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Determining the Depositional Environment of Amherstburg Formation

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Author's Note

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Abstract

The Amherstburg Formation is a unit that stretches from Ontario to Michigan and was deposited during the Devonian Period. The goal of this project was to determine the depositional environment of the Amherstburg Formation. Facies associations were defined based on observations from three cores in northern and southeastern Michigan and later grouped into facies associations. The four facies associations were reef rubble, lagoonal, lagoonal and reef-rubble, and lagoonal and peritidal environments. These environments were deposited as laterally adjacent environments along a ramp shelf in a humid tropical climate. Sea level was relatively high during the deposition of the Amherstburg Formation. During this period, the Michigan Basin was covered by open marine waters where a diverse fauna flourished in reefs and adjacent lagoons. There was a regression following the deposition of the Amherstburg Formation, as the overlying Lucas Formation consists of shallow-water to emergent facies deposited in a semi-arid carbonate shelf.

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I. Introduction

The Michigan Basin is a low-lying area of land that covers the Lower Peninsula of Michigan, a small portion of the Upper Peninsula, eastern Wisconsin, the northeastern corner of Illinois, northern Indiana, the northwestern corner of Ohio, and the western side of Peninsular Ontario, Canada. The Basin also underlies all of Lake Michigan, western Lake Erie, and Lake Huron. "The Michigan Basin is a nearly circular, intracratonic Basin 400 km in diameter and 5 km deep…," (Leighton, 1996, as cited in Howell and van der Pluijm, 1999, p. 974). An intracratonic Basin is a low-lying area that lies completely in continental crust. This paper will specifically discuss the Middle Devonian rocks of the Amherstburg Formation. During the Devonian, the Michigan Basin experienced three major subsidence patterns; a narrowing of the Basin, a broadening of the Basin, and an eastward tilt (Howell and van der Pluijm, 1999). During the deposition of the Amherstburg Formation, the Michigan Basin was experiencing a narrowing of the Basin. The Basin kept tilting throughout the early Carboniferous. These major subsidence episodes controlled the rate of deposition and the types of materials being deposited (Howell and van der Pluijm, 1999).

The Amherstburg Formation stretches from Ontario to Michigan and was deposited during the Devonian Period. As seen in Figure 1, the Amherstburg Formation is positioned stratigraphically between the Sylvania Sandstone and the Lucas Dolomite. The Amherstburg Formation conformably overlies the Sylvania Sandstone in a diagonal belt from the southeastern Lower Peninsula (Lenawee, Monroe and Wayne Counties) to the northwestern Lower Peninsula (southeastern Grand Traverse and southwestern Kalkaska Counties). Everywhere else in the Lower Peninsula, the Amherstburg Formation unconformably overlies the Bois Blanc Formation. The contact between the Amherstburg and underlying Sylvania Sandstone is gradational and conformable in the central basin. The contact with the overlying Lucas Dolomite is also transitional with interbedding of more typical open marine Amherstburg facies and more restricted Lucas Dolomite facies (Landes, 1951). The Sylvania Sandstone, the Amherstburg Formation, and the Lucas Dolomite were deposited during the Middle Devonian Period and make up the Detroit River Group. The Amherstburg Formation consists of a limestone or a dolostone with interbedded layers of sandstone near the base of the unit. At the surface, the dolostone appears gray to brown in color. The dolostone is darker in color than its surrounding beds making it easy to differentiate from the surrounding beds. The Amherstburg Formation outcrops at the surface in southeast Michigan and northwestern Ohio (Landes, 1951). Most of the fossils found within the Amherstburg Formation are located in the limestone beds (Landes, 1951). The Amherstburg has been assigned to the Devonian based on biostratigraphic analysis (Fagerstrom, 1961).

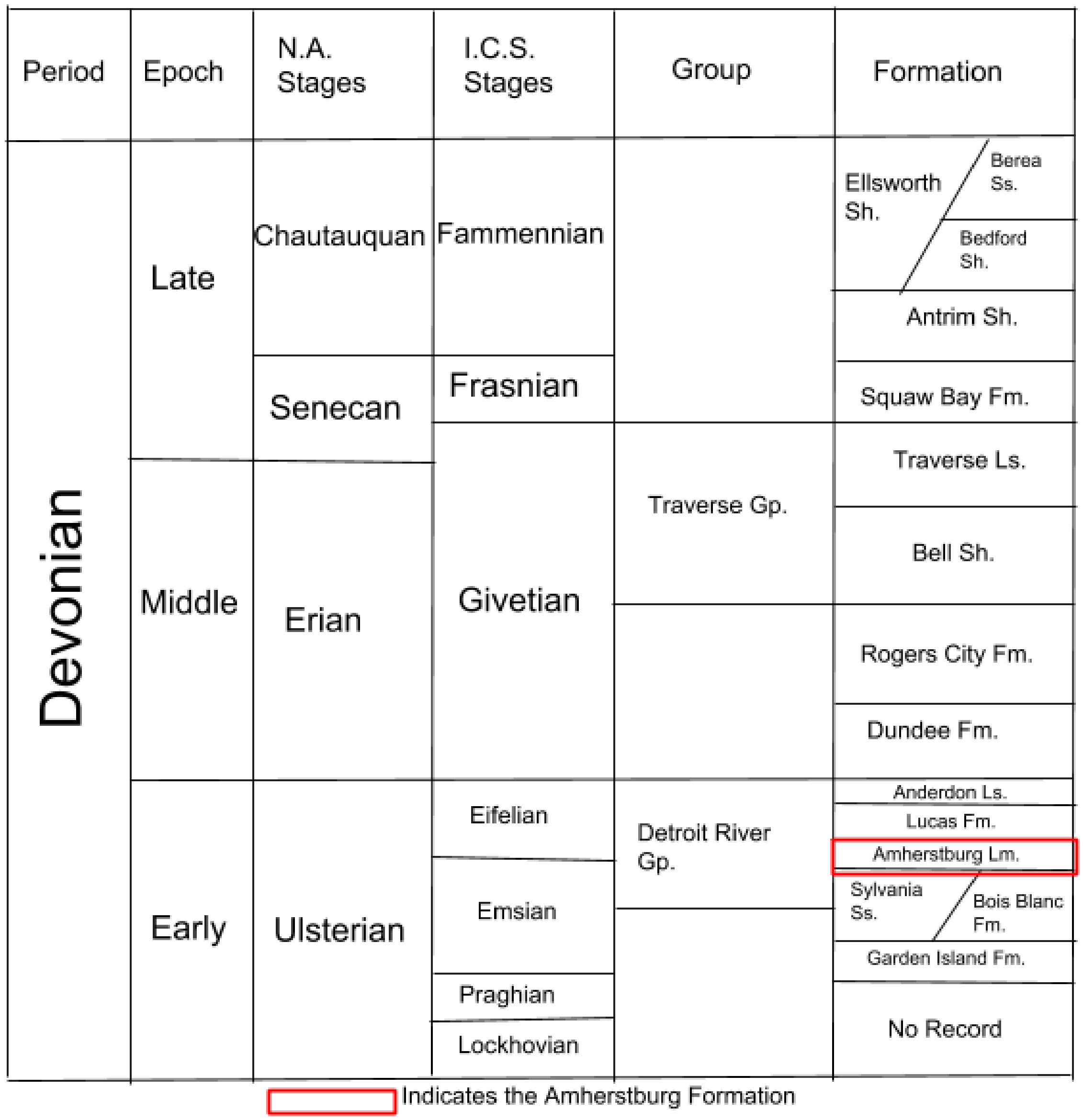


Figure 1: The stratigraphic chart for the Devonian for the Michigan Basin. The Amherstburg Formation is outlined in red.

The Devonian occurred roughly 415 million to 360 million years ago (Stanley and Luczaj, 2014). North America and Europe had collided to form a larger landmass, Euramerica (Stanley and Luczaj, 2014). The center of Euramerica was located about ten degrees south of the equator (Stanley and Luczaj, 2014). At the same time, the modern southern continents were part of a larger supercontinent, Gondwana (Stanley and Luczaj, 2014). During the Devonian Period, the Michigan Basin was near the equator (Stanley and Luczaj, 2014). Figure 2 shows the locations of the Earth's land masses during the Middle Devonian. North America is the landmass slightly south of the equator in the center of the view in the image. Much of the State of Michigan was below sea level during this time.

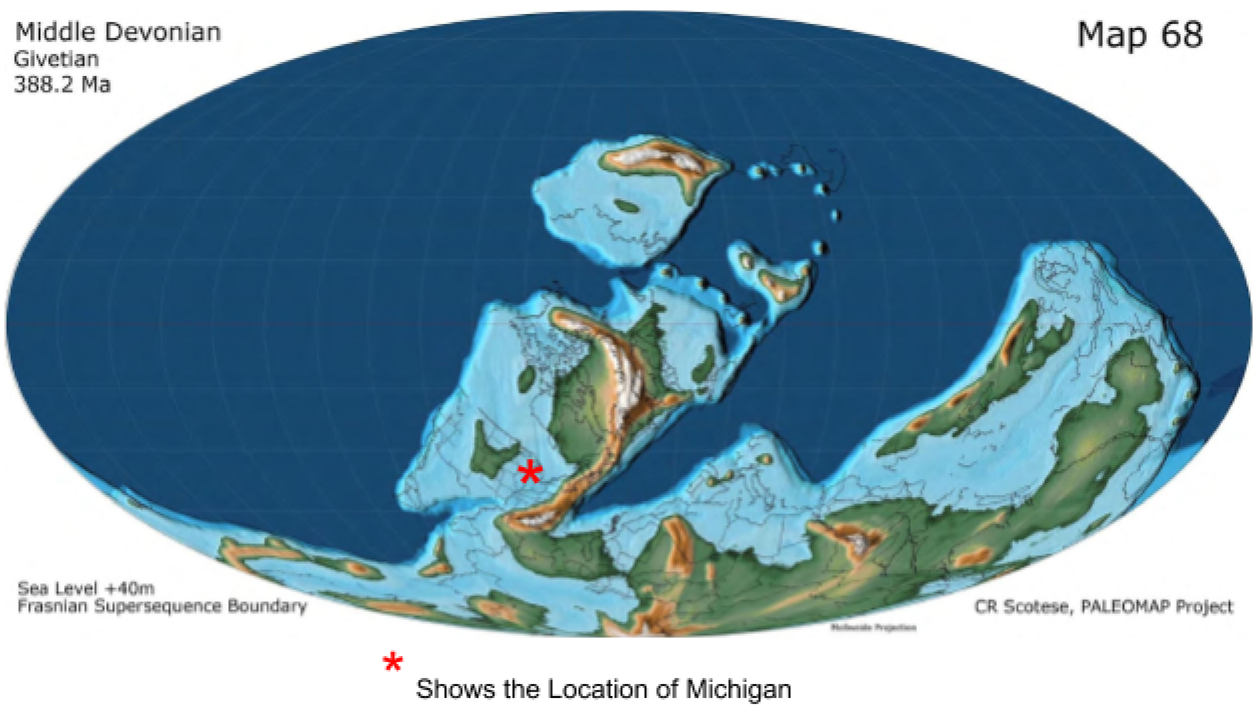


Figure 2: Location of the land masses in the Middle Devonian. North America is located in the center of the map. (Source: Adapted from Scotese, C. R. (2014))

Early vegetation was present on the continents as well as some of the first land dwelling organisms (Stanley and Luczaj, 2014). The Devonian was a time of transgression with much of the continents flooded by the end of the Devonian (van Geldern et al., 2006). Seas flooded portions of the interiors of the continents, including the area that is now Michigan. Most of the state during the deposition of the Amherstburg Formation was flooded. Parts of the Michigan Basin were restricted, creating lagoons with higher salinity waters. By the time of deposition of the Lucas Formation, the Michigan Basin had became partially shut off from the world ocean (Gardner, 1974). The water in the Michigan Basin became hypersaline favoring the precipitation of evaporite minerals and generating an environment that was harmful to normal marine life (Gardner, 1974). This restriction of the basin is tied to a major regression and resulted in the deposition of the evaporite-prone Lucas Formation (Gardner, 1974).

Literature Review

Landes (1951) was one of the first geologists to publish work on the Amherstburg Formation. The study focused on defining the stratigraphy of the Detroit River Group of the Michigan Basin. Landes (1951) stated the Amherstburg was limestone or dolomite. He noted that the Sylvania Sandstone was not included in the Amherstburg Formation in previous studies. However, Landes (1951) assigned the Sylvania Sandstone as a member in the Amherstburg Formation, due to the gradational contact between the sandstone and the carbonate rocks. Additionally, “The only evaporites within the Formation [were] occasional nodules of anhydrite…” (Landes, 1951, p. 7). The Amherstburg Formation is described as a gray to brown dolomite where it outcrops in the southeastern part of Michigan and the northwestern part of Ohio (Landes, 1951). However, the carbonate rocks in the southeastern part of Michigan and the northwestern part of Ohio of the Amherstburg Formation are a dark brown to black. The rocks become lighter in color in the central Basin (Landes, 1951). The Amherstburg Formation was interpreted to be deposited during a time of high sea level. The seas began to regress and the basal Lucas Formation in the central basin (the “Freer Sandstone” of Gardner, 1974) was deposited from sands being blown eastward from present day Wisconsin (Landes, 1951). The rounded and well-sorted grains are in a vertical relationship with emergent facies. This description fits better with an aeolian system. The Lucas Formation is defined as a dolomite with diagnostic Middle Devonian fossils (Landes, 1951). The Lucas Formation also contains thick beds of dolomite, anhydrite, salt, limestone, and sandstone (Landes, 1951).

A few months after Landes published his work, Ehlers, Stumm, and Kesling (1951) published a study on the Devonian rocks of the southeastern part of Michigan and the northwestern part of Ohio based on analysis of the units in quarries, shallow wells and outcrops. Ehlers et al. (1951) stated that the Amherstburg Formation was a, "...thick bedded, brown dolomite…" (p. 9). They did not include the Sylvania Sandstone as a member of the Amherstburg Formation. According to Ehlers et al. (1951), "The Amherstburg rests on… [the] Sylvania Sandstone," (p. 9). At the time of Ehlers et al. (1951), the only location where the Amherstburg could be found outcropping in Michigan was at an abandoned quarry in the southeastern corner of the state. The dolomite is also exposed near the town of Silica, Ohio (Ehlers et al., 1951). The dolomite, "... is about 50 feet thick… [and] increases in thickness toward the Detroit area where it has a thickness of about 70 feet," (Ehlers et al., 1951, p. 9).

In 1960, William Langenbahn published a thesis on the facies of the Amherstburg Formation in southeastern Michigan identified from cores sampled from wells in the Wayne County Airport as part of an economic analysis of the evaporite deposits of the Devonian and Upper Silurian. Langenbahn divided the Amherstburg into three distinct facies. The first facies was described as a buff to light gray dolomitic rock (Langenbahn, 1960). Gypsum was found within the fractures of the cores and small chert nodules were also found. The bottom of the Amherstburg was noted as being sandier than the rest of the Amherstburg due to the transitional boundary between the Amherstburg and the Sylvania Sandstone. The second facies was described as a dark to medium gray dolomitic rock with tan organic banding (Langenbahn, 1960). Gypsum is present as secondary cements in fractures and vugs after fossils. "The abundance of bituminous layers and the dark colors are the most striking characteristics of this facies," (Langenbahn, 1960, p. 8). The third facies was divided into three smaller sub-facies. Facies 3-A was described as a buff dolomitic rock that varies from dense to organic-rich (Langenbahn, 1960). This sub-facies was similar to facies 1 except for the shape of the dolomite grains and the color of the matrix. The dolomite grains were mainly anhedral in shape and had fewer rhombs lining the pores. Facies 3-A was only a buff color, while facies 1 was a buff to light gray color. Facies 3-B was described as a medium buff dolomitic rock. "The texture is one of a sandy carbonate… [and] No definite fossils are apparent in the rock…" (Langenbahn, 1960, p. 12). Facies 3- C was described as a buff to brown dolomitic rock with high organic content and high porosity. This sub-facies is also fossiliferous, which sharply contrasts with facies 3-B. "This subfacies represents good reef core material," (Langenbahn, 1960, p. 13).

The Michigan Basin Geological Society published a study done by W. C. Gardner in 1974. The study covered the stratigraphy and the depositional environments of the Michigan Basin during the Middle Devonian. The Amherstburg Formation was described as a gray, brown, or black carbonaceous wackestone (Gardner, 1974). Stromatoporoids, *Cladopora sp.*, favositids, brachiopods, and crinoids can be found in the Amherstburg Formation (Gardner, 1974). Gardner (1974) subdivides the Amherstburg Formation by defining two members. He identified a lower Meldrum Member and an upper Filer Sandstone Member along with some undifferentiated Amherstburg lithofacies that cannot be placed into any recognized units. "...the Meldrum Member is characteristically dark gray-brown to black, microcrystalline biocalcarenitic limestone which is generally classified as a wackestone…" (Gardner, 1961, p. 30). The Meldrum Member is informally known as the "Black Lime" facies.

Fagerstrom (1961) was one of the first geologists to publish a study on the Devonian reefs of the Michigan Basin. At the time that this study was published, it could not be determined whether the reefs were in the Amherstburg or Lucas Formation (Fagerstrom, 1961). The Lucas and Amherstburg Formations could not be easily distinguished from one another, so Fagerstrom (1961) combined the two formations into an undifferentiated Detroit River Group. Fagerstrom defines a member of the Amherstburg Formation, the "Formosa Reef Limestone", which he described as a light gray limestone found within the Detroit River Group (Fagerstrom, 1961). The limestone that composes the "Formosa Reef Limestone" is described as extremely pure limestone: "The average calcium carbonate content of four samples is 99.13 per cent," (Fagerstrom, 1961, p. 346). Over half of the "Formosa Reef Limestone" is composed of stromatoporoid and tabulate coral colonies (Fagerstrom, 1961). There are also abundant brachiopods and vugs. Currently, the "Formosa Reef Limestone" is not formally recognized by the Ontario Geological Survey as a formal lithostratigraphic unit (Armstrong and Carter, 2010). Below the "Formosa Reef Limestone", Fagerstrom (1961) described the Detroit River Group as a brown to buff fine-grained dolomite in the Dominion Natural Gas Company J.B. McKenzie Well No. 1 to the southwest of the city of Teeswater, Ontario. Fagerstrom (1961) identified a light gray limestone calcarenite between the "Formosa Reef Limestone" and the upper Detroit River Group. The Detroit River Group is identified as a dark brown dolomite with increasing amounts of chert as it approaches the "Formosa Reef Limestone".

In 1989, Pratt published a study on the “Formosa Reef Limestone” and the Lower Devonian Stromatoporoid reefs of North America. Pratt (1989) examined patch reefs in southwestern Ontario. The dominant organisms in the limestone were stromatoporoids, tabulate corals, and rugose corals. The, “...matrix is richly fossiliferous, containing trilobites, ostracods, bryozoans, brachiopods, gastropods, rostroconchs and cephalopods (Fagerstrom, 1961a; Ludvigsen, 1987),” (Pratt, 1989, p. 508). Pratt (1989) observed tabular stromatoporoids. Pratt (1989) also observed the primary interskeletal porosity being preserved locally. Small cavities formed underneath the stromatoporoid fragments and prevented the deposition of cement or sediment (Pratt, 1989). These two observations are diagnostic properties of the Stromatoporoid reefs. Prosh and Stearn (1993) showed that the characteristic stromatoporoids in the Detroit River Group were similar to stromatoporoids from Devonian rocks outcropping in the Canadian Arctic Archipelago. Dating the Detroit River Group based on fossil content is difficult due to the endemism occurring in the region (Prosh and Stearn, 1993). Endemism refers to the creation of unique species as a result of geographic barriers. The Michigan Basin was part of a restricted biogeographic province during this period, which hosted species not found elsewhere in the world. The new species of stromatoporoids found in the Arctic allowed more accurate dating of the Detroit River Group. Based on their data, Pratt and Stearn (1993) determined the Detroit River Group was Lower Devonian in age.

II. Core Location and Methods

There were cores from three wells examined for this study. The first core was the St. Charlton #4-30 (PN: 57916) from 30-31N-1W in Otsego County. The section of the core that was examined for this project was located 3090 ft (942 m) to 3030 ft (924 m) below the ground surface. The second core was the TB-7 from the Detroit International Crossing construction project in eastern Wayne County. The section of the TB-7 that was examined for this project was located 456 (139 m) to 381 ft (116 m) below the ground's surface. The third core that was examined was the Kalman #1-16 (PN: 33013) from 16-30N-1W from Otsego County. The cored interval from the Kalman #1-16 that was examined for this project was located 3235 (986 m) to 3179 ft (969 m) below the ground's surface. Table 1 summarizes the geographic locations and cored intervals for each well described in this study.

Permit Number	Company	Well Name	County	Section	Township /Range	Top of Core (ft.)	Bottom of Core (ft.)
57916	Core Energy	State Charlton #4-30	Otsego	30	31N-1W	3030	3090
0500	Michigan Department of Transportation	DRICXIOTB7 (TB-7)	Wayne		2S-11E*	381	456
33013	Reef Petroleum	Kalman #1-16	Otsego	16	30N-1W	3179	3235

Table 1: Information on the location of the wells examined. *The DRICXIOTB7 is located at 42.2901°N, 83.1018°W.

A hand lens and dilute hydrochloric acid was used to analyze the core samples. After analyzing each core, a description of each facies found in the core sample was recorded. The descriptions include the color of the sample, the fossils present, mineral composition, the presence of sedimentary structures, the presence of stylolites and other diagenetic/secondary features, rock clasts, the nature of the bedding or laminations, and the bioturbation index. The cores were also examined using previously cut thin sections. The thin section descriptions include the same items as the core sample descriptions. Each facies was classified using the modified Dunham classification system of limestones (Dunham, 1962; Embry and Klovan, 1971). The bioturbation index of the core samples was defined using the methods of Taylor and Goldring (1993). Core profiles and depositional models were drafted with Adobe Illustrator using templates courtesy of Mike Grammer (Voice, personal communication, 2019).

III. Results

Facies of the St. Charlton #4-30 well:

Facies 1: fossiliferous mud-lean packstone

Facies 1 is a dark gray fossiliferous lime mud-lean packstone. The matrix consists of a finely ground up skeletal material. The packstone is weakly bedded. The size of the fossils ranges from coarse sand to pebbles. There are some larger clasts observed floating in the matrix. Facies 1 contains disarticulated brachiopod shells, colonial rugose corals, tabulate corals, and stromatoporoid fragments (Figure 3). There are abrasions on the edges of the fossils and most of the corals and shells are broken. Some of the fossils are partially silicified. The majority of the smaller skeletal grains are highly abraded fragments that are not identifiable to the class or phyla. Abundant wispy stylolites were also found in the facies.

Figure 3: Facies 1 of the St. Charlton #4-30 at a depth of 3090 ft (942 m). Facies 1 shows the large amount and variety of fossils like corals (white clasts) found in the facies. The fossils were broken and abraded. Figure 3 shows the finely ground up skeletal matrix.

Facies 2: light gray to brown wackestone

Facies 2 is a light gray to brown lime wackestone. There are a few abraded skeletal clasts of corals and disarticulated brachiopods. The facies contains a chert nodule (Figure 4). Swarms of stylolites are abundant throughout facies 2. The morphology of the stylolites range from wispy to jagged. The stylolites wrap around the chert nodule. There is a swarm of stylolites that wraps around the chert nodule.

Figure 4: Facies 2 of the of the St. Charlton #4-30 at a depth of 3088 ft (941 m). The picture shows a large chert nodule (light gray) with stylolites wrapped around the nodule.

Facies 3: gray to brown mud-rich packstone to wackestone

Facies 3 consists of two sub-facies. Facies 3-A is a gray mud-rich lime packstone. There are chert nodules throughout the sub-facies. Facies 3-A contains tabulate corals, colonial rugose corals, and solitary rugose corals, sheet-like stromatoporoids, crinoids, and bryozoans (Figure 5). The fossils are not in their growth position.

Figure 5: Facies 3-A of the St. Charlton #4-30 at a depth of 3086 ft (940.6 m). The picture shows the tabulate corals, colonial rugose corals, and solitary rugose corals, sheet-like stromatoporoids, crinoids, and bryozoans.

Facies 3-B is a gray to brown lime wackestone. Tabulate and rugose corals are the only fossils found within this sub-facies (Figure 6). This sub-facies is matrix dominated. There are small clasts of corals and crinoids observed within facies 3-B. The fossils are not in their growth position.

Figure 6: Facies 3-B of the St. Charlton #4-30 at a depth of 6 and a half inches past 3078 ft (938 m). This picture shows the contrast between facies 3-A (upper half) and facies 3-B (lower half). This image shows the small fossil grains and is matrix dominated.

Facies 4: dark gray to black mud-lean packstone

Facies 4 is a dark gray to black, mud-lean lime packstone. The facies is grain supported. The matrix is composed of finely ground up indeterminate fossils. Skeletal clasts include tabulate corals, rugose corals, stromatoporoids, bryozoans, and brachiopods (Figure 7). The fossils are not in their growth position. There are three thin sections from this facies available. The thin section observations support the hand sample description of this facies as a dark gray to black grain-supported mud-lean packstone. The lime mud matrix is composed of smaller silt-sized, disarticulated and abraded indeterminate skeletal grains (Figure 8). There are also larger clasts of brachiopods, bryozoans, and crinoids.

Figure 7: Facies 4 of the St. Charlton #4-30 at a depth of 3070 ft (936 m). This image shows the black matrix and the large amount of tabulate corals, rugose corals, stromatoporoids, bryozoans, and brachiopods.

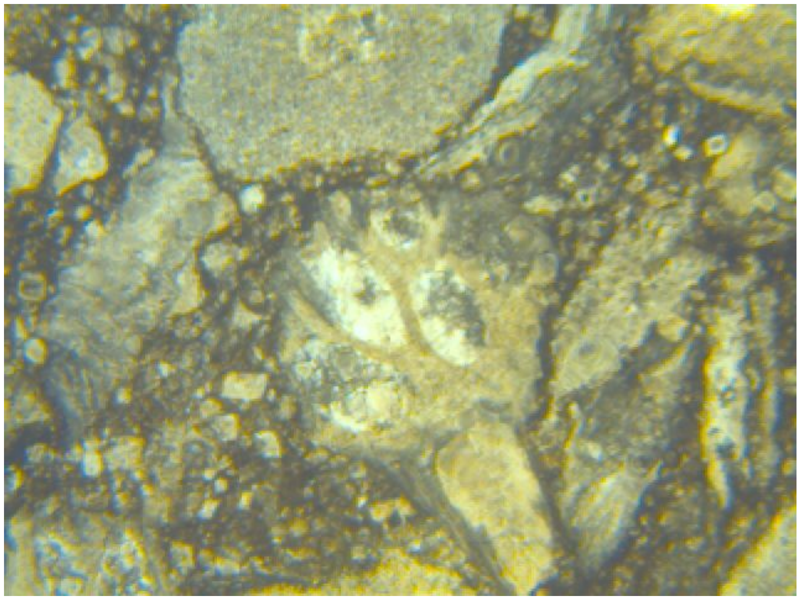


Figure 8: Facies 4 thin section of the St. Charlton #4-30 at a depth of 3044 ft (928 m). The thin section shows the grain supported facies with identifiable brachiopods, bryozoans, and crinoids.

Facies 5: grayish tan wackestone to mudstone

Facies 5 is a grayish tan lime wackestone to mudstone. The facies is matrix supported. Facies 5 includes clasts of corals, gastropods, trilobites, and ostracods, as well as disarticulated brachiopods, and one large solitary rugose coral (Figure 9). The fossils were not in their growth positions.

Figure 9: Facies 5 of the St. Charlton #4-30 at a depth of 4 and a half inches past 3068 ft (935 m). The image shows a large solitary rugose coral.

Facies 6: black mudstone to wackestone

Facies 6 is a black lime mudstone to wackestone. Stromatoporoid, coral, bryozoan, and crinoid fragments are found in facies 6 (Figure 10). The fossils are not in their growth positions. Facies 6 exhibits massive bedding. There were eight thin sections available. The thin sections confirm the identification of this facies as a black mud-rich packstone to wackestone. Embedded in the matrix are mixes of silt- to fine-sand sized abraded skeletal grains (Figure 11). There are also clasts of crinoid, brachiopod, colonial tabulate coral, trilobite, and bryozoan grains in the matrix. There are abundant smaller indeterminate skeletal grains between the larger clasts.

Figure 10: Facies 6 of the St. Charlton #4-30 at a depth of 3059 ft (932 m). The image shows the dark colored fossiliferous rock with large brachiopod and coral clasts.

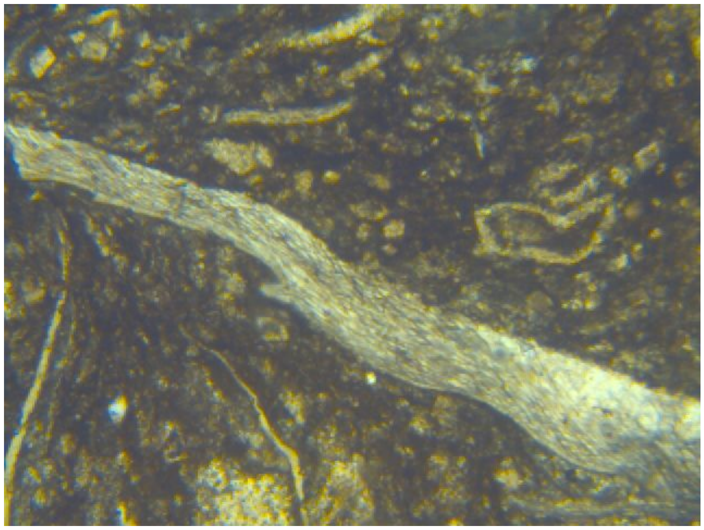


Figure 11: Facies 6 thin section of the St. Charlton #4-30 at a depth of 3058 ft (932.1 m). The image shows a large bryozoan fragment with a finely ground up skeletal matrix.

Facies 7: gray to tan bafflestone

Facies 7 is a gray to tan lime bafflestone. The facies consists of rounded finger-like tabulate corals that are clumped together in their growth positions (Figure 12). Stylolites were observed to wrap around the corals. Facies 7 lacks bedding.

Figure 12: Facies 7 of the St. Charlton #4-30 at a depth of 3054 ft (931 m). The image shows large coral bafflestones. The corals are in their original growth position.

Facies 8: gray to tan wackestone

Facies 8 is a gray to tan lime wackestone. There are fewer fossils present in facies 8 than the other facies. In facies 8, there was more mud than observed in the previous facies. Facies 8 contains large rugose and tabulate corals (Figure 13). There were a few indeterminate fossil fragments in the matrix between the larger coral clasts.

Figure 13: Facies 8 of the St. Charlton #4-30 at a depth of 3051 ft (929.9 m). The core shows a muddy matrix with a few interbedded large coral fragments.

Facies 9: brown to dark gray mudstone

Facies 9 was a slightly brown to dark gray lime mudstone with gastropod fragments and rugose corals. The fossils are concentrated into beds composed of fining-upward skeletal clasts. The skeletal-rich beds are interbedded with mud-rich beds (Figure 14). The fossils are not in their initial growth positions. Abundant wispy stylolites are present in facies 9.

Figure 14: Facies 9 of the St. Charlton #4-30 at a depth of 3033 ft (924 m). The center of the image shows the normal grading of the coral and gastropod fossils. There are stylolites wrapped around the normally bedded fossils.

Facies of the Kalman #1-16 well:

Facies 10: dark gray to black lime mud-lean packstone

Facies 10 is a dark gray to black lime mud-lean packstone with stromatoporoid, tabulate corals, rugose corals, crinoids, and brachiopods clasts. Stromatoporoid fragments are the dominant fossil found in this facies (Figure 18). The fossils are not in their growth position. In the thin section, facies 10 is a dark brown mud-lean packstone. The thin sections contain disarticulated brachiopods, coral clasts, and crinoid stem fragment (Figure 19). The matrix is mud with finer-grained indeterminate skeletal grains.

Figure 15: Facies 10 of the Kalman #1-16 at a depth of 3189 ft (972 m). The image shows the large amount of stromatoporoid fossils grains.

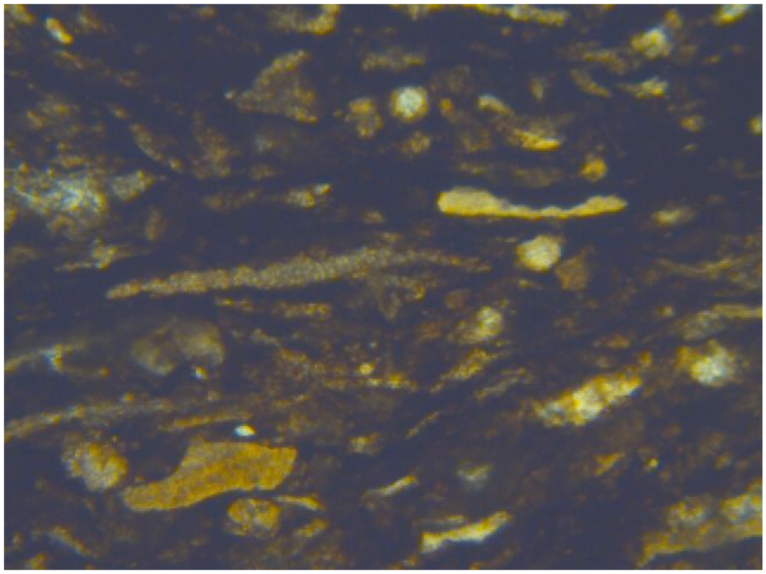


Figure 16: Facies 10 thin section of the Kalman #1-16 at a depth of 3234 ft (986 m). The thin section shows disarticulated brachiopods, coral clasts, and crinoid stem fragments with finer-grained indeterminate skeletal grains.

Facies 11: brown to gray lime mud-lean packstone

Facies 11 is a brownish gray lime, mud-lean packstone. The facies is dominated by small skeletal clasts of corals (Figure 20). There are also some tabulate corals and stromatoporoid fragments. Interbedded within the mud-lean packstone are intervals of 2 to 3 inches (5 to 8 cm) thick wackestone deposits. Three thin section slides are available. The thin sections suggested a dark gray to brown mud-lean packstone. There are trilobite and crinoid skeletal fragments floating in the matrix (Figure 21).

Figure 17: Facies 11 of the Kalman #1-16 at a depth of 3229 ft (984 m). The image shows the small coral clasts and the interbedded wackestone (bottom of core).

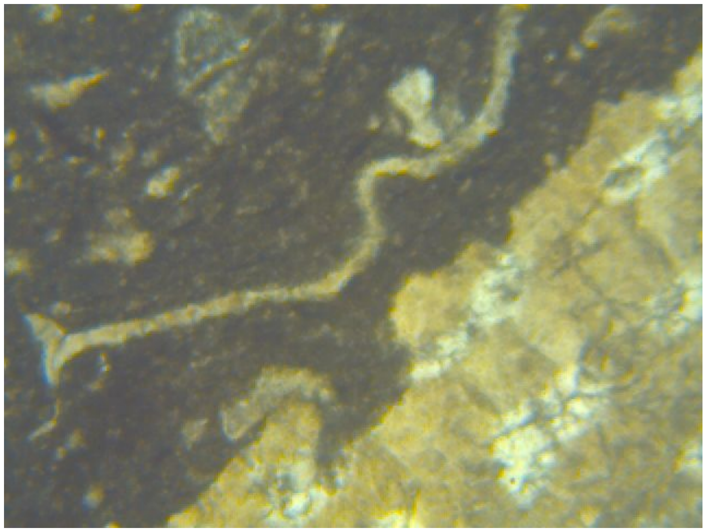


Figure 18: Facies 11 thin section of the Kalman #1-16 showing a clast of a trilobite thoracic segment at a depth of 3188 ft (972 m).

Facies 12: dark gray to black lime mudstone to wackestone

Facies 12 consists of two sub-facies. Facies 12-A is a dark gray to black lime, mudstone to wackestone with small skeletal fragments (Figure 22). Most of the skeletal shell fragments are heavily abraded and floating in the matrix; however, there are a few disarticulated valves of brachiopods present floating in the matrix. Stylolites range from digitate to wispy in facies 12-A. Facies 12-B is similar to facies 12-A with the exception that facies 12-B is thicker and more laminated than facies 12-A. The laminations are approximately one millimeter thick. Facies 12-B has planar to rippled bedding. There are also anhydrite crystals present. There are four thin section slides available for this facies. The thin sections contain brachiopod valves with fibrous shell textures (Figure 23). The background matrix is composed of pellets. There are patches of cement sheltered beneath the larger skeletal grains.

Figure 19: Facies 12 of the Kalman #1-16 at a depth of 3227 ft (983 m). The image shows a lack of fossils and is very fine material. There is also a stylolite present as a black line in the top of the core sample. The red arrow indicates a digitate stylolite.

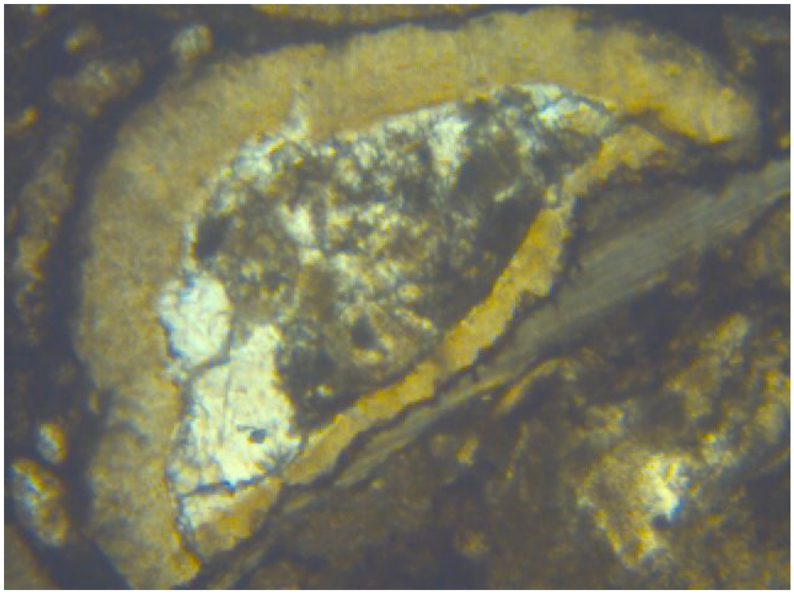


Figure 20: Facies 12 thin section of the Kalman #1-16 at a depth of 3221 ft (982 m). The image shows a brachiopod valve with a fibrous texture.

Facies 13: brownish gray lime mudstone to wackestone

Facies 13 is a brownish gray lime mudstone to wackestone with large anhydrite nodules (Figure 24). There is some slight oil staining throughout facies 13. Wispy and digitate stylolites are observed in facies 13.

Figure 21: Facies 13 of the Kalman #1-16 at a depth of 3219 ft (981 m). The image shows anhydrite at the bottom of the core. There are abundant sylolite as well respresented as black lines.

Facies 14: light gray lime mudstone to wackestone

Facies 14 is a light gray, nodular, lime mudstone to wackestone. There are abundant digitate stylolites present in facies 14 (Figure 25). Facies 14 contains burrows filled in with the surrounding matrix.

Figure 22: Facies 14 of the Kalman #1-16 at a depth of 3120 ft (951 m). The image shows the abundant digitate sylolites found within the facies.

Facies 15: dark brown to black lime mudstone to wackestone

Facies 15 is a dark brown to black limes mudstone to wackestone. There are a range of structures composed of anhydrite including nodular anhydrides (Figure 27) and anhydrite laths. Facies 15 is microbially-laminated. The laminations wrap around the anhydrite crystals. As the crystals grew, the laminations deformed around the anhydrite nodules. The laminations formed before the anhydrite crystals grew. The anhydrite laths (Figure 26) cross-cut stylolites and bedding features suggesting that they are secondary features formed well after deposition and lithification.

Figure 23: Facies 15 of the Kalman #1-16 showing the anhydrite crystals at a depth of 3189 ft (972 m).

Figure 24: Facies 15 of the Kalman #1-16 showing the anhydrite nodules at a depth of 3201 ft (976 m).

Facies 16: light brown to tan lime mudstone

Facies 16 is a light brown to tan lime mudstone. The facies is microbially laminated and the laminations alternate between tan and black (Figure 28). The black bands are assumed to be enriched in organic matter. There are mud-cracks present in facies 16.

Figure 25: Facies 16 of the Kalman #1-16 at a depth of 3183 ft (970 m). The image shows the light and dark colored laminations.

Facies 17: gray mudstone

Facies 17 is a gray lime mudstone. Facies 17 is dominated by centimeter-scale burrows that are filled in with sediment. The bioturbation index of facies 17 is 4. Facies 17 exhibits massive bedding (Figure 29). There are sharp stylolite contacts throughout facies 17.

Figure 26: Facies 17 of the Kalman #1-16 at a depth of 3180 ft (969 m). The image shows a lack of bedding planes with a few small burrows.

Facies of the TB-7 well:

The TB-7 core is markedly distinct from the St. Charlton #4-30 well. There were very few fossil grains observed in the core. The core that was analyzed for the TB-7 well was a whole core sample as opposed to the slabbed cores used for the St. Charlton #4-30 and Kalman #1-16 cores. Whole core samples are more challenging to work with than slabbed cores as textures and structures may look distorted from the curvature of the core. There can also be more mud and other materials on the outside of the whole core.

Facies 18: gray to brown sandy dolomite

Facies 18 was a light gray to brownish gray sandy dolomite. The facies is characterized by small clasts of mud. There are small skeletal fragments in the core sample. The skeletal grains had been leached making the rock appear porous. Quartz sand grains float in a dolomite matrix. There are abundant burrows found in facies 18 (Figure 15). The burrows are irregularly shaped and discreet. The small burrows are filled in with sand. Using the Taylor and Goldring (1993) bioturbation index, facies 18 had a bioturbation index of 1, but at 453.8 ft (138.3 m) the bioturbation index increased to 3. The facies exhibits massive bedding, but some of the pores are aligned suggesting faint bedding. There are intervals of distinct cross bedding throughout facies 18. Stylolites can be found throughout the facies. There are places in facies 18 where salt-filled vugs were observed.

Figure 27: Facies 18 of the TB-7at a depth of 453 ft (138 m). The image shows abundant burrows and a stylolite near the bottom of the image.

Facies 19: brown to gray sandy dolomite to dolomitic sandstone

Facies 19 is a brownish gray sandy dolomite to dolomitic sandstone. The facies contains a large amount of burrows. The burrows are filled with a quartz sand. The bioturbation index of facies 19 is 2 to 3. There are abundant chert beds and nodules (Figure 16). Digitate stylolites appear in facies 19.

Figure 28: Facies 19 of the TB-7 at a depth of 429 ft (131 m). The image shows chert beds and digitate stylolites as black lines. Red arrows show stylolites and blue arrow indicate microbial mats.

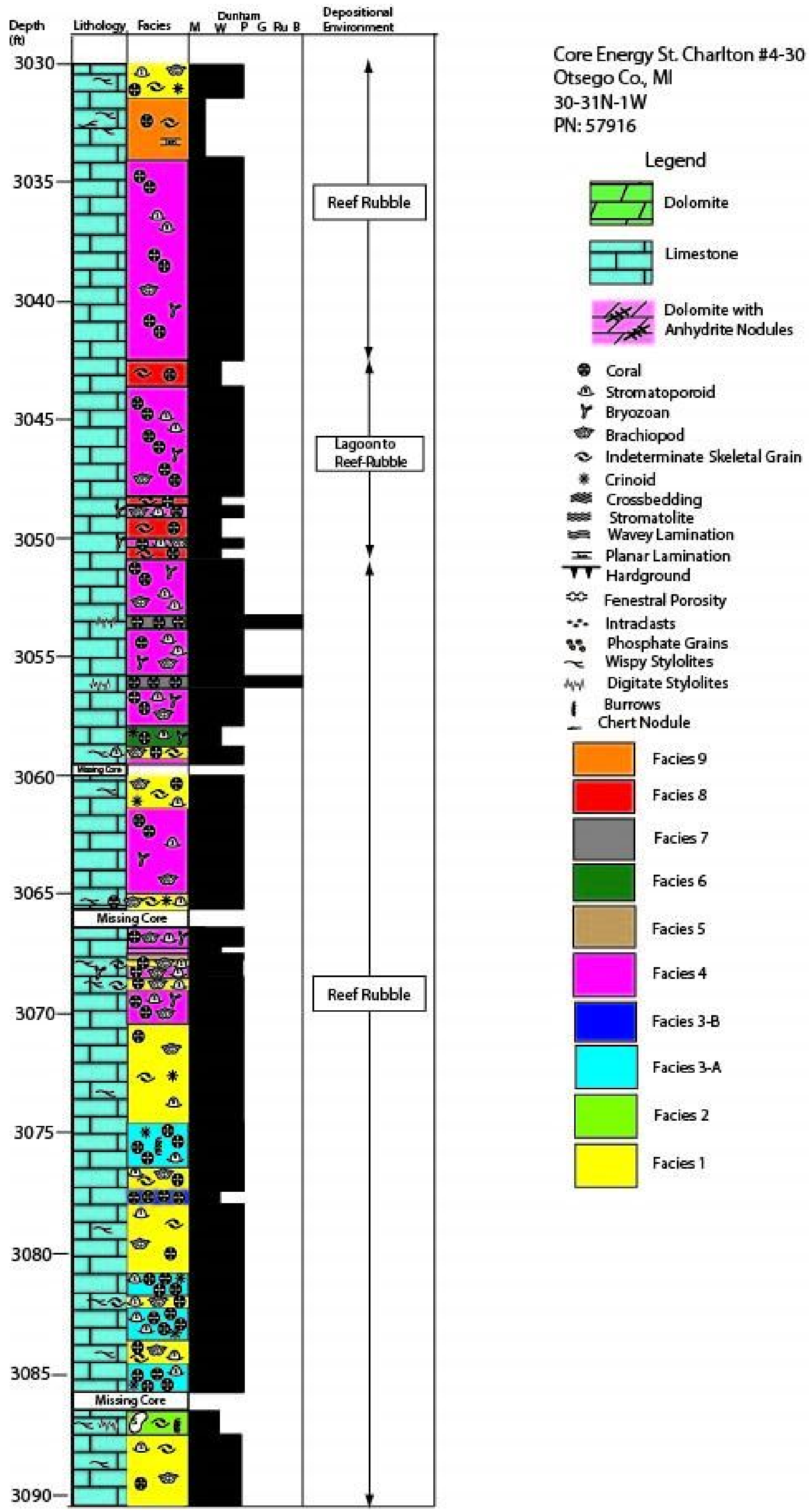
Facies 20: dark brown sandy dolomite

Facies 20 is a dark brown sandy dolomite. The facies contains indeterminate shell fragments. There are burrows filled in with the surrounding matrix. The facies had a bioturbation index of 2 to 3. Facies 20 has small chert nodules and salt-plugged vugs. Stylolites are present throughout the facies (Figure 17). The stylolites are more closely spaced. The core sample exhibits light and dark color banding.

Figure 29: Facies 20 of the TB-7 at a depth of 387 ft (118 m). The image shows the abundant stylolites shown as black lines. The image also shows the light and dark color banding.

Stratigraphic Profiles

Once descriptions of each core was collected and separated into facies, three sedimentary profiles of the three cores were made. These profiles are a way of vertically showing the changing deposition of sediments at a site over time. After defining facies in the St. Charlton #4-30, a corresponding sedimentary profile was constructed from the data (Figure 30). The sedimentary profile outlines the changes in deposition over time. The time aspect of the data is represented by the depth of the core. According to the Principle of Superposition, it is assumed the units found on the bottom of a formation were deposited first and the units found on the top of the formation were deposited last. In the St. Charlton #4-30 core, the lithology throughout the entire core was limestone. Nine different facies were identified in the St. Charlton #4-30 core. The Amherstburg Formation was dominantly a packstone throughout the St. Charlton #4-30 core. However, there were facies with a wackestone to mudstone grain size. There were two boundstones within the facies as well. A majority of the fossils found in the St. Charlton #4-30 were corals and stromatoporoids.



Depth (ft)
Lithology
Facies
Dunham
M W P G Ru B
Depositional Environment
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
Missing Core
Missing Core
Missing Core
Reef Rubble
Lagoon to Reef-Rubble
Reef Rubble
Core Energy St. Charlton #4-30
Otsego Co., MI
30-31N-1W
PN: 57916
Legend
Dolomite
Limestone
Dolomite with Anhydrite Nodules
Coral
Stromatoporoid
Bryozoan
Brachiopod
Indeterminate Skeletal Grain
Crinoid
Crossbedding
Stromatolite
Wavey Lamination
Planar Lamination
Hardground
Fenestral Porosity
Intraclasts
Phosphate Grains
Wispy Stylolites
Digitate Stylolites
Burrows
Chert Nodule
Facies 9
Facies 8
Facies 7
Facies 6
Facies 5
Facies 4
Facies 3-B
Facies 3-A
Facies 2
Facies 1

Figure 30 (previous page): Sedimentary Profile of the St. Charlton #4-30 core. The column next to the depth represents the lithologies observed in the core.The column to the right of the lithology represents the specific facies identified.The next column to the right represents the Dunham classification of carbonates. The final column presents the interpreted depositional environment for each facies or facies association. Throughout the facies column, there are small symbols. These symbols represent the fossils or sedimentary structures found within the facies.

A sedimentary profile was also construct for the Kalman #1-16 core (Figure 31). The core ranged from 3179 ft (969 m) to 3235 ft (986 m). The lithology of the Kalman #1-16 is represented by the blue brick pattern which corresponds to limestone. There were eight different facies identified in the Kalman #1-16 core. The Kalman #1-16 was dominated by mudstones and wackestones, though a few smaller intervals of packstone were observed. A majority of the fossils found within the Kalman #1-16 were indeterminate fossil grains and stromatoporoids. There were abundant stylolites present in the Kalman #1-16.

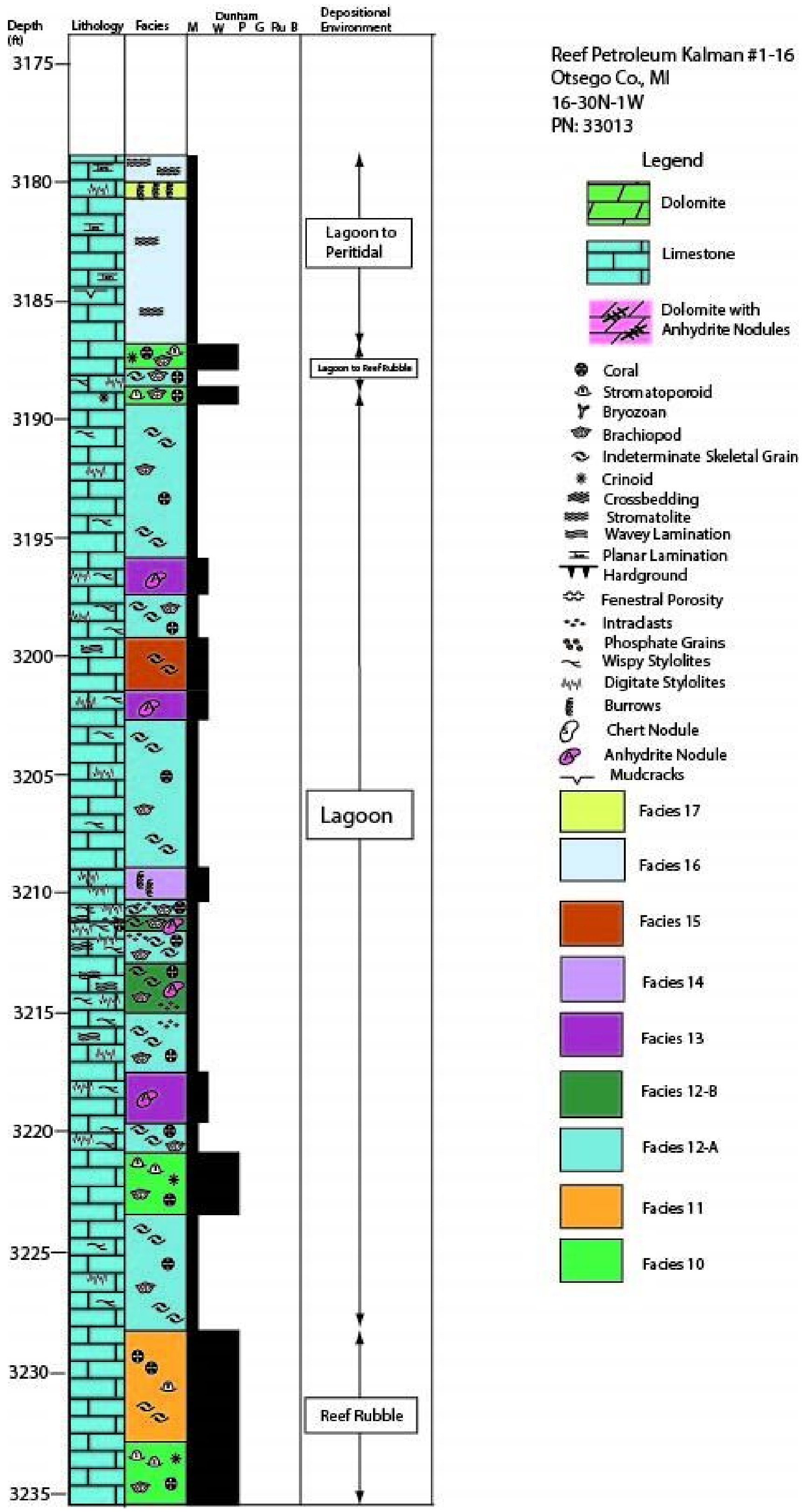


Figure 31: Sedimentary Profile of the Kalman #1-16 core.

A sedimentary profile was also constructed for the TB-7 core (Figure 32). The profile ranged from 381 ft (116 m)to 456 ft (139 m). The lithology of the TB-7 core is dominantly dolomite. This is represented in the lithology column by the green brick pattern. In total, three distinct facies were identified in the TB-7 core. All three of the facies fall into the Dunham classification of packstone. All three facies in the TB-7 core were determined to be a lagoonal to peritidal environment. The main fossil present in the TB-7 was coral. There were many indeterminate fossil grains present in the core. There were also many anhydrite fossil grains present in the TB-7. Digitate and wispy stlolites are present in the TB-7.

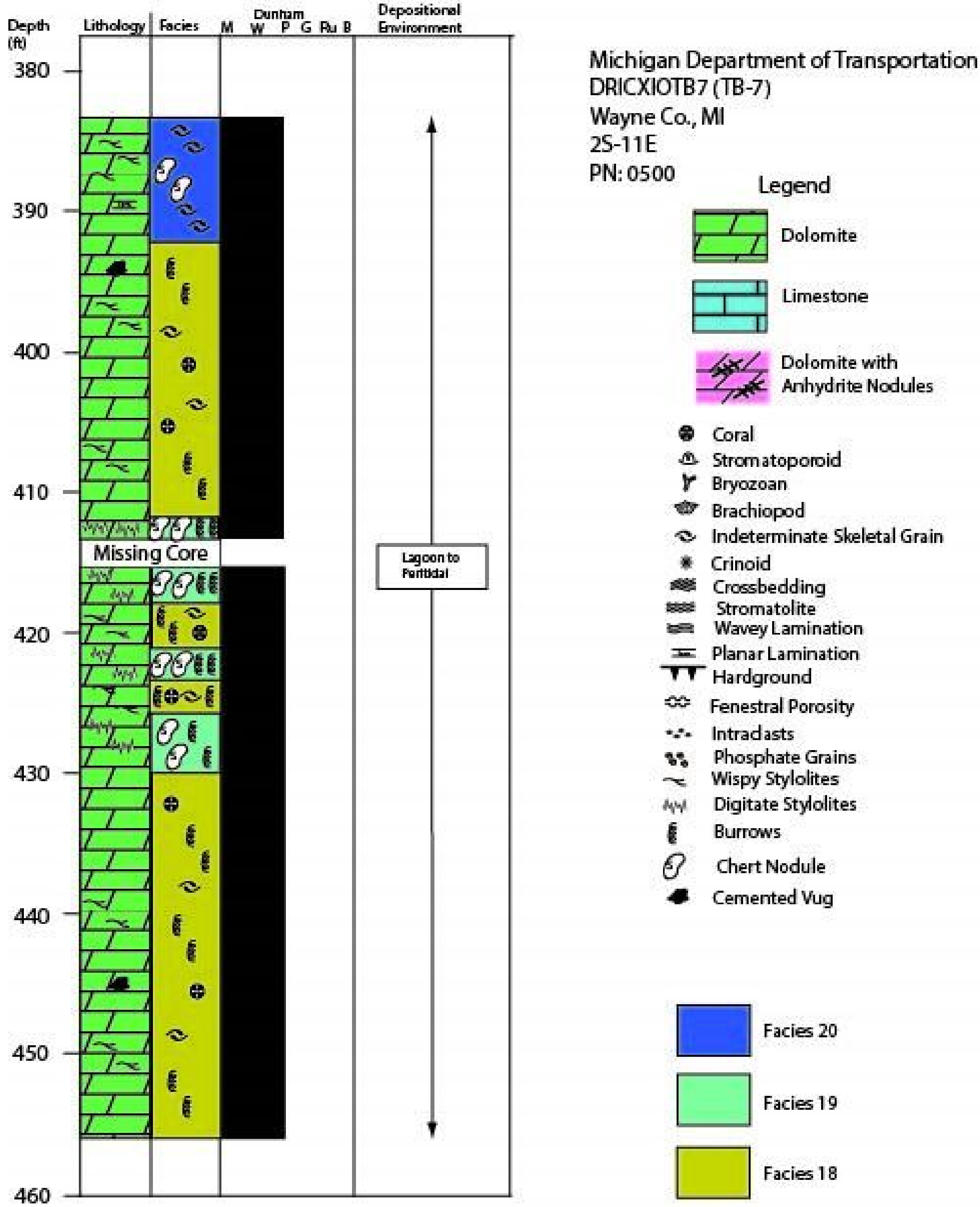


Figure 32: Sedimentary Profile of the TB-7 core.

IV. Discussion

In total, twenty different facies were identified between the three cores. The facies were sorted into four facies associations based on similarities in lithology and facies stacking patterns, fossil content, and the Dunham textural classification. The facies associations were then interpreted and assigned to larger-scale depositional environments. The four associations defined in this study are reef rubble, lagoonal, lagoonal and reef-rubble, and lagoonal and peritidal environments. The four facies associations were combined to create a depositional model that represents the depositional area of the Amherstburg Formation (Figure 33). Reef rubble facies associations can be found in the St. Charlton #4-30 core and the Kalman #1-16 core. The only core with lagoonal facies was the Kalman #1-16. Lagoonal and reef-rubble facies associations were found in the St. Charlton #4-30 core. The lagoonal and peritidal facies associations were seen in the TB-7 and the Kalman #1-16.

Reef Rubble Facies Association

In general, the reef rubble facies association can be described as a lime packstone to wackestone. The reef rubble facies associations consisted of a finely ground up skeletal and pelletal matrix with abundant larger clasts floating in the matrix (Tucker and Wright, 1990). There are many fossils present in the reef rubble environment such as corals, stromatoporoids, crinoids, brachiopods, and bryozoans. All of the major Paleozoic marine fauna were present in the reef rubble environment. The abundant and diverse fauna suggests that the reef rubble facies were adjacent to the reef. None of the fossils were found in their growth positions, which implies that they were transported from the sites where they lived. A reef rubble can be shed both basinward and landward from the reef by tidal currents, wave action and storms. The basinward reef rubble environment should exhibit interbedding with open-shelf deposits deposited below or near storm wave base. The shoreward reef rubble system borders the lagoonal system and will have characteristics of low-energy, sheltered environments. This reef rubble environment includes characteristics of a lagoonal system. The reef rubble environment that was seen in this study was most likely the shoreward reef rubble environment.

In facies 1, the fossils appeared to be transported to the location where the rock formed based on the abrasion sustained by the fossils. A dark colored packstone is indicative of higher organic content. This usually suggests an area under more reducing conditions. There were some larger clasts found within the matrix that indicate a small amount of movement from the source area. The matrix is very fine which may have been broken during a storm or by tidal waves. It is more likely that the grains were broken during a storm event based on the well sorted nature found in the sample. The matrix is composed of finely abraded skeletal material. The presence of large corals and stromatoporoids suggests the reefs were nearby. This reef rubble environment is likely just off of the edge of the actual reef (Tucker and Wright, 1990). A very small portion of an ancient reef is preserved. Most ancient reefs are found today as rubble and fill (Tucker and Wright, 1990). The abrasions on the fossils indicate they were rolled or bounced down the slope. The facies contained some wispy stylolites, which indicates the area had a muddy matrix.

Facies 2 indicates a reef rubble environment. The fossils were all fragments and had been transported from their initial source area. Facies 2 contained a chert nodule that grew parallel to the bedding. The facies contained a small amount of oil staining. This suggests the area was high in organic content. The thin sections for facies 2 also suggested the presence of organics, which were represented by dark patches (Flügel, 2010).

Facies 3 contained a large amount of skeletal grains. The fossils were not in their growth position indicating they had been transported. The most likely depositional environment of facies 3-A is a reef rubble environment. Facies 3-A contained corals as well as crinoid and stromatoporoid fragments. There were less fossils in facies 3-B than in facies 3-A. The only intact fossils found in 3-A was coral fragments. There were smaller, more abraded fossils found within the matrix. Facies 3-A can be described as a lime packstone, while facies 3-B can be described as a wackestone.This indicates the area of deposition for facies 3-B is more distal from the source area than facies 3-A. The differences between facies 3-A and B could also be attributed to different energy levels. The depositional environment of facies 3-B is most likely a reef rubble environment.

Facies 4 also contained a large amount of skeletal grains. The fossil grains were not in their growth position indicating they had been transported. The facies was most likely deposited at the top of a reef-rubble to lagoonal patch reef. The matrix consisted of a lime mud. The lime mud suggests sediment is coming from two sources; the reef and the lagoon. This suggests the reef rubble environment is shoreward of the actual reef system.

Facies 5 was classified as a wackestone to mudstone. The increase in mud from previous facies indicates a depositional environment that is in quieter, low energy water depths. All of the fossils were not in their growth positions and heavily abraded and broken. This indicates the fossils have been transported some distance from their source area. The matrix was a dark black muddy mix of indeterminate fossil grains. The most likely depositional environment of facies 5 is in the outer rims of a reef rubble environment.

Facies 6 contained some large coral, stromatoporoid, bryozoan, and crinoid fragments within the indeterminate fossil matrix. Facies 6 does not contain as much mud as facies 5. This indicates the depositional environment is a higher energy environment than facies 5. The depositional environment of facies 6 is near the reef in the reef rubble environment.

Facies 7 contained large rounded finger-like tabulate corals. The corals were nearly in their growth position indicating they have moved very little since their initial growth. This facies was deposited near where corals grew. The most likely depositional environment of facies 7 is a patch reef to reef rubble environment. Facies 7 also lacked bedding, which is typical of reef environments (Tucker and Wright, 1990).

Facies 9 contained larger, but fewer fossils than facies 8. This suggests the facies was deposited in deeper water, low energy environment. The fossils were concentrated into beds and abraded which indicates that these beds were deposited during storm events (Tucker and Wright, 1990). Therefore, the depositional environment must be above the storm wave base. The fossils were not in their initial growth position indicating they had been transported. The most likely depositional environment for facies 9 is a reef rubble environment on the deeper open shelf.

Facies 10 was a dark gray or black mud-lean packstone. There was a large amount of skeletal grains in the facies. Based on the fossil content and composition, the depositional environment of facies 10 is most likely a reef rubble environment. The fossils found in the facies were not in their initial growth position. This indicates the fossils have been transported down the ramp. The matrix consisted of indeterminate sand skeletal grains which also suggests the grains were transported a long distance. The high degree of abrasion of the sand dominated particles suggests they have been transported some distance.

Facies 11 was a brownish gray mud-lean packstone. The facies contained fewer whole fossil grains and more ground up skeletal material than facies 10. The skeletal hash represents a high energy environment. The most likely depositional environment is a reef rubble environment near the reef.

Lagoonal Facies Association

The lagoonal facies association is composed of lime packstones to mudstones. The lagoonal facies association did not contain as many fossils as the reef rubble facies associations. The lagoonal facies consisted of stromatoporoids, corals, crinoids, and brachiopods. Like the reef rubble facies association, none of the fossils were in their growth position. All of the skeletal grains found in the matrix were heavily abraded, implying that these organisms were transported into this environment by storms or tidal currents. There were many burrows in the rock. The abundance of burrows suggests that either conditions in the lagoon were only partly restricted or that the burrowers were adapted for more restricted conditions in a hypersaline lagoon (Tucker and Wright, 1990). The lagoonal facies are characterized by laminations (Tucker and Wright, 1990). Lagoons tend to be restricted environments with poor circulation (Wright, 1984). Sedimentation in this environment is likely dominated by suspension settling of sediment punctuated by rarer higher-energy storm or tidal events that introduce the larger skeletal clasts into the environment.

Facies 12 was a dark gray to black mudstone to wackestone. The facies was most likely deposited in a low energy environment. Occasionally, there were rare storm events as evidenced by lenses of course-grained sediment. The storm beds were homogenized into muddy sediments by the abundant burrowing into the facies. Sections of wackestones were created where the abraded coarse-grained sediments mixed with the normally deposited mudstones. The wispy stylolites indicate a large amount of mud in the rock (Flügel, 2010). This suggests a low energy environment like a lagoon. Overall, facies 12-B has the same compositional characteristics as facies 12-A. However, facies 12-B is more laminated than facies 12-A. This is indicative of an environment dominated by suspension settling. The depositional environment of facies 12-A is a lagoon. Facies 12-B was most likely deposited in a lagoonal to reef rubble environment.

Facies 13 was a brownish gray mudstone to wackestone. The wispy stylolites suggest a muddy environment, which is common in lagoonal environments (Flügel, 2010). There were a few digitate stylolites. The digitate stylolites suggest a more grainy matrix. The grainy appearance is most likely from the presence of silt-sized pellets. The pellets are composed of mud and are likely fecal pellets of burrowing organisms living in this environment (Tucker and Wright, 1990). The silt-sized pellets seen in the thin sections are too small to see visually and appear muddy in the hand-sample. Overall, the most likely depositional environment of facies 13 is a lagoonal environment.

Facies 14 was a gray mudstone to wackestone. There were many digitate stylolites found in the core, which suggest a grainy matrix. The grainy matrix was most likely pelletal in nature, but thin sections would be needed to confirm this hypothesis. There were many burrows in facies 14. This suggests the area was inhabited by many organisms. This area was most likely a low energy, quiet water environment. The most likely depositional environment of facies 14 is a lagoonal environment.

Lagoonal to Reef-Rubble Facies Association

The lagoonal to reef-rubble facies associations were a limestone packstone to wackestone. This facies association was grain supported. In hand samples the rock looked more muddy, but when the thin sections were analyzed the rock was more grainy. There were stromatoporoid, coral, crinoid, and brachiopod fragments in the rock. There were some larger whole corals in the rock. Like the other facies associations, the fossils were not in their growth positions. There were larger but fewer fossil grains in the lagoonal to reef-rubble facies than the previous two facies associations.

Facies 8 contain very few fossils and the most mud of all the facies in the St. Charlton #4-30 core. The depositional environment is most likely a lagoonal to reef-rubble setting. The matrix was mostly mud with a few finely ground up skeletal grains, which suggests a low energy, quiet water environment. Since the fossil grains were indeterminate and very small and broken, it can be inferred they have been moved a long distance from their source.

Lagoonal to Peritidal Facies Association

The lagoonal to peritidal facies association is dominated by dolomite to lime packstones and wackestones. These facies were very porous. The facies was laminated which is common in lagoonal environments. There were many burrows in this environment. This is indicative of an active fauna. Mudcracks were found in the facies. This suggests an environment that portions of this facies association were deposited in emergent conditions (supratidal environments) where the land surface was alternately wet and dry allowing desiccation of the mud and formation of mud-cracks. There were small amounts of evaporites, which is also indicative of peritidal to lagoonal environments and the transition to supratidal conditions (Wright, 1984).

Facies 15 was a brown to black mudstone to wackestone. A brown to black mudstone to wackestone is indicative of an intertidal to lagoonal environment. The laminations are current induced. There are large anhydrite crystals present in facies 15. Anhydrite crystals form during times of evaporation. The crystals form in intertidal to sabkha environments. Therefore, the most likely depositional environment of facies 15 is a sabkha adjacent or landward of the lagoon.

Facies 16 was a light brown to tan mudstone. There are dark and light laminations in the facies. The dark bands are enriched in organic matter. The organic matter is most likely microbial mats that formed from cyanobacteria being buried by tides. Microbial mats are found in arid peritidal environments. There were also mudcracks present in the facies. Mudcracks infer a quiet depositional environment that dries for long periods of time. Mudcracks can be found in arid peritidal environments. During times of flooding or high tide, the mudcracks become filled in with sediments. The filled in mudcracks were found in facies 16. The most likely depositional environment of facies 16 was a lagoonal to peritidal environment.

Facies 17 was a gray mudstone. The gray color indicates more reducing conditions. Typically, reducing conditions are seen in lagoonal systems. Circulation in lagoons is often restricted by the presence of barriers (barrier islands, reef tracts, etc.), so seawater chemistry in lagoons can be quite variable. This variability in seawater circulation is reflected by changes in rock composition (muddy carbonates, sometimes associated with evaporites), faunal composition (low diversity and low abundance of organisms suggesting stressed conditions), and higher preservation of organic matter (changes in rock color to darker grays and blacks) (Wright, 1984). The rock is full of burrows, which indicates a system with a large amount of organisms. A majority of organisms that live in the ocean live in lagoonal systems, reef environments, or open water shelves. High bioturbation indices indicate calm, shallow water environments. The most likely depositional environment of facies 17 is a lagoonal to peritidal environment.

Facies 18 was a light brown sandy dolomite. Because the facies contains a significant amount of eolian sand, the depositional environment is one in which wind-blown sediment can accumulate with marine sediments, likely near shore in the lagoon. The small skeletal fragments were likely washed ashore during high tides. There was a vuggy texture in the rock that suggested the skeletal grains had been leached. There were many rounded vugs in the rock. Since the vugs took the shape of the leached skeletal grains, the rounded vug shape tells us the skeletal grains were also rounded. This infers the skeletal grains were highly abraded, which can be indicative of a peritidal environment. The quartz found in the facies was likely sourced from the continents which also indicates the depositional environment is nearshore. The rocks are heavily burrowed. This is indicative of a low energy environment that host a large amount of organisms. The depositional environment of facies 18 of the TB-7 core is lagoonal to peritidal.

Facies 19 can also be described as a sandy dolomite. The quartz sand can be interpreted as an being sourced from terrestrial environments. The facies was extensively burrowed. This suggests organisms were able to live in this environment. The area was most likely a quiet, low energy environment.

Facies 20 was a dark brown sandy dolomite. The facies contained more skeletal fragments than facies 18 or 19. This is indicative of an environment down the ramp from the sabkha. The most likely depositional environment is lagoonal to peritidal. This facies experienced wetting and drying. When the water was evaporated, chert and salt nodules were left behind. The evaporation periods were shorter than the evaporation periods in facies 18 and 19. This is evident based on the size of the evaporites.

Depositional Model

The vertical sedimentary profiles observed in the cores were used to create a model of laterally adjacent depositional environments. Walther's law says that "...facies adjacent to one another in a continuous vertical sequence also accumulate adjacent to one another horizontally," (Maliva, 2016, p. 601). Therefore, the vertical sedimentary profiles also represent the lateral environments. The reef rubble environment was most basinward environment found within the cores analyzed in this study. The reef rubble environment surrounded the actual reef in the area (Gardner, 1974). This environment consisted of the material that was shed of the reef itself. The lagoonal to reef-rubble environment was shoreward of the reef rubble environment. Shoreward of the lagoonal to reef-rubble environment was the lagoonal environment. Finally, the lagoonal to peritidal environment was the most shoreward environment identified in the cores analyzed in this study. Figure 33 shows the depositional model created for the Amherstburg Formation. The reef rubble environment was towards the basin and the lagoonal to peritidal environment was near the shore.

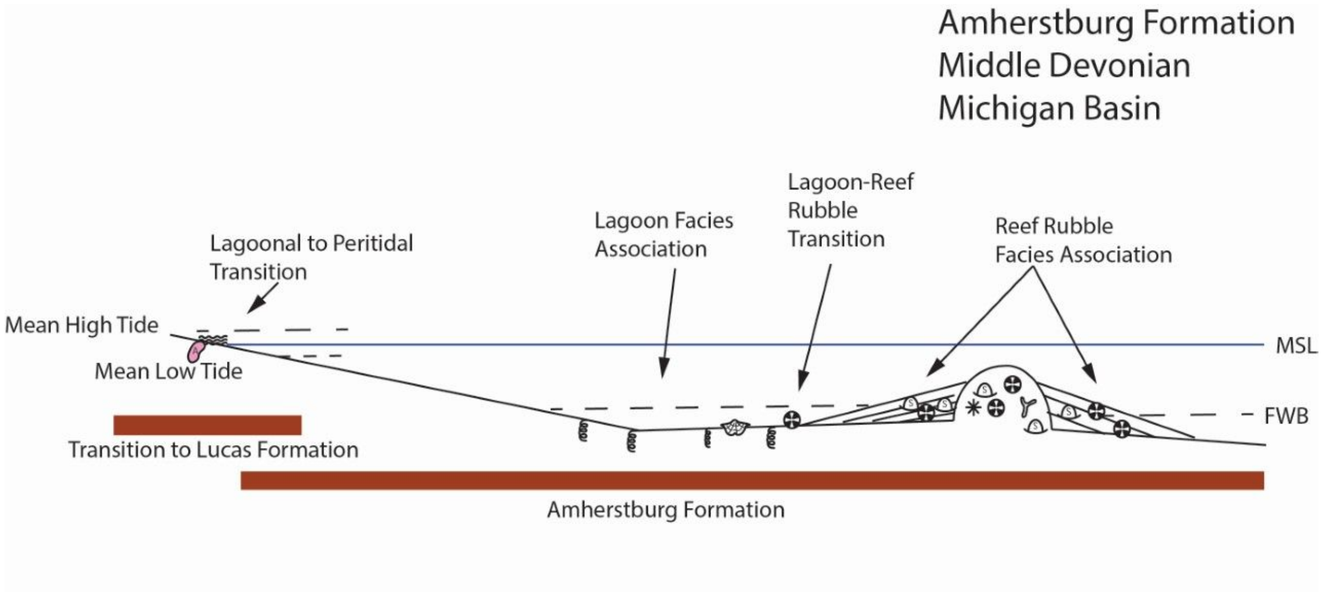


Figure 33: Depositional Model for the Amherstburg Formation. The model represents a ramp depositional system.

Relative Sea Level

Relative sea level was high during the Devonian. The sea level allowed for the widespread growth of reef and patch reef environments throughout the area that is now Michigan. Therefore, sea level was relatively high during the deposition of the Amherstburg Formation (van Geldern et al., 2006). Van Geldern et al. (2006) found that sea level rose directly before the deposition of the Amherstburg Formation and dropped directly after the deposition. Some of the lagoonal to peritidal facies correspond to this trend. The top of the Kalman #1-16 core and the entire TB-7 core reflected this regressive trend. These cores transitioned into the Lucas Formation, which was identified as a shallow water Period in the Devonian (van Geldern et al., 2006).

The reef rubble environment represents deep water deposits of the Amherstburg Formation. In the St. Charlton #4-30 core, the reef rubble environment at the bottom of the core represents the initial deep water setting. There was a facies shift at the 3050 ft (929 m) in the core suggesting more regressive conditions. This regression marks the transition between reef rubble and lagoonal to reef-rubble deposits. A second shift in relative sea level was interpreted from a facies change at 3042 ft (927 m) in the St. Charlton well.

The TB-7 represents a time of shallow water or an environment near the outer margin of the basin on the Algonquin Arch. The TB-7 saw facies of similar water depth, so the depth can be assumed to have been constant at the depositional location of the TB-7. The shallow water corresponds to a lagoonal to peritidal environment.

Sea level in the Kalman #1-16 core was interpreted to be relatively high during the deposition of the basal portion of the core. At 3227 ft (984 m), a facies shift was recorded that is interpreted as a regression. The area transitioned to a lagoonal environment, which is more shallow water environment than the reef rubble environment. A second transgression was interpreted at 3189 ft (972 m), when sea level rose. This small increase in sea level is reflected by a brief return to the reef rubble facies association. However, this relatively high sea level was short lived. A third shift in facies at 3187 ft (971 m)was interpreted as a regression. The water level was even shallower than the lagoonal environment. During this time of shallow water, the area was a lagoonal to peritidal environment. There are different patterns of sea level change between the three cores. It is not known if the Amherstburg Formation is the same age in all three cores. There is not a fine enough control on the age to determine the sequence of deposition in the three cores.

V. Conclusion

This study analyzed three cores from the Amherstburg Formation in the Michigan Basin. The analyzed cores were the St. Charlton #4-30, TB-7, and the Kalman #1-16 core. From these cores, twenty facies were identified based on the color of the sample, the fossils present, mineral composition, the presence of structures, the presence of stylolites, rock fragments, the bedding or laminations, and the bioturbation index. Three sedimentary profiles were constructed based on the lithology, facies, fossil content, sedimentary structures, and the Dunham texture. Using the profiles the facies were then grouped into four interpretative depositional environments; reef rubble, lagoonal and reef-rubble, lagoonal, and lagoonal and peritidal environments. Using Walther's law, the vertical profiles were converted into a lateral depositional model.

In general, the relative sea level trends observed by van Geldern et al. (2006) is consistent with the relative sea level determined in this study. The relative sea level was high during the deposition of the Amherstburg Formation. There were some small deviations in the sea level that were likely caused by regional events or conditions. The top and bottom of the cores analyzed in this study suggests the Amherstburg Formation was deposited during a time of high relative sea level compared to the lower sea level before and after its deposition. Even though the Amherstburg Formation was deposited during an interval of relatively high sea level, the facies do not suggest deep basin conditions were prevalent in the Michigan Basin at that time.

The depositional setting of the Amherstburg Formation was a carbonate ramp system. Ramp systems are platforms with a very low slope from the shore to the basin (Wright, 1984). Many of the boundaries between the separate facies were gradational boundaries rather than sharp boundaries. This suggests the environments migrated laterally during changes in sea level. The most basinward environment was the reef rubble environment. Moving shoreward the next environment that was deposited was the lagoonal to reef-rubble environment, followed by the lagoonal and lagoonal to peritidal environments respectively. Based on the core descriptions, sedimentary profiles, and the interpretative environments, the Amherstburg Formation was deposited in a humid tropical carbonate ramp.

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