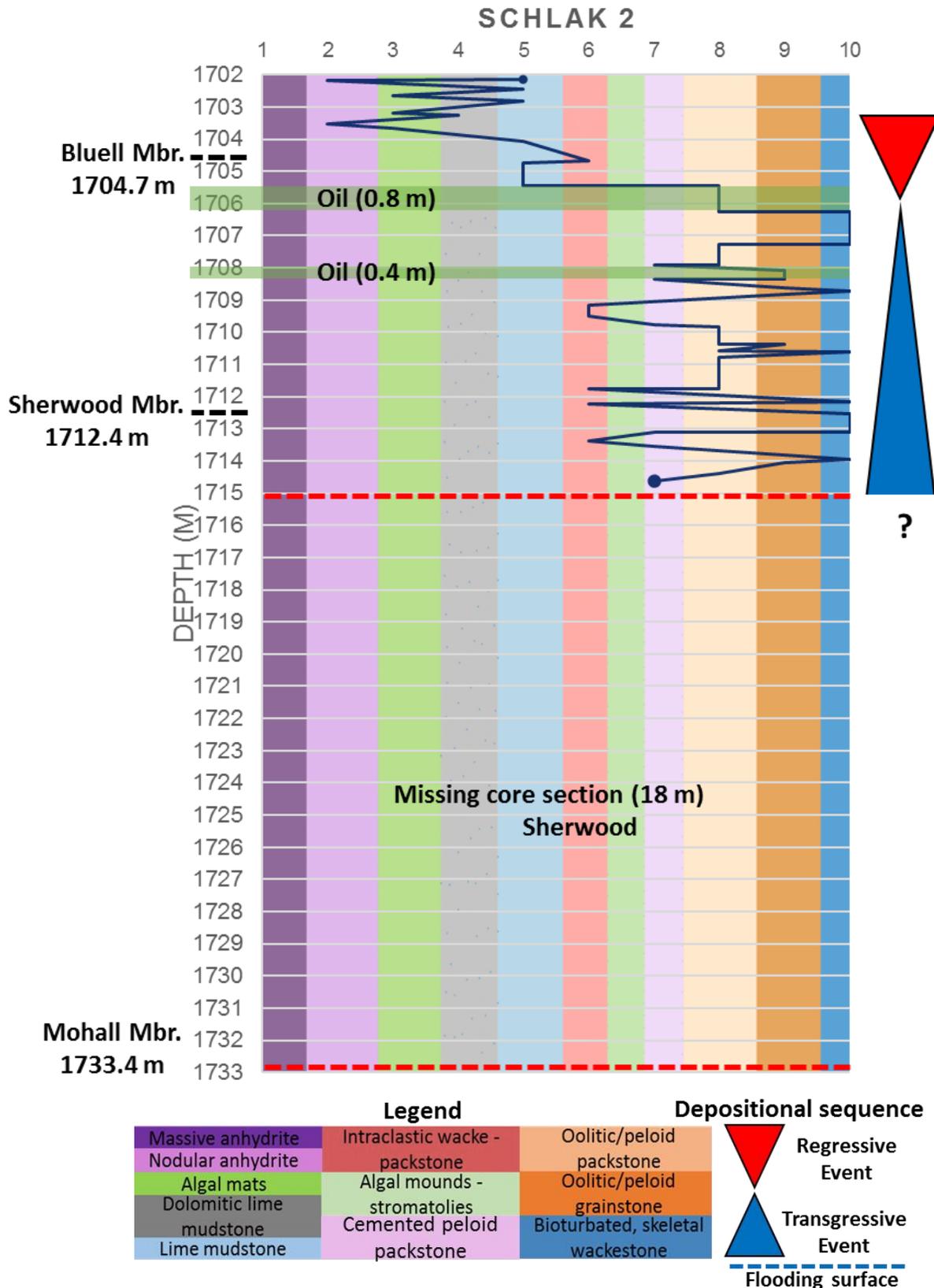
Figure 7.7. Stacking pattern for Schlak 2 with well log top markers for Mohall, Sherwood and Bluell Members. The green section specifies observed oil staining within the packstone/grainstone facies. Note that the depositional sequence is not from the shallowest part in time for the system, due lack of sufficient core material. Still the depositional sequences reflect the upward shallowing and overall basinward progradation within the Bluell and upper Sherwood Members.

CHAPTER 8   RESULTS OF ANALYSIS, DISCUSSION

Depositional model

Eleven interpretational facies were identified within the Bluell and upper Sherwood Members of the Mission Canyon Formation within Renville County. They reflect a range from supratidal to shallow marine and inner to back ramp conditions as described in chapter 6. The suggested models can be seen in figure 8.1 and 8.2.

The core analyses revealed facies and conditions typical of a very shallow, carbonate ramp setting. A carbonate ramp is characteristically a dipping, very low-angle (less than 6-2 degrees) slope within a carbonate depositional system that extends from the shoreline or a platform surface into the basin (Burchette and Wright, 1992). Such an interpretation is in-line with numerous and other authors working Mission Canyon Formation within the Eastern Flank of the Williston Basin (Hendricks et al., 1987, Lindsay, 1988, Petty, 1988).

Lindsey (1998) described a ramp setting that consists of a shallow and gentle slope with sediment accumulation of shallow to marginal marine carbonates to evaporites. Because of the gentle slope, small intervals of sea-level fluctuations caused shoreline progradation into the basin, combined with small periodic transgressions that flooded the ramp, allowing repeated progradation (Lindsay, 1988). The observed facies in the study closely resemble depositional facies within an inner to back ramp setting. The inner back ramp setting is between the upper shoreline and the fair-weather wave base, where the sea floor in this zone experiences almost constant wave and tidal wave agitation (Burchette and Wright, 1992)

The new and suggested depositional model for a shallow and open marine carbonate ramp within the Bluell and upper Sherwood Member within The Mission Canyon Formation
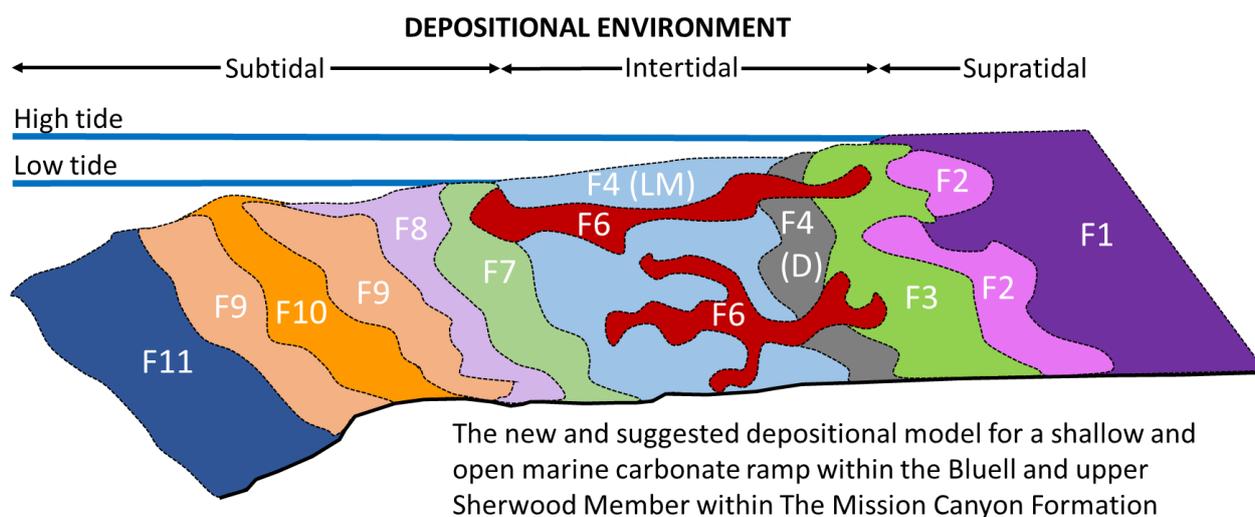
Figure 8.1. The complete depositional model that was reviewed and defined within chapter 6. Contains the distribution of 10 facies observed from the seven wells. Summary for each facies is shown within table 6.1 in chapter 6.

8 RESULTS OF ANALYSIS, DISCUSSION

The core results showed that the facies consisted primarily of evaporites, algae, dolomite, limestone and carbonates and commonly, the thin thickness of these facies range between centimetre and decimetre scales, and rarely on metre scales, with a fast shifting alternation between the facies, possibly due to the described small and subtle sea-level fluctuations that occur on the very gentle slope ramp.

Figure 8.2 below displays the labelled and different zones, together with processes that occur within a shallow to inner-back ramp setting for each observed facies. The figure 8.2. visualizes the shallow to open marine, starting within the subtidal depositional regime where the deepest facies consist of bioturbated, skeletal wackestone (Facies 11), possibly deposited further basin ward within deeper water, where low to moderate energy setting is more accessible (Facies 8, 9 & 10). At the fair-weather wave base, accumulation of low relief shoals, consisting of oolitic and peloidal packstone and grainstone (Facies 8, 9 & 10), reflect subtidal conditions, which underwent earlier, extensive reworking and abrasion in a higher energy and wave-dominated environment. Where sedimentary grains are transported, reworked and deposited by waves and tidal currents that are effectively washing away the finer particles (clay fraction), we observe the deposition of thin (decimetre to metre scale) shoals consisting of pack to grainstones. The oolitic and peloidal packstone (Facies 9) with interbedded lime mud laminae, occurs on the sides of the grainstone shoals, slightly protected and restricted from the complete washing of the waves and tidal currents.
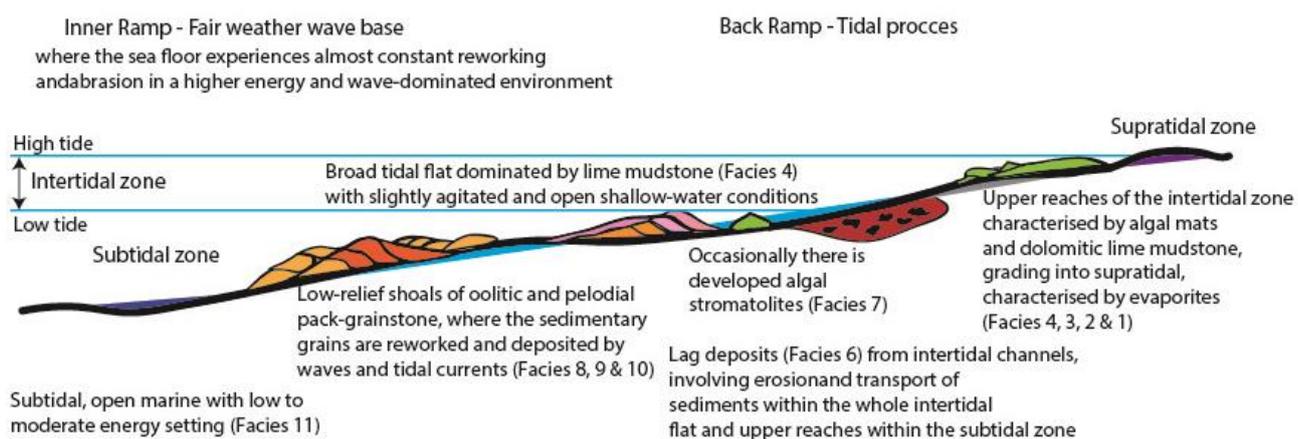
Carbonate ramp depositional model for Bluell and upper Sherwood Member

Figure 8.2. Cross section for the depositional model showed in figure 8.1. This figure includes general descriptions for the different zones and processes that occurs within a shallow to marginal marine ramp environment for each observed facies.

8 RESULTS OF ANALYSIS, DISCUSSION

The cemented peloid packstone (Facies 8) is of a less well-sorted nature and displays an absence of oolitic grain composition when compared to facies 9 and 10. Occasionally between these shallow and low relief shoals there is developed algal stromatolites (Facies 7), which form within the shallower part of the subtidal regime, close to the lowermost intertidal zone.

Further landward, within the back ramp, in the intertidal zone and the broad tidal flat setting, we observe primarily lime mudstone (Facies 4), deposited within slightly agitated and open, shallow-water conditions. These tidal flat sediments occur as widespread sheets, often cross-cut by intertidal channels (Facies 6), involving erosion and transport of sediments within the whole intertidal flat and possibly near at the subtidal zone.

Within the uppermost reaches of the intertidal flat, the alternation between dolomitic lime mudstone and non-dolomitic lime mudstone starts to occur more frequently. Together with the flat laminated algal mats (Facies 3), this creates wide and shallow algal-marsh deposits near the shoreline. Within the upper most tidal flat, with close association to the supratidal zone, evaporitic ponds with nodular anhydrite (Facies 2) occur, possibly due to repeated wash overs of water and from the small and subtle fluctuations of sea-level. These evaporitic ponds eventually grade into the furthermost landward succession of the upper supratidal zone that belongs to a marine sabkha environment, with deposits of abundant evaporites and anhydrite (Facies 1).

A similar and modern analogue to the recently described depositional model can be viewed at the northern coast of Qatar in figure 8.3. Shallow facies observed in the Bluell and Sherwood Members, can be linked to similar facies at the northern coast of Qatar in a shallow to marginal marine, carbonate ramp environment. This modern analogue has an extensive and broad intertidal flat with developed marine sabkha, where the development of evaporites are creating this typical marine sabkha environment.

1.6 km

Figure 8.3. Satellite image of the northern coast of Qatar. Similar analogue with a broad and extensive intertidal zone with facies variations, similar to the shallow and gentle slope carbonate ramp environment described in the suggested model. The dark patches within the supratidal zone are the evaporites that forms the modern marine sabkha environment.

Comparison with previous depositional models

Numerous studies with previous and different understandings of the details of the depositional system and number of facies, e.g. (Hendricks et al., 1987, Petty, 1988, Lindsay, 1988) have been made over the years within the Mission Canyon Formation, describing and correlating different facies and units since the early 1980s.

The model presented within this thesis are comparable to the overall interpretation of the depositional conditions but differ in details and in the consequences of the understanding of facies and porosity development. Petty (1998 & 1996) describes a similar facies relationship, with six major facies and a depositional model within the Mission Canyon formation in the western North Dakota (Fig. 8.4). This earlier model describes an environment ranging from open marine to restricted marine, lagoon and coastal sabkha or salina. Oil production came from the reservoir deposits of multiple shoaling-upward sequences, comprising of oolitic-pisolitic, intraclasts-bearing packstones and grainstones (Petty, 1988, Petty, 1996).
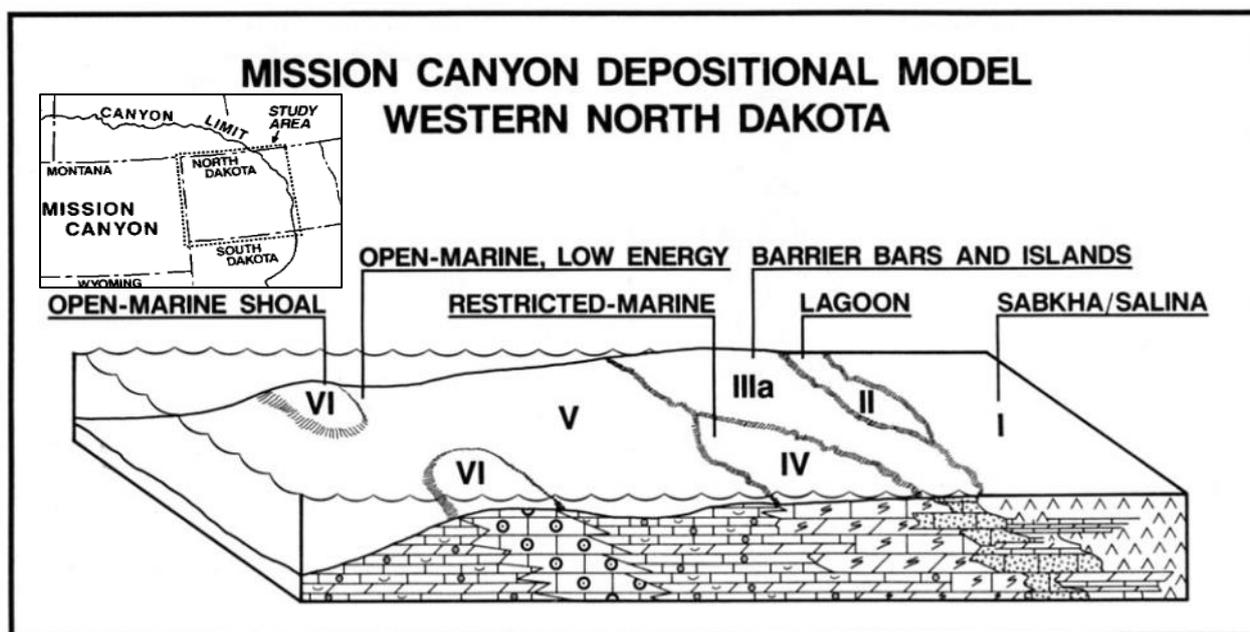
Figure 8.4. Previous depositional model and map over the study area for the Mission Canyon in western North Dakota from Petty, 1996.

Facies I: *anhydrite, stromatolitic mudstone.* **Facies II:** *burrowed mudstone, wackestone, stromatolitic mudstone.* **Facies III:** *peloidal-pisoliticintraclastic grainstone/packstone or peloidal-oolitic-skeletal grainstone.* **Facies IV:** *burrowed mudstone.* **Facies V:** *burrowed skeletal wackestone or packstone.***Facies VI:** *skeletal grainstone.*

These underlying reservoirs are mainly described as barrier island and shoreline build ups with evaporites to the east and shallow offshore marine deposits, basin ward on a very gently dipping ramp (Petty, 1996). Petty's interpretation (1996) of facies I to facies V has similarities with the new model and suggested facies, although the previous model has a broad facies interpretation and a much larger and extensive study area.

Facies I and II include both anhydrite and stromatolitic mudstone, burrowed mudstone and wackestone, which could be compared to facies 1, facies 2, facies 3 and facies 4 and possibly facies 6 within the new model. The shoal grainstone facies as described by Petty (1988; his facies VI) has not been observed within the study material. However, a few skeletal fragments could be observed within the oolitic and peloid grainstone facies, although these skeletal fragments were rare and the interpretation did not support any deep-water grainstone shoal deposits or any abundant deep marine fauna for that matter. This indicates a more shallow and landward setting of the depositional ramp, compared to the earlier model.

8 RESULTS OF ANALYSIS, DISCUSSION

The difference between these two models is the previous interpretation of shallow, back-barrier and lagoon zones with restricted marine setting that includes thick barrier bars and islands that allowed the development of back-barrier regions and lagoons. Facies III from Petty, (1988, 1996) includes various packstone and grainstone subfacies and the thickness was described commonly as 10-25 meter-thick beds, dependent on the location within the study area. These beds were described as generally porous throughout the area of its distribution as indicated by neutron-density logs and cuttings analysis (Petty, 1996). Alternatively, the ten meters scale shoals implied by Petty (1996) has not been observed within the study area making such an interpretation less probable, similarly the vertical stacking pattern nor lateral mappable relationship corroborates the existence of large shallow lagoons developed inside an extensive barrier dominated coastline as invoked by Petty (1996).

This is in contrast to the new model and subsequently, the new suggested model defines these shoals, consisting of packstone and grainstone facies (Facies 8, 9 & 10), actually lack the extensive thickness, throughout the wells and these observed shoals cannot support any thick barrier-bars and protective islands, at least not on the same scale as invoked by Petty (1996). This is due to the relatively thin distribution between observed decimetre scale, rather than metre scale of packstone and grainstone beds, with a maximum thickness of 2-3 meters.

The assumption for this discrepancy comes from the core results and the clarification through the stackings patterns, which shows the thin pack-grainstone beds and their subtle and fast distribution, related to the subtle variations in the depositional system. The general thickness for all other facies observed in the cores are centimetre and decimetre, rather than metre-scale, which reflects the, and the exceedingly low angle of the slope for the depositional system. This understanding advocated here is marked in contrast to the system from Petty (1996) comprising substantial topographic relief and facies associations not observed in the studied core material.

Correlation from facies stacking patterns

The variability and evolution of the depositional system that was identified from facies stacking pattern, allowed for an easier visualisation and understanding of the facies distribution and their thickness within the depositional system. The facies stacking patterns revealed that these shallow marine to marginal marine successions consists of thin (decimetre-scale) beds with rapid upward shifts in facies, reflecting the very shallow sea-level at the time of deposition.

8 RESULTS OF ANALYSIS, DISCUSSION

The depositional sequences that were set within each stacking pattern reflects the general upward shallowing and overall basinward progradation for the depositional ramp system and that the system is upward fining and upward shallowing with more aggradation than progradation of the depositional system. This is because of the typically thin thickness seen at centimetre and decimetre scale, rather than metre scale observed in all wells. Furthermore, the stacking patterns enable correlation of each observed facies across the study area, rather than trying to correlate lithology from well logs, given the challenges of understanding carbonates with conventional wireline logs.

Petty (1996) also tried to use core material to help identify a sequential break-down of The Mission Canyon Formation, however, in this case the cores was only used to corroborate the log interpretation and not in their own right, to capture the details of the depositional system as undertaken in this work. Because well logs was the main tool to use within the Williston Basin and the Mission Canyon Formation and were originally defined as a series of 12 units based on discontinuities expressed as marker beds on well logs (Petty, 1996), previously defined as "subintervals" within the Mission Canyon Formation, and has been described previously in chapter 3. These 12 units were described with a thickness that generally varies from 10-30 meters and was defined by gamma-ray marker beds consisting of lithologies, which vary from silty, argillaceous, dolomitic mudstone to argillaceous, dolomitic siliciclastic sandstone.

But the two best developed marker beds are the evaporite-carbonate transition (anhydrite has a high density) for a subinterval or portion of a subinterval due to the density and neutron change (Petty, 1996).

Facies can be described as these lithologic suites and facies are generally mappable with neutron-density and gamma logs, once the logs have been tied to core data in a particular area. However, the problem with tying facies interpretations to well logs comes when the facies is so detailed, with similar characteristics, that smaller changes within the facies cannot be mapped with logs alone, because the log resolution does not enable identification of the facies variations, as documented through this study. This can be viewed in the figure 8.9 and will be further discussed during the relationship between facies and reservoir distribution discussion.

Well logs can give an incorrect understanding of where you actually are within a fast fluctuating depositional system, as it has been seen in the Bluell and Sherwood Members. In comparison, core interpretation still allows mapping of these smaller lithologic suites in places where sufficient core material is available. Put differently, mapping the variability needed to understand the smaller reservoir variations are only possible with sufficient core material.

A good comparison for this statement is to observe and compare the old top markers from well logs for the Bluell and Sherwood Members from each stacking pattern within each particular well. This is demonstrated in the facies stacking pattern for Laura Funke 4 (Fig. 7.1), where the Sherwood top maker can be observed to be 10 metres below first occurrence of anhydrite (Facies 1). Instead the top marker can be seen near cemented packstone facies 7, which technically can also have a very high density and low neutron porosity due to the very tight and cemented nature of this facies. This is just an example, but together by looking at old well logs and the careful core description undertaken in this study, it illustrates the challenges of understanding carbonates through well log patterns alone within the Members (e.g. Bluell and Sherwood) in Mission Canyon Formation, which essentially are determined by thin and similar depositional facies, which represent a depositional system that changes rapidly.

Nevertheless, together with the usage of core results and stacking patterns, it enables comparison and correlation of each observed facies across the study area, rather than trying to correlate lithology from well logs alone, at least in this type of carbonate depositional system that changes rapidly. Because logs do not capture the variability and correct evolution of the depositional system, as emerges from systematic core description and the use of subsequent facies stacking pattern. However, it can still enable correlation between wells and logical prediction of facies distribution. But it is important to understand that the logs do not capture the variability and correct identification of the smaller and detailed facies, which shouldn't be mapped with well logs alone. This can be further observed in the two figures 8.5 and 8.6 below, where two different correlations differ: one from the conventional well logs and one from the interpreted depositional sequences.
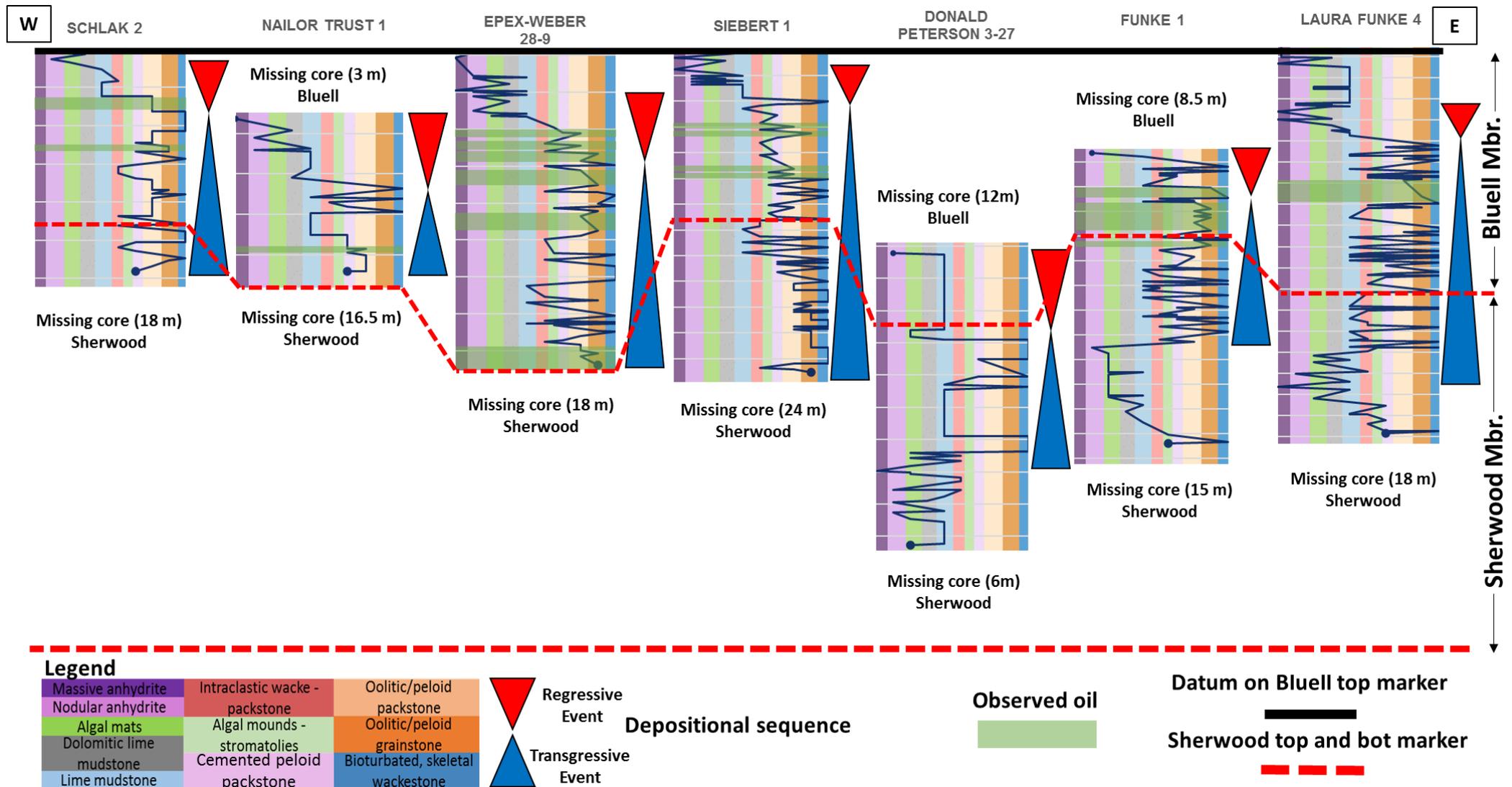
Figure 8.5. Correlation from stacking patterns with datum set on the Bluell top marker. The best developed marker beds are the defined evaporite-carbonate transition (anhydrite has very high density) but as seen in the figure, the well logs can give an incorrect understanding of where you actually are within the fast fluctuating depositional system, in comparison to core interpretation and the usage of depositional sequences, which can be seen in the next figure 8.6.
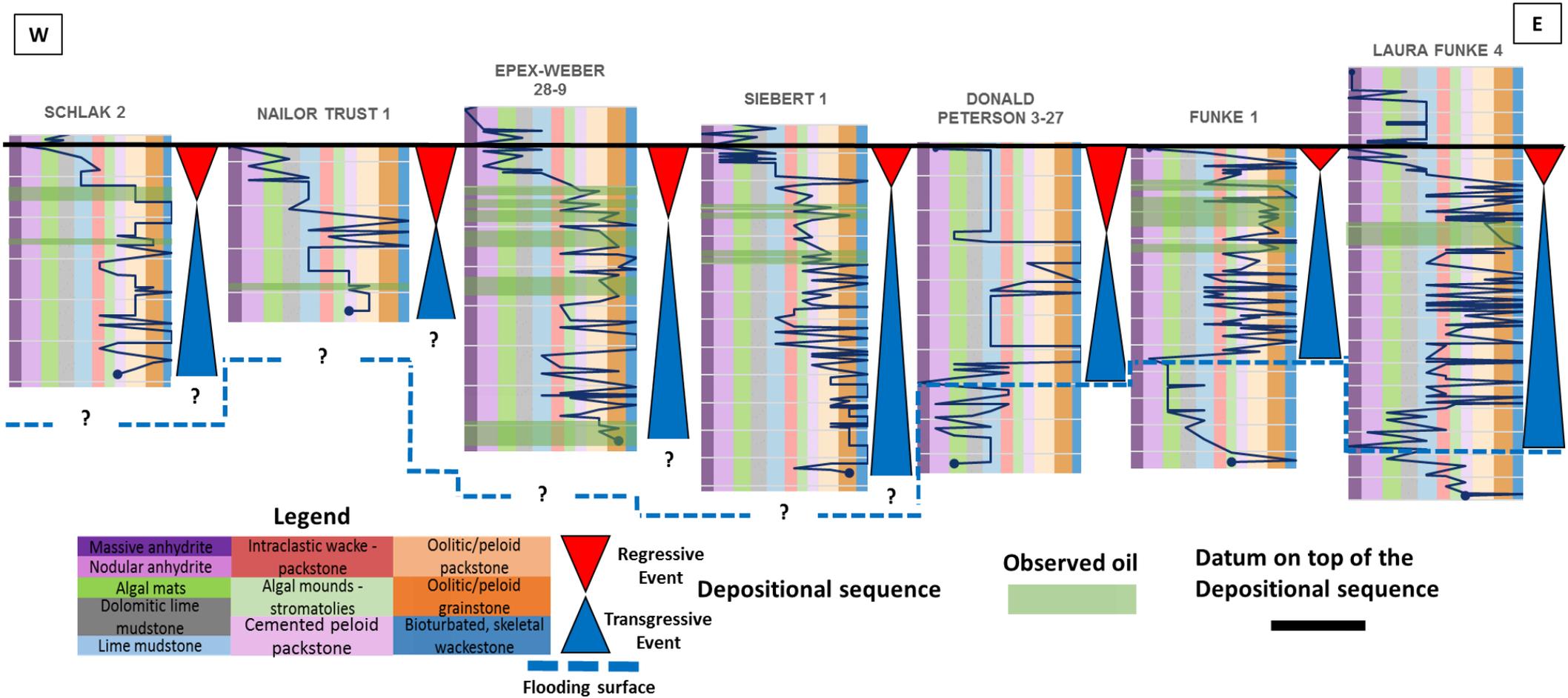
Figure 8.6. Sequence stratigraphic definition with the help of stacking patterns that enables correlation of each observed facies that is already tied down to a specific environment. It allows you to understand and realise during what time in space that validates the most landward or the most basin ward point within the depositional system, which can be seen within these depositional sequences. The depositional sequences set within each stacking pattern reflects the general upward shallowing and overall basinward progradation for the depositional ramp system from the sufficient core material available. Three of seven wells furthest to the east had a complete depositional sequence.

Facies identification consequences for porosity distribution

One of the challenges within the Mission Canyon Formation is that most of the original porosity is cemented and thereby effectively reducing permeability to zero. The major indication of open porosity within Bluell and upper Sherwood Members was secondary enhanced-solution porosity. This moldic to vuggy porosity is identified in the core photographs as small voids, usually within the millimeter scale on the surface of the rocks (Fig. 8.7). The facies interpretation observed that this developed moldic to vuggy porosity, together with cementation within the study area, are often observed to alternate within fast and complex vertical facies changes and irregular distribution of diagenetic cementation and porosity. In some cases, there appears that the original (interparticle) porosity is all cemented so that observable porosity is all due to secondary dissolution effects (that has not been completely cemented)

This type of porosity and its relationship with each observed facies is complex and results in a large uncertainty for the porosity and permeability relationship seen within the area. Lucia's classification and concept of vuggy pore space mentions that pore-size distribution, which is the spatial distribution of pore sizes within the rock, controls permeability and saturation and that pore-size distribution is related to rock fabric. According to the concept suggested by Lucia (2008), pore space belongs to one of the three major pore-type classes: interparticle, separate-vug, or touching-vug (Lucia, 2007). The interparticle porosity always exists and is controlled by particle size and sorting, and by the volume of interparticle cement and that the interparticle porosity will be reduced proportionally to the volume of cement (Lucia, 2007).

Lucia (2007) classification system, derived from looking at the end fabric of the rock, but the idea for porosity distribution for this study is established by first looking at the sedimentary system to come up with an understanding of what facies could potentially be good reservoirs. By combining the many observations made from the core results, to understand that within two certain facies (Facies 9 and 10), dissolution is causing secondary porosity at different degrees and when the degree of secondary porosity is high enough, the later cementation does not totally fill the pores in all the beds, resulting in these open and 'active' reservoirs observed throughout core sections. These reservoir distributions can be seen within the correlations in figures 8.5 and 8.6.

Figure 8.7. Core section from Nailor Trust 1 within the depth interval of 1713-1715.5 m (5620-5628 feet). The white coloring on the rock is cementation. Between the highly cemented sections, the cores showed that parts of the rock can contain open, moldic to vuggy porosity and occasionally together with oil stains (red box). But commonly, most of the original porosity in the cores seemed to have little or no original porosity, due to the highly degree of cementation throughout the wells.

Reduced original porosity is a major challenge within the pack-to grainstones within the Mission Canyon Formation. Lindsay (1988) described that the cementation within the Mission Canyon Formation belongs to either anhydrite, calcite or dolomite cement and the cementation drastically reduced porosity and permeability within large parts of the facies within Bluell- and Sherwood Members. Lindsay (1998) described that these beds have undergone several diagenetic changes, which converted sediment into porous, lithified rock. Later diagenetic modifications include leaching of anhydrite cement and carbonate dissolution, which improved solution-enhanced moldic to vuggy pores. Lindsay (1988) suggest that this leaching of anhydrite created most porosity in the Mission Canyon reservoir beds (Lindsay, 1988).

The secondary porosity results in a higher porosity development within the facies and can be classified and explained by two mentioned classes, including the separate and touching-vug from Lucia's classification. The Separate vug porosity are defined as pore space that is interconnected only through interparticle pore space and the pore size of separate vugs in carbonates will vary depending upon source and can vary from large to micro pores within grains (Lucia, 2007). Touching vugs are defined as pore space that forms an interconnected pore system independent of interparticle pore space (Lucia, 2007).

Ideally, the moldic to vuggy porosity observed within the core photographs should be divided into separate-vug, or touching-vug porosity. However, by only having access to core photographs, which restrict the observations made to the surface of the cores, it is impossible to classify if the moldic to vuggy porosity either belongs to separate-vug, or touching-vug porosity. However, Nailor Trust 1 well had available thin-sections (Fig. 8.8) within the depth interval of 1713-1715 meters (5620 to 5626 feet), which are within the same core interval showed in the figure 8.7.

These thin-sections shown in figure 8.8. were interpreted as cemented peloid packstone (Facies 8), which is typically what most of the core sections seen in figure 8.7. consists of.

The oolitic and peloid packstone (Facies 9) description belongs within the small area shown in the red box in figure 8.7, which contains open moldic to vuggy porosity and oil staining.
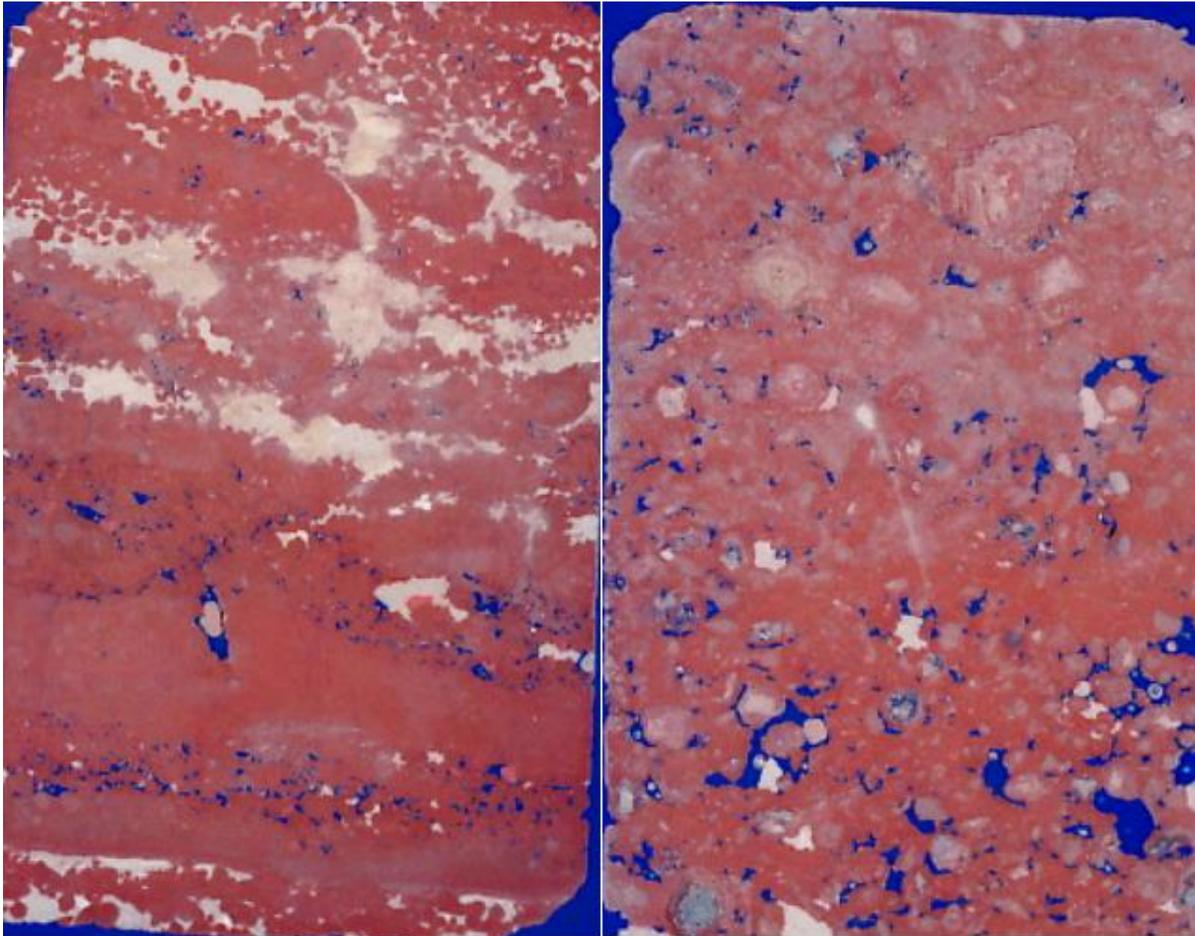
*Figure 8.8. Two thin-sections taken from Nailor Trust 1 from the depth interval of 1713 to 1715 meter (5620 to 5626 feet). These images show the challenge with porosity and cementation in the core section within the figure 8.7. **A)**. Described as cemented peloid packstone (Facies 8), highly cemented and little porosity (blue colour). **B)**. Described as oolitic and peloid packstone (Facies 9), contains open moldic to vuggy porosity but lack permeability, due to the separate-vug porosity previously explained. This type of porosity can't be observed in the core photographs.*

Although one set of thin-sections doesn't make a complete and accurate observation for the enhanced solution porosity seen throughout the whole study area, but together with careful core analysis its fully possible to know what to expect within the area and for forthcoming production and future studies. The benefit with careful core analysis is the systematic build up from the core description, which describes exactly where the dissolution porosity was seen throughout every well. It also confirms that when the cores were classified as highly cemented, then they are likely to have the original porosity completely cemented as seen in thin-sections and the observed moldic to vuggy porosity within the core photographs seems to be defined at least by one of the classification of vuggy porosity (the separate-vug system).

This type of observed porosity is only interconnected through the interparticle pore space, which is one of the main problems, because most of the original porosity around the voids and through general part of the rock have a high degree of cementation, which means that the rock will have porosity, but no permeability. In short, to get a producing reservoir you need to have a secondary dissolution porosity that together with whatever is left of the original intergranular porosity enables fluid flow. This in turn means that you need the observed open, moldic to vuggy porosity, which most likely are made of separate vug porosity, together with high enough original porosity to be able to get the reservoir to flow. Because it comes back to the description of observed separate-vug porosity, since it is only interconnected through the interparticle pore space, as mentioned by Lucia, (2007).

But if the so called dual porosity exists (open moldic, together with high enough original porosity), then cementation is probably not sufficient enough to block all pore-connections and the potential for an "active and open" reservoir can be found.

Siggerud (2014) suggested that most of the original porosity in the cores has been cemented with calcite, with the result that the rock can contain porosity but little or no permeability. This is the reason why the cores can contain, and seemingly bleed oil from pore-spaces exposed when cores are recovered from the well (on-site) and later when cut in the laboratory), but still produce mostly water during production. This can be seen in figure 8.7 and this could essentially be the explanation for the degree of oil observed in the core photographs, and why neighboring wells, where five (including Nailor Trust 1 in figure 8.7) out of seven wells with observed oil still weren't taken into production, with the exception of Epex-Weber 28-9, which is the only well that produces and Donald Peterson 3-27 that completely lacks a reservoir.

Relationship between facies and reservoir distribution

Lindsay (1988) makes the point that simple facies interpretations covering large areas do not capture the porosity variability recently discussed, as it can be observed in core. Lindsay (1988) also goes on to say that porosity and permeability within the units in The Mission Canyon Formation (e.g. Bluell and Sherwood) are essentially determined in part by the depositional facies, which represents a continuum of sediments deposited in a depositional system that changes rapidly.

By building up a better understanding from all the detailed core observations made and trying and to get a better understanding of the seemingly random porosity within the Bluell and Sherwood Members, we wanted to see if it was possible to find a relationship so that a logical prediction of the observed porosity in the cores could be made by recognizing various and detailed facies to see if a relationship actually can be facies controlled.

An example of log to core calibration is shown for the well Sibert 1. The systematic core descriptions and interpretations observed in figure 8.9, constructed from data taken from the digital template of the well Siebert 1, illustrate this previously non-understood and subtle relationship between sediment and reservoir development. There seems to be a direct link between facies, sorting, degree of cementation, observed moldic to vuggy porosity and reservoir potential, which is in the end is related to the depositional processes and the subtle variations between where you are in the depositional system. The subtle relationship shows that the core results are tied to the more well sorted beds that are interpreted as packstone and grainstone facies. Whenever they are together with a well-sorted nature and open moldic to vuggy porosity, then the beds have the highest likelihood of containing oil, which can be observed in the stacking patterns in chapter 7.

The rest of the core analysis in the other wells back this statement up because the core results showed that it is within these well sorted facies (Facies 9 and 10), oil staining, together with the highest degree of developed moldic to vuggy porosity can be observed, which makes facies 9 and 10 the best possible and active reservoirs.

The core analysis defines these two particular facies are commonly on decimetre rather than metre-scale, which reflects the flatness of these low-relief shoals, the gentle slope and the broad tidal flat range. The results also determined that more well sorted these facies were, a higher degree of moldic to vuggy porosity seemed to occur as seen in figure 8.2.1.

By having a well sorted nature, it introduces most likely a higher interparticle porosity level, because the size of interparticle porosity is controlled by particle size and sorting (Lucia, 2007). Together with dissolution and creation of secondary porosity, this allows for the formation of dual porosity. By coming back to the previously discussed possibility of what is needed for a viable producing reservoir within these members, you need the dual porosity, which is the combination of original intergranular porosity, and dissolution porosity.
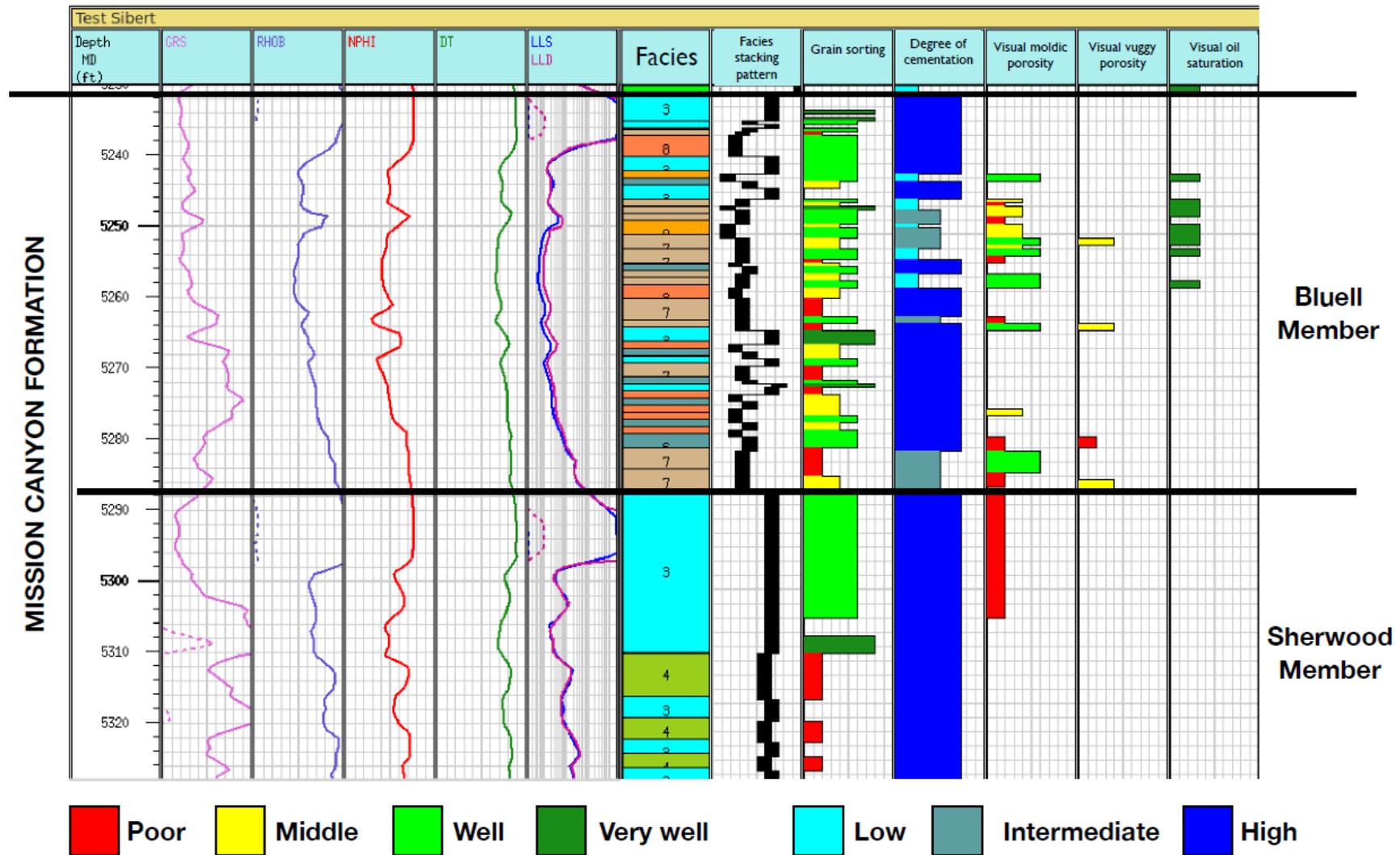
Figure 8.9. This figure addresses the following points; relationship between logs and core, which is depth-shifted to the logs. This shows that the logs are not suited to capture the details observed in the core, although the main lithology can be captured; lime-mudstone, carbonate, anhydrite and dolomite, the next point is the observation of cement versus visual porosity that also is where there is oil, stacking pattern that reflect the limited thickness of the pack-grainstone units as discussed in the text, referred to the text for more discussion on the points.

The sections with the highest overall (combined) porosity has insignificant volume of cement to cause complete blocking of pores. Because the facies are containing more pore-space to infill, there is not enough cement in the system to fill it all, which means not everything is cemented when cementation later took place. Smaller vugs can be observed to be cemented, but it is usually the larger and more developed vugs that are still open. In addition; the higher degree of cementation is that the facies with higher clay content could have a higher probability of cementation due to easier diagenetic alterations within the clay minerals, together with the lesser sorting, smaller pore-space and the lack of porosity. The size of interparticle porosity is controlled by particle size and sorting, similar to the understanding advocated by (Lucia, 2007).

Reservoir distribution

As previously mentioned, the core results defined two particular facies with the highest well-sorted nature, with a high degree of developed open, moldic to vuggy porosity, which was observed to contain all oil staining, which certainly set the facies 9 and 10 as the best possible active reservoirs in the study area. The packstone and grainstone reservoirs (Facies 9 and 10) had observed oil within six out of seven wells, with the exception of Donald-Peterson 3-27, because the well completely lacked a packstone or grainstone reservoir from facies 9 and 10.
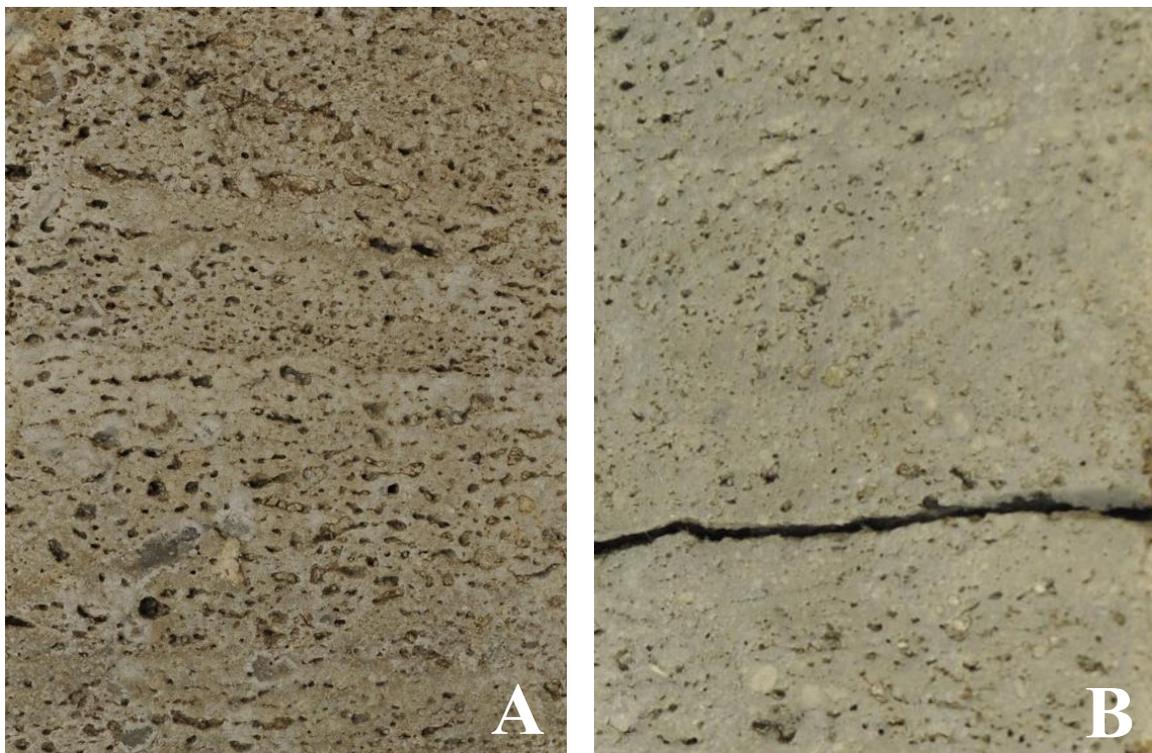
*Figure 8.2.1. **A).** example on facies 10, Grainstone (Siebert 1: 1698 m). **B).** example on facies 9, packstone (Laura Funke 4: 1601 m). In both cases porosity is not completely cemented and visible secondary enhanced porosity can be observed in various degree.*

8 RESULTS OF ANALYSIS, DISCUSSION

The oil can be observed throughout the wells within the stacking patterns in chapter 7 and in figure 8.5 & 8.6 within the stacking pattern correlations.

The observed packstone and grainstone reservoirs can be observed to be occurring as thin beds between 0.2-3 meters. This observation is in-line with Lindsay (1988) where previous studies relied on excessively broad facies interpretations over an extensive area, correlated with well logs that make it difficult to predict what facies actually includes the correct porosity and permeability.

This comes back to the challenge of well logs, previously mentioned in the discussion of stacking patterns (P. 94-97). There are several challenges with log analysis, one is that the resolution is not good enough since porosity and permeability seen in the cores varies on a scale smaller than the logs can resolve, also seen in figure 8.9. However, detailed facies interpretation enables prediction not only of the depositional facies, from the facies vertical stacking pattern, but also the architecture of the depositional system, hence the logical prediction of facies and, from this, porosity distribution given the relationship discussed above.

This illustrates the importance of detailed description of facies and in understanding the depositional system, which enable a better understanding of facies by being able to logically predict the location of the best possible, well-sorted packstone and grainstone reservoirs in time and space. Hence as show the controlling factor appears to be the subtle increase of dual porosity within the best sorted intervals of the pack and grainstones as demonstrated here (see Figure 8.9) what have maintained some porosity/permeability post burial and subsequent cementation. As has been demonstrated this is beyond the resolution of the wells logs to identify, and requires careful core analysis to be able to map facies distribution in time and space.

Because of the subtle relationship recognized, it seems that the active reservoirs in the core results are tied to the more well sorted beds, interpreted as open and low cemented packstone and grainstone facies. Whenever they are together with open moldic to vuggy porosity and low cementation rate, the beds have the highest likelihood of containing oil. The well sorted nature most likely introduces a higher interparticle porosity level and together with secondary porosity, it eventually allows the formation of a high enough dual porosity. In this case, cementation is not sufficient to block all pore-connections, which is important because it means one can now systematically map facies and thus porosity development in future work. In rapidly depleting and heterogeneous reservoirs, such as the Mission Canyon Formation, which has been producing since the 1960s, these beds with dual porosity development will become increasingly more significant as they present the best locations for active reservoirs in the hunt for new potential targets.

8 RESULTS OF ANALYSIS, DISCUSSION

CHAPTER 9   CONCLUSIONS

- The systematic core analysis approach with detailed digital template for recording of sedimentological details, it enabled not only a high optimization when working with the core but a high degree of consistency in facies identification and the making of detailed vertical facies stacking patterns for each well.

- Detailed core analysis from seven wells with cores from the Bluell and Sherwood Members of the Mission Canyon Formation, located in Renville County, North Dakota, resulted in the identification of eleven depositional facies. These depositional facies revealed conditions, typical for a shallow, carbonate ramp setting that reflect, a range from supratidal to shallow subtidal marine and inner to back ramp conditions with wide, open intertidal to very shallow subtidal, characterised by thin subtidal shoals.

- The facies stacking patterns revealed that these shallow marine to marginal marine successions consists commonly of thin (decimetre-scale) beds with rapid upward shifts in facies, reflecting the very shallow sea-level at the time of deposition and the variability and evolution of the depositional system was captured from the use of subsequent facies stacking pattern. It reflects the general upward shallowing and overall basinward progradation for the depositional ramp system, with more aggradation than progradation of the depositional system.

- Core results and stacking patterns, enabled correlation as it enabled comparison and correlation of observed facies between wells and logical prediction of facies distribution across the study area.

- The core results defined facies 9 and 10 as the best possible active reservoirs in the study area, due to the highest well-sorted nature, with a high degree of developed open, moldic to vuggy porosity, and observed to contain all observed oil staining throughout the study area. These active packstone and grainstone beds was observed with reservoirs of 0.2 to 3 meters. The limited thickness of these beds (some 40-60 cm) also explains the challenge in prediction location of active reservoir as experienced in the past.

- The challenges of understanding carbonates with conventional wireline within a fast fluctuating depositional system, determined by thin and similar depositional facies as seen in Bluell and Sherwood Members. This can give an incorrect understanding of the system and not capture the variability and correct identification of detailed facies, and shouldn't be mapped with well logs alone when a depositional system changes rapidly.

9 CONCLUSIONS

- While this work enabled detailed facies mapping to be undertaken, the seemingly random porosity distribution represented a major challenge in oil exploration and production within the eastern Flank of the Williston Basin in The Mission Canyon Formation.

- The core analysis revealed that to preserve porosity and thus permeability, it was dependent on a combination of depositional, original porosity and secondary dissolution, moldic and vuggy porosity, only observed within the pack- to grainstone facies reflecting shallow marine conditions.

- Systematic core analysis furthermore established a relationship between sediment grain-size, sorting, development of moldic to vuggy porosity and degree of cementation. Whereby the former is related to location within the depositional processes and the subtle variations within the depositional system.

- The combination of higher interparticle porosity, together with the secondary porosity, result in that cementation is not sufficient to block all pore-connections. Thereby creating the active reservoir intervals observed in core within Facies 9 and 10.

- The controlling factor appears to be the subtle increase of dual porosity within the best sorted intervals of the pack and grainstones as demonstrated here that have maintained some porosity/permeability post burial and subsequent cementation.

- As has been demonstrated this is beyond the resolution of the wells logs to identify, and requires careful core analysis to be able to map facies distribution in time and space.

- Consequently, there has been established a relationship between facies types and facies distribution and the development of porosity and hence, active reservoir enabling logical prediction of more producing reservoir within the Mission Canyon Formation along the eastern Flank of the Williston Basin.

- The importance of recognition from detailed description of facies, related to the depositional processes and the subtle variations in the depositional system enables a better understanding and that allows to logically predict the location of best possible and well-sorted packstone and grainstone reservoirs in time and space. This becomes increasingly more significant for finding new potential targets in rapidly depleting and heterogeneous reservoirs, such as the Mission Canyon Formation.

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