DEPOSITIONAL ENVIRONMENT, HISTORY, DIAGENESIS, AND PETROLEUM GEOLOGY OF THE CLEVELAND SHALE MEMBER, NORTHEASTERN OHIO

Saeed S. Alshahrani

A Thesis

Submitted to the Graduate College of Bowling Green State University
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2013

Committee:
Dr. James Evans, Advisor
Dr. Jeffrey Snyder
Dr. Sheila Roberts
ABSTRACT

James E. Evans, Advisor

The Cleveland Shale Member is the uppermost member of the Ohio Shale that was deposited on the western edge of the Catskill Delta. This delta is underlain by middle and upper Devonian strata. The sediments were derived from the Acadian Mountains that were formed as a result of a collision between the Euramerica plate and the Europe plate at about 390 Ma. Because of the rise of the Acadian Mountains, large volumes of sediments were eroded and delivered to a marine environment called the Appalachian Basin. During the Late Devonian period, the Ohio Shale was deposited in that basin.

This study is based on lithofacies analysis from three outcrops located around the city of Cleveland and from five well cores obtained from four counties in northeast Ohio. There are 161 samples collected from the outcrops and the well cores. A total of 33 thin sections, 11 from sandstones and 22 from mudstones, were prepared and analyzed to determine the textural properties, sedimentary structures, and microstructures. In addition, 12 samples were analyzed using SEM methods for mineralogy, surface textures, and microfacies analysis. Paleocurrent analysis is based on 56 measurements from groove casts located at the base of tempestites, and these indicate flow direction from NE to SW.

Analysis of the outcrops and cores identified 14 lithofacies which are classified into seven lithofacies associations, four mudstone lithofacies associations and three sandstone lithofacies associations. The green-gray claystone lithofacies association was mostly observed in the lower part of the Cleveland Shale Member with mean thickness of 51cm. It consists of light green-gray planar laminated siltstone (lithofacies SSl), medium green-gray planar laminated clayshale (lithofacies Cl), and dark green-gray massive claystone (lithofacies Cm). The green-
gray siltstone and mudshale rhythmite lithofacies association is observed in the middle part starting after a bundle of event deposits. This lithofacies association consists of light green-gray planar laminated siltstone (lithofacies SSl) and dark green-gray planar laminated mudshale (Lithofacies Ml) and has a mean thickness of 19 cm. The dark blue-gray mudrock lithofacies association, which has a mean thickness of 52 cm, is found in the middle and upper parts, consisting of medium blue-gray planar laminated mudshales (lithofacies Ml), concretionary massive mudstone (lithofacies Mc), and dark blue-gray planar laminated clayshales (lithofacies Cl). The mudshale and clayshale rhythmites are only observed in the upper part, consisting of medium blue-gray planar laminated mudshale (lithofacies Ml) and dark blue-gray planar laminated clayshale (lithofacies Cl). These rhythmites have a mean thickness of 23 cm.

Three types of event layers are interbedded with the deposits described above. They represent 12% of the total outcrop thickness. First, there are storm deposits, known as tempestites, which consist of massive-to-normally graded sandstone (lithofacies Smg), overlain by hummocky stratified sandstone (lithofacies Sh), overlain by planar laminated sandstone (lithofacies Sl), and topped by ripple laminated sandstone (lithofacies Sr). This lithofacies association is observed seven times, having a mean thickness of 13 cm. Second, there is a distal turbidite lithofacies association which consist of massive to normally graded sandstone (lithofacies Smg), overlain by planar laminated sandstone (lithofacies Sl), overlain by rippled sandstone (lithofacies Sr), and covered by laminated siltstone (lithofacies SSl). This lithofacies is identified five times, having a mean thickness of 14 cm. The third lithofacies association consists of hyperpycnites which has a mean thickness of 1.74 cm. Each hyperpycnite consists of massive to normally graded sandstone (lithofacies Smg), overlain by planar laminated sandstone (lithofacies Sl), overlain by rippled laminated sandstone (lithofacies Sr), overlain by planar
laminated siltstone (lithofacies SSI), overlain by siltstone and claystone rhythmites (lithofacies SSCI), and/or topped by planar laminated clayshale (lithofacies CI). A *Neonereites* trace fossil was identified from the base of a turbidite layer. In addition, a *Chagrinichnites* fish fossil was observed at the base of a tempestites. The fossilized remains of 60% of a lower part of this fish fossils indicates rapid burial in a storm event.

The results of this study support the interpretation that the Cleveland Shale Member depositional environment received clastics from the northeast, which were primarily transported westward as density underflows (turbidities and hyperpycnites). The deposits of mudstone and turbidite indicate deposition occurred on a clastic marine shelf at water depths deeper than fair weather wave base (FWWB). However, the presence of significant storm deposits (tempestites) within the Cleveland Shale Member indicates deposition occurred at water depths shallower than storm weather wave base (SWWB). Together, these results indicate a shallow muddy shelf, in contrast to the pelagic models suggested by other workers.
ACKNOWLEDGMENTS

Working on a master’s degree involves two different aspects: two years of great experiences and a great deal of hard work. It is very difficult to describe such feelings after the long journey of thesis writing ends. Therefore, I would like to thank those who stood beside me on this journey.

No thesis ever is written without the help of faculty and other professionals in the field. For this reason, I must acknowledge my deep thanks to Dr. Jim Evans who has supported, encouraged, and helped me during the last two years. The success of this thesis is primarily due to Dr. Evans. I also extend thanks to Dr. Jeff Snyder who helped me not only during the two years, but also in his role as a graduate advisor before I came here. Dr. Sheila Roberts also helped me throughout my two years of study. I would like also to thank Dr. Margaret Yacobucci for assistance in identifying fossils and trace fossils. I would also like to thank Dr. Charles Onasch for his help on the optical analysis. I would also like to thank the Ohio Geological Survey, especially Mr. Greg Schumacher, for assistance with access to the Horace R. Collins Core Laboratory (HRCL) in Alum Creek State Park. Furthermore, I would also like to thank Dr. Carol Hickman and Marilyn Cayer from the BGSU Biology Department for giving me access to the SEM lab and for their support.

Finally, I owe great gratitude to my family and friends: to my father Saad and my mother Aisha for their continuous care and support; to my wife, Haya, and my daughter, Siba, who did everything for me, special thanks; and to my friends, Addisu and Emad, for their help in the field and in the department.
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................................. II

ACKNOWLEDGMENTS .................................................................................................................... V

TABLE OF CONTENTS ........................................................................................................................ VI

LIST OF FIGURES ................................................................................................................................ VIII

LIST OF TABLES ................................................................................................................................ X

INTRODUCTION ............................................................................................................................. 1

BLACK SHALES ............................................................................................................................. 1

SHALLOW WATER SEDIMENTARY ENVIRONMENTS ...................................................................... 2

TEMPESTITES ............................................................................................................................... 9

TURBIDITES .................................................................................................................................. 12

HYPERPYCNITES ......................................................................................................................... 15

PURPOSES AND OBJECTIVES OF THIS STUDY ...................................................................... 18

GEOLOGICAL BACKGROUND ..................................................................................................... 21

DEPOSITIONAL HISTORY OF THE APPALACHIAN BASIN ....................................................... 21

REGIONAL STRATIGRAPHY ........................................................................................................... 22

OHIO SHALE ................................................................................................................................. 26

METHODS ................................................................................................................................... 30

OUTCROP LOCATIONS ................................................................................................................ 30

WELL CORE LOCATIONS ............................................................................................................ 34

GEOPHYSICAL LOGS ..................................................................................................................... 34

PETROLOGY ................................................................................................................................ 39
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCANNING ELECTRON MICROSCOPY (SEM) ANALYSIS</td>
<td>41</td>
</tr>
<tr>
<td>RESULTS</td>
<td>45</td>
</tr>
<tr>
<td>LITHOLOGY ANALYSIS</td>
<td>45</td>
</tr>
<tr>
<td>LITHOFACIES ANALYSIS</td>
<td>58</td>
</tr>
<tr>
<td>LITHOFACIES ASSOCIATIONS</td>
<td>84</td>
</tr>
<tr>
<td>STRATIGRAPHY</td>
<td>105</td>
</tr>
<tr>
<td>OUTCROP CORRELATIONS</td>
<td>112</td>
</tr>
<tr>
<td>SUBSURFACE ANALYSIS</td>
<td>115</td>
</tr>
<tr>
<td>DEPOSITIONAL ENVIRONMENT</td>
<td>120</td>
</tr>
<tr>
<td>PALEONTOLOGY</td>
<td>122</td>
</tr>
<tr>
<td>PALEOCURRENT ANALYSIS</td>
<td>124</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>127</td>
</tr>
<tr>
<td>DEPOSITIONAL ENVIRONMENT</td>
<td>127</td>
</tr>
<tr>
<td>EVENT HORIZONS</td>
<td>132</td>
</tr>
<tr>
<td>CONDENSED SECTION</td>
<td>141</td>
</tr>
<tr>
<td>PALEOGEOGRAPHY</td>
<td>143</td>
</tr>
<tr>
<td>STRATIGRAPHIC TRENDS</td>
<td>144</td>
</tr>
<tr>
<td>SUMMARY AND CONCLUSIONS</td>
<td>147</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>150</td>
</tr>
<tr>
<td>APPENDIX A: STRATIGRAPHIC SECTIONS</td>
<td>163</td>
</tr>
<tr>
<td>APPENDIX B: THIN SECTION DATA</td>
<td>165</td>
</tr>
<tr>
<td>APPENDIX C: WELL CORE DATA</td>
<td>168</td>
</tr>
<tr>
<td>APPENDIX D: SEM DATA</td>
<td>174</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIG. 1. TYPICAL SEDIMENTARY ENVIRONMENT AND THE THREE EFFECTIVE FACTORS</td>
<td>4</td>
</tr>
<tr>
<td>FIG. 2. CROSS-SECTIONAL PROFILE OF THE SHALLOW WATER ENVIRONMENTS</td>
<td>6</td>
</tr>
<tr>
<td>FIG. 3. STORM-DOMINATED MARINE SHELF ENVIRONMENTS</td>
<td>10</td>
</tr>
<tr>
<td>FIG. 4. IDEAL MODEL OF TEMPESTITES</td>
<td>11</td>
</tr>
<tr>
<td>FIG. 5. SCHEMATIC OF THE BOUMA SEQUENCE</td>
<td>14</td>
</tr>
<tr>
<td>FIG. 6. IDEAL MODEL OF HYPERPYCNAL TYPES</td>
<td>16</td>
</tr>
<tr>
<td>FIG. 7. GENERALIZED STRATIGRAPHY OF WEST-CENTRAL OHIO</td>
<td>24</td>
</tr>
<tr>
<td>FIG. 8. STRATIGRAPHIC COLUMN OF THE UPPER DEVONIAN ROCK UNITES</td>
<td>25</td>
</tr>
<tr>
<td>FIG. 9. MAP OF OUTCROP LOCATIONS</td>
<td>32</td>
</tr>
<tr>
<td>FIG. 10. MAP OF WELL CORES</td>
<td>36</td>
</tr>
<tr>
<td>FIG. 11. EXAMPLE PHOTOGRAPH OF CORE SAMPLES</td>
<td>37</td>
</tr>
<tr>
<td>FIG. 12. SANDSTONE CLASSIFICATION SCHEME</td>
<td>47</td>
</tr>
<tr>
<td>FIG. 13. PHOTOMICROGRAPH OF SANDSTONE SHOWING POINT COUNT ANALYSIS</td>
<td>49</td>
</tr>
<tr>
<td>FIG. 14. MUDROCK CLASSIFICATION SCHEME</td>
<td>51</td>
</tr>
<tr>
<td>FIG. 15. PHOTOMICROGRAPH OF CLAY MINERALS IN SEM</td>
<td>54</td>
</tr>
<tr>
<td>FIG. 16. SEM IMAGES OF PLANT DEBRISE</td>
<td>55</td>
</tr>
<tr>
<td>FIG. 17. SEM IMAGES OF SEDIMENTARY STRUCTURES</td>
<td>57</td>
</tr>
<tr>
<td>FIG. 18. PHOTOMICROGRAPH OF LITHOFACIES S_MG, S_L, AND M_L</td>
<td>60</td>
</tr>
<tr>
<td>FIG. 19. PHOTOMICROGRAPH OF LITHOFACIES S_L, S_H, S_SCL, S_L, AND S_R</td>
<td>63</td>
</tr>
<tr>
<td>FIG. 20. PHOTOMICROGRAPH OF HUMMOCKY STRATIFICATION</td>
<td>67</td>
</tr>
<tr>
<td>FIG. 21. PHOTOMICROGRAPH OF OF LITHOFACIES S_SG, S_S, AND S_SSL</td>
<td>70</td>
</tr>
<tr>
<td>FIG. 22. PHOTOMICROGRAPH OF CLAYSTONE LITHOFACIES S_SL, AND S_SCL</td>
<td>72</td>
</tr>
</tbody>
</table>
FIG. 23. PHOTOMICROGRAPH OF LITHOFACIES SSCL RHYTHMITES ........................................ 75
FIG. 24. PHOTOMICROGRAPH OF LITHOFACIES MM AND MLA ......................................... 77
FIG. 25. PHOTOMICROGRAPH OF CONCRETIONARY MUDSTONE LITHOFACIES Cm .......... 79
FIG. 26. PHOTOMICROGRAPH OF LITHOFACIES Cm AND CL ........................................... 82
FIG. 27. PHOTOMICROGRAPH OF TURBIDITE LITHOFACIES ASSOCIATION ...................... 86
FIG. 28. PHOTOMICROGRAPH OF TEMPESTITE LITHOFACIES ASSOCIATION ..................... 90
FIG. 29. PHOTOMICROGRAPH OF HYPERPYCNITES LITHOFACIES ASSOCIATION ............. 94
FIG. 30. PHOTOMICROGRAPH OF LITHOFACIES ASSOCIATION SSC ................................ 97
FIG. 31. PHOTOMICROGRAPH OF LITHOFACIES ASSOCIATION SSM ................................ 100
FIG. 32. PHOTOMICROGRAPH OF LITHOFACIES ASSOCIATION MMC .............................. 102
FIG. 33. PHOTOMICROGRAPH OF LITHOFACIES ASSOCIATION MC ................................. 104
FIG. 34. PHOTOGRAPH OF THE HUNTINGTON BEACH OUTCROP .................................... 106
FIG. 35. STRATIGRAPHIC SECTIONS OF THE HUNTINGTON BEACH OUTCROP ............... 107
FIG. 36. PHOTOGRAPH OF THE BROOKLYN HEIGHT PARK OUTCROP ............................ 109
FIG. 37. PHOTOGRAPH OF CORE 2720 SAMPLES ............................................................ 110
FIG. 38. OUTCROP CORRELATION ...................................................................................... 113
FIG. 39. CORE 2793 AND IT’S GEOPHYSICAL LOGS CORRELATION .................................. 116
FIG. 40. OUTCROP AND WELL CORES CORRELATION ...................................................... 118
FIG. 41. PHOTOGRAPH OF NEONEREITES AND CHAGRINICHNITES TRACE FOSSILIS .... 123
FIG. 42. ROSE DIAGRAM OF GROOVE CAST DATA ............................................................. 125
FIG. 43. STRATIGRAPHIC SECTION OF OUTER SHELF ENVIRONMENT ........................... 129
FIG. 44. STRATIGRAPHIC SECTION OF INNER SHELF ENVIRONMENT ........................... 131
FIG. 45. STRATIGRAPHIC INTERPRETATION ...................................................................... 145
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE 1. SUMMARY OF THE THREE OUTCROPS</td>
<td>31</td>
</tr>
<tr>
<td>TABLE 2. SUMMARY OF THE FIVE WELL CORES USED IN THIS STUDY</td>
<td>35</td>
</tr>
<tr>
<td>TABLE 3. SAMPLES LOG FOR THIN SECTION</td>
<td>40</td>
</tr>
<tr>
<td>TABLE 4. SAMPLE LOG FOR SEM SAMPLES</td>
<td>43</td>
</tr>
<tr>
<td>TABLE 5. SUMMARY OF POINT COUNT DATA</td>
<td>46</td>
</tr>
<tr>
<td>TABLE 6. SUMMARY OF LITHOFACIES AND THEIR INTERPRETATIONS</td>
<td>59</td>
</tr>
<tr>
<td>TABLE 7. SUMMARY OF TURBIDITES IN THE OUTCROPS</td>
<td>87</td>
</tr>
<tr>
<td>TABLE 8. SUMMARY OF TURBIDITE LITHOFACIES AND THEIR INTERPRETATION</td>
<td>88</td>
</tr>
<tr>
<td>TABLE 9. SUMMARY OF TEMPESTITE LITHOFACIES</td>
<td>92</td>
</tr>
<tr>
<td>TABLE 10. SUMMARY OF HYPERPYCNITES LITHOFACIES</td>
<td>95</td>
</tr>
<tr>
<td>TABLE 10. SUMMARY OF PALEOCURRENT DATA AND VECTOR STATISTICS</td>
<td>126</td>
</tr>
</tbody>
</table>
INTRODUCTION

Black Shales

Black shales were poorly understood until the mid-1970s. The history of black shale investigation started with the collection of observational data from outcrops. Because of weathering and alteration, this information was not suitable for biological interpretations to understand the factors that formed and controlled the organic materials. According to Schott et al. (1978), current investigations of eastern U. S. black shales as a source of gas, particularly the Chattanooga Shale and its correlatives of Late Devonian and Mississippian ages, has produced a new generation of data, and the time is appropriate to better understand the processes involved in the accumulation of black shale. In addition, Tourtelot (1979) believed that the growing body of geochemical data for both biological as well as non-biological components of black shales has provided the opportunity to determine the origin of such rocks. By the early-1970s, as oil industries started to drill deep-sea wells, scientists started to analyze and interpret the organic matter from their environments.

The Devonian system ranges from about 416 Ma until approximately 359 Ma (International Commission on Stratigraphy, 2004). Devonian black shales are widely distributed in the United States and other parts of the world. Of the world's original petroleum reserves, 8% are estimated to have been generated by Late Devonian-Mississippian source rocks (Klemme and Ulmishek, 1991), which dominantly contain marine or type II kerogen (Arthur and Sageman, 1994). Most of these black shale source rocks are widely present on the North American, South American, Russian, and North African cratons (Duval et al., 1998). They also occur in Eastern Europe and in Australia. In North America, the Devonian black shales are mostly found in the Michigan Basin, Illinois Basin, and Appalachian Basin.
Shallow Marine Sedimentary Environments

Shallow-marine sedimentary deposits can be found on the continental shelves or in epeiric or epicontinental seas. The depth of water in the shallow marine environments is variable but generally less than 200 m. Those environments have variable widths that can reach hundreds of kilometers (Fig. 1). Because of sea level rise, these environments extend to cover large areas of the earth’s surface and may encompass huge volumes of sediments deposited in the basin. The origin of the Cleveland Shale Member is controversial, with previous workers arguing for both offshore and nearshore environments. Therefore, it is beneficial to provide a brief review of shallow-marine sedimentary environments.

One of the earliest ideas about marine environments is that grain size changes from coarse-grained sediments in shallow marine environments to very fine-grained sediments in deep marine environments. This idea was termed the “graded shelf” by Johnson (1919). It is simple to recognize that the marine sediments vary in texture from very fine- to very coarse-grained. This difference of texture may be related to the depth of the water and the availability of sediment supply (Sharped, 1932). However, sediment complexity has been suggested in the idea of “relict” sediments (Emery, 1968). For example, when sea level rises, older coarse-grained shallow water sediments could be left on the outer shelf, and then partly or completely reworked and brought into the dynamic equilibrium with shelf processes (Swift et al., 1971).

Sediment transport near the beach and in the upper shoreface is driven by waves that generate oscillatory currents through the orbital motion of water under the wave. Sediments are also moved along the shore by the long-shore currents and are moved offshore by the rip currents generated as waves shoal and break. As the wave enters shallow water, and the ratio of wave height to the water depth is 1:3, the frictional drag on the seabed causes the wave crest to topple
forward as a breaker in the surf zone. Some of the wave energy is translated into a landward rush of water up the beach – the swash. The swash is capable of moving pebbles that accumulate at the top of the beach and is fast enough to produce planar lamination in sand (Plint et al., 2010).

Three main factors can affect shallow marine deposits. First, storm waves can take sediments from the beach or dunes and migrate the sediments along the coast; thus, waves act as the primary transport mechanism. In addition, waves action results in sedimentary structures like oscillation ripple marks, current ripples, trough x-beds, festoon x-beds, and inclined planar (beach) stratification (Fig. 1). Second, currents can also play an important role in the re-distribution of sediments. Current can produce sedimentary structures such as giant ripples, lingoid and rhomboid ripples, and small cross bedding. Finally, the tides may also have a strong influence on re-distribution of sediments in shallow marine environments. Evidence for tidal influence includes tidal bundles, reactivation surfaces, and sedimentary structures such as herringbone cross-bedding; flaser, wavy, and lenticular bedding; planar lamination; and graded rhythmsites.

On many modern shelves, mud from the continent forms narrow belts parallel to the coastline where the sand sediment supply is low or where sand has been trapped in local estuaries or lagoons. Near large deltas, however, mud may originate at the coast and be dispersed by marine currents to cover the large portion of the outer shelf resulting in extensive mud-sheets or mud-blankets extending thousands of square kilometers. Extensive shelf mudstones or shales that contain open-marine environment fossils were produced in this way. At present, the outer shelves have only been covered to their actual depth by water since the last rise of the sea level.

Tidal environments are part of a marine shoreline that is affected by the tides (Fig. 1). Two main astronomical features can influence this environment: 1) the changing position of the
Figure 1 Diagram showing typical sedimentary environments. Three factors can affect shallow marine environments, including waves, currents, and tides (modified from Boggs, 2010).
sun, the moon, and the earth around their elliptical orbits (synodic tide), and 2) the daily changing of sea tides (declinational tide). As a result of the earth’s rotation around its axis, the tide changes its elevation from maximum to minimum values every 12 hours and 42 minutes. Tides create many important and easily visible features in their environments. Tidal rhythmites consist of alternating sand and mud layers repeated in a systematic way due to the daily changing position of the moon and earth. Ripple marks also have been observed in tidal environments, where alternating sand ripples and mud drapes form flaser, wavy, or lenticular bedding. Mud cracks are another type of sedimentary structure associated with tidal environments.

Within the shallow marine environment, which can reach depths up to 200 m, a number of zones can be recognized: mean low water (MLW), mean high water (MHW), mean fair weather wave base (FWWB), and mean storm weather wave base (SWWB) (Fig. 2). Each zone can be recognized based on different sediment structures. MLW refers to the mean low wave level that occurs during quiet wave conditions or low wind effects. MHW refers to the mean high wave that occurs when waves reach maximum heights during high winds or storms. The storm weather wave base (SWWB) is the water depth that is affected by the wave base of storm-generated waves. This depth may range from 30 m to 130 m deep on shelf areas, but normally it is between 30 – 40 m depth. The fair weather wave base (FWWB) is a water depth affected by the wave base of surface waves that form under normal weather conditions. The depth of the fair weather wave base is variable, but mostly ranges from 5 to 30 m. The portion of the sea floor above FWWB is known as the shoreface (Walker and Plint, 1992).

Eolian sand dunes dominate the backshore, which is inundated only when occasional conditions make storms or strong tides. This zone is separated from the foreshore by crests of berms, which are created during a storm by waves. Changing tidal levels or storm surges during
Figure 2 Generalized cross-sectional profile on the beach and nearshore zone, showing also the principal zones of wave activity (modified from Boggs, 2001). MHW = Mean High Wave and MLW = Mean Low Wave.
the summer and winter seasons make this zone harder to determine. Boggs (2001) suggests that sedimentary structures that characterize the backshore include horizontal laminae interrupted by bioturbation such as crustacean burrows. These structures contain planar beds that are overlain by small- to medium-scale eolian cross-bedded sand. Further inshore, the eolian dunes consist of well-sorted fine-grained sand with large-scale (1-10m) cross bedding and climbing ripples (Baedke et al., 2004).

The foreshore refers to region between the MLW and MHW, which include the beach. This zone has sediments of fine- to medium-grained sand and, in some cases, gravel such as pebbles. Boggs (2001) reported that this zone could also contain heavy minerals alternating with quartz. McCubbin (1982) stated that the swash zone, which is dominated by waves, typically contains shell debris and drift wood, but lacks mud. Reading (1996) reported that foreshore has a stable sloping beach face. This zone is affected by the swash, which originates form the surf and breaker dunes (upper shoreface).

The shoreface zone is the area that extends from the FWWB up to the foreshore zone. Storms and waves are the main factors that affect the shoreface deposits and sedimentary structures. During normal conditions, the sediments can be reworked and deposited in the shoreface zone. However, during storm events, waves and currents can transfer the sediments either along the beach or to the offshore. This area can be divided into three different zones: lower, middle, and upper shoreface. The upper shoreface is that area that extends from the foreshore to the breaker zone. McCubbin (1982) stated that when sediments are thrown into suspension load as a result of wave breaking, the surf zone is created because the interior breaking waves have reworked the sediments. The grain size varies from fine-grained sand to gravel. Boggs (2001) observed that the typical sediment structures are multidirectional, low-
angle trough cross-bedding and planar lamination because of the combination of oscillatory 
waves and unidirectional currents.

The breaker zone is the area that extends from the surf zone to the lower shoreface; it is 
actually the high-energy area of the shoreface (McCubbin, 1982; Reading, 1996). The 
sedimentary structures found here include current ripples, planar lamination, landward-dipping 
trough cross-bedding and hummocky stratification (Boggs, 2001). Sediments range from fine- to 
coarse-grained sand and pebbles. The lower shoreface is extended from the FWWB to the 
breaker zone. Reading and Collinson (1996) found that this zone is characterized by lower-
energy waves and deposited fine-grained sand. Boggs (2001) reported that the sediments vary 
from very fine- to fine-grained sand with intercalated silt and mud. Sedimentary structures that 
can be found in this zone include oscillation and current ripples, and planar lamination. 
Interbedded with fine-grained sediment, hummocky stratified very fine- to medium-grained sand 
may form during storm events, and these storm deposits may contain mud intraclasts overlain by 
thin ripple laminated sand (Reading and Collinson 1996).

The offshore transition zone is the area that extends from the mean FWWB to SWWB. 
This zone is characterized by the deposition of sand, silts, and mud due to deposition of the 
suspended load (McCubbin, 1982). During storm conditions, the deeper wave base causes 
erosion followed by deposition of extensive sheets of hummocky stratified and planar laminated 
sand (Harms et al., 1975). The area that extends from below SWWB to the break of the 
continental shelf, at about 200 m depth, is called the offshore zone. This area is mainly affected 
by oceanic currents. The sediments found here are muds, silts, and very fine-grained sands. The 
sediment structures that can be found in this zone include planar lamination, ripple lamination, or 
sandstone-mudstone graded rhythmites.
**Tempestites**

Shallow marine environments respond to storms, waves, and currents. In shallow water environments, wind shear stress and fluctuations in barometric pressure can transfer the storm energy to the water surface, creating oscillatory waves and unidirectional currents (Reading, 1996). During storms, three processes can generate storm deposits: geostrophic currents, wave oscillations, and excess-weight forces (Myrow and Southard, 1996). Geostrophic currents originate when seawater moves from high to low hydrostatic pressure and the gravity force pushes the seawater to a low-pressure area. However, in addition to the gravity force, the movement of the water is influenced by the earth’s rotational force, the Coriolis force. The resultant of the gravity force and the Coriolis force is that the water turns and moves along parallel lines of equal pressure. There conditions may be modified by the excess weight forces which are caused by pressure differences when high-suspended sediment concentrations at the sea floor generate density flows. Einsele (2000) stated that these high sediment concentrations are created especially by the combination of oscillatory storm waves and geostrophic currents (or combined flow), and that these result in erosion and then fallout from suspension of entrained sediments (Figs. 2 and 3).

A tempestite is a sequence consisting of an erosional surface at the base with overlying sole marks, overlain by hummocky stratified sandstone, overlying by planar laminated fine-grained sandstone, following by ripple laminated sandstone, and finally by massive mudstone (Fig. 4). Each tempestite may be preserved partly or completely, because later events can destroy part or all of the previously deposited features (Einsele and Seilacher, 1991). The correct recognition of turbidites versus tempestites is that turbidites show graded bedding in the lower part and current ripple lamination in the upper part of the deposit, whereas tempestites have
Figure 3. Storm-dominated shelf used to illustrate the possibility of deposition of tempestite and turbidite by storm in shallow and deep parts of the same basin (Walker, 1984).
Figure 4. Different parts of an ideal model of tempestite as cited in literature by Einsele (2000).
hummocky stratification in the lower part and wave ripple lamination in the upper part of the deposit.

Einsele (2000) discusses idealized sequences of tempestites with their sedimentary structures (Fig. 4). These consist of, from the bottom to the top; a pervious bioturbated mud layer overlain by an erosional surface followed by hummocky stratified sandstone, followed by planar laminated sandstone, followed by wave (oscillation) ripple marks in sandstone, followed by a new, bioturbated, mud layer.

Tempestites can be divided into proximal tempestites and distal tempestites. Proximal tempestites are thicker bedded and may be bioclast-dominated, and are typically more coarse-grained. Proximal tempestites are also typically amalgamated (multistory sandstone consisting of the lower portions of several tempestites separated by erosion surfaces). Distal tempestites tend to be thinner bedded and finer-grained, and may show only the upper parts of the tempestite sequence. For example, in a mud-dominated deeper water depositional environments (e.g. offshore) tempestite may consist of planar-laminated sandstone and ripple laminated sandstone, but lack the lower parts of sequence seen in the lower part of the idealized tempestite sequence (e.g. hummocky stratified sandstone) (Flugel, 2009).

**Turbidites**

Turbidity flows are a class of sediment-gravity flows that move downslope towards the sea floor or lake bottom. This movement is a result of a density contrast between water containing suspended sediments and the ambient fluid. The flows can reach high speed, depending on the sea floor relief, slope angle, slope length, and the turbidity current thickness.
(Einsele, 2000). During the 1929 Grand Banks earthquake, the flow travelled with a speed of ~25 m/s for over 400 km (Shor et al., 1990; Reading, 1996).

Many factors can trigger turbidity currents. Initially, the sediment has to fail by losing strength. This could occur due to loss of cohesion (e.g. earthquakes), increased slope angle, surcharge loading from waves, and/or dewatering processes (Boggs, 2001). Subaqueous debris flows may evolve to become turbidity currents after engulfing additional fluid content. Large amounts of sediments ranging from mud to very coarse-grained sand can be deposited by deceleration and frictional freezing of a turbidity flow (Fig. 3). Turbidity flows are one of the most important processes for transferring coarse-grained sediments from shallow to deep marine environments (Stow and Tabrez, 1998; Stow et al., 2001).

The percentage of the suspended load in a turbidity flow can produce two different flows: high-density turbidity flows and low-density turbidity flows (Boggs, 2001; Einsele, 2000; Reading, 1996). In high-density turbidity flows, high sediment concentrations cause hindered settling and dispersive pressure effects. These flows, which may contain coarser turbidity grain sizes such as gravel, can be found in proximal regions. In contrast, low-density turbidity flows shows settling of grains in low sediment concentrations, producing normal grading.

The deposit of turbidity current is called a turbidite. Low-density turbidity flows produce a characteristic set of layers called the Bouma sequence (Fig. 5). The Bouma sequence is divided into five layers (A, B, C, D, and E) where A is at the bottom and E is at the top. Turbidites can show the entire Bouma sequence, or one or more layers may be missing. Starting from the bottom, Bouma division A consists of normally graded, fine- to coarse-grained sandstone. This division often overlies an eroded base. Bouma division B is characterized by its planar lamination, which is produced by the upper flow regime. The next layer is Bouma division C,
Figure 5. Schematic of the Bouma Sequence. (Modified from Bouma, 1962).
which consists of cross-laminated or climbing ripples in fine-grained sandstone. On the top of
Bouma division C, Bouma division D is characterized by planar laminated siltstone, representing
the deposition of fine-grained sediment from the tail, end of the turbidity flow. Bouma division E
is the uppermost bed of the Bouma sequence and consists the fallout from suspension of the most
dilute portion of the turbidity flow.

**Hyperpycnites**

Hyperpycnal flows are density underflows that form where plumes of suspended
sediment that formed during floods (high discharge from fluvial sediments at the mouth of a
river) enter an ambient standing body of water (Mulder et al. 1997) (Fig. 6). Hyperpycnal flows
may travel for long distances just above the seabed owning to the density contrast of the
suspended sediment inflow versus the ambient surrounding water (Mulder and Syvitski, 1995).
In practice, this means that only finer-grained sediments will be transported, but possibly for
long distances.

Syvitski et al. (1990) reported that underflows could occur from a high-latitude glacially
ted river system. Olatundo and Roger (2007) stated that a high percentage of bottom flows are a
mixture of seawater and sedimentary materials. There are similarities between hyperpycnal flows
and turbidity flows because they both are density contrast flows. On the other hand, hyperpycnal
flows are generated by non-ignitive processes, such as fresh water with a high percentage of
mud, where because of density contrasts, river discharge of suspended and bed loads can create
hyperpycnal currents. Mulder et al. (2003) distinguished turbidity currents from hyperpycnal
currents based on the dynamic of generation. In subaqueous environments, ignitive processes
generate turbulence that creates turbidity currents. Hence, when these currents proceed to the
Figure 6. Three different flows can occur during river floods: hypopycnal flow, homopycnal flow, and hyperpycnal flow. Mesopycnal flows are hyperpycnal flows that detach from the bottom, and flow in the middle of the water column (Modified after Ducassou et al. 2008).
marine environments, they move downslope just above the seabed because of very high-suspended loads and variable intensity with the ambient seawater. Other factors, such as temperature and salinity, can also affect these processes (Fig. 6).

Mulder and Alexander (2001) classified incoming flows into ambient water based on density contrasts as three different types of flows:

I. Hypopycnal flows: Bates (1953) called this type of flow “overflow” and defined it as when the density of the inflow is less than the ambient fluid. It can be found at mouths of many rivers because that enters the ocean. The fresh water inflows are less dense than the seawater, and the sediment is dispersed on the water surface as buoyant plume (Nemec, 1995). The density contrast is always a negative, because the density of the inflow plus suspended sediment is less than the density of the ambient fluid due to temperature and salinity (Fig. 6).

II. Homopycnal flows: These flows can be found where the densities of the inflows are equaled to the density of the ambient fluid (Bates, 1953). This means the depth of the inflow is dependent on the slightly negative or positive values of the density difference. Because there slight differences can change locally, a common siltstone is a slightly hypopycnal flow becomes hyperpycnal, and the flow tends to plunge from the basin surface (Fig. 6).

III. Hyperpycnal flow: These flows can be found where the inflows have a higher density than the ambient fluid, despite the effects of salinity and/or temperature. At some point, the inflows have such a positive density contrast that they plunge to the basin floor to become hyperpycnal flows.

Sediconcentration temperature, and salinity play an important role in the modifying density of the hyperpycnal flow. Mulder et al. (2003) determined that the critical sediment
concentration is 36 to 43 kg/m$^3$ for the flow to exceed the normal density of seawater and to plunge to the basin floor. Based on the slope, the amount of discharge, and the component of gravity and fraction forces, hyperpycnal flow can be relatively long-lived and travel for long distances. Mulder et al. (2003) stated that during a major flood in 1994 from Var River, flows containing 11 to 14 times the normal suspended sediment load were transferred to the basin during 18 hours. In another study, Nakajima (2006) reported that hyperpycnal flow traveled 700 km at a speed of about 1.1 km/h in the Japan Sea over a period of a few weeks. Both Olatundo and Roger (2007) and Bhattacharya and MacEachern (2009) found that muddy hyperpycnites would be more difficult to analyze than sandstone hyperpycnites because of smaller grain size, the relative lack of sedimentary structures, and effect of fissility in the lithified shales obscuring primary structures.

**Purposes and Objectives**

The Devonian Ohio Shale has been the focus of scientific research for a long period of time. For example, Newberry (1871) studied the Ohio Shale as part of the geology of Ohio in general. Winchell (1874) produced the geological map of central Ohio showing the stratigraphic position of the Ohio Shale. Prosser (1912, 1913) studied the Devonian units of northern Ohio including the Huron Shale Member and Cleveland Shale Member of the Ohio Shale. When oil companies started to explore for oil and gas, many studies focused on these units as the potential source rocks. Cushing (1912) established the age of the Cleveland Shale Member. The correlation of the Devonian black shale between Ohio and Pennsylvania also started in the 1910s. VerWiebe (1917) noted the similarities of the stratigraphic column in southeastern Ohio and northwestern Pennsylvania. The correlation of Devonian black shales was started early in the last century by Kindle (1912) and expanded by Roen (1981) as well as Broadhead et al. (1982).
Much has been written about the depositional model of Devonian black shales. Hoover (1960), Swanson (1961), Janssens (1969), Conkin et al. (1980), Potter et al. (1980), Broadhead et al. (1982), Jordan (1980), Lewis (1988), Hancock and Brian (2000), Coogan (1996), and Dyni (2006) have all published significant works for understanding the Ohio Shale sequence. These works have helped to illustrate the Devonian black shale depositional style and analyzed its sequence from different locations with various techniques.

An issue in the interpretation of the depositional environment for the Devonian black shale has been the paleo-depth of the water. Many geologists suggest that the Devonian black shale was deposited in shallow water (< 200 m) whereas others have argued for water depths up to thousands of meters. Ver Streeten (2012) interpreted relatively deep water based on two pieces of evidence. First, condensed black shales in the foreland basin center (central to western NY) are in accord with the modern understanding of the difficulties of transporting largely flocculated marine muds great distances across the basin floor. Second, if central to western NY was deposited in a shallow marine environment, especially over a sharply pronounced fore bulge, relatively shallow marine carbonates should have formed on all the parts of the Appalachian Basin.

Ettensohn (2012) stated that alternating units of black shale and coarser clastics not only reflect the cyclic nature of Acadian tectonism and subsidence, but also provide an internal means of approximating water depths during black shale deposition. In addition, a large granitic lonestone with a mass of approximately 3 tons has been observed embedded within the uppermost Ohio Shale in northeastern Kentucky. This boulder was apparently transported by an iceberg from about 500 km east of the current location (Lierman, 2012).
The purpose of my thesis is to better characterize the Cleveland Shale Member in terms of its sedimentological, stratigraphic, and petrophysical properties using four methods, all of which will be described later. Furthermore, identifying the lithofacies of the Cleveland Shale Member in northwest Ohio is necessary due to its potential contribution to the world’s energy supply. Another aim of this research is to better define the location of Ohio on the Appalachian Basin in order to set the water depth using different methods to analyze those event strata. Finally, my research may help resolve the controversy over the interpretation of the environments. Hyperpycnites, tempestites, and turbidites are significant event strata in the Cleveland Shale Member that can be used to determine the depositional environment.
GEOLOGICAL BACKGROUND

Depositional History

The Appalachian Basin

The Appalachian Basin was the product of a collision between Euramerica (including the North America plate) and an island arc during the early Ordovician (about 480 Ma). At this time, two major landmasses, Gondwana and Euramerica, were separated by the Rheic Ocean (Fig. 5). This ocean formed during the Cambrian and destroyed during the Hercynian and Alleghenian orogenies during the Carboniferous. Euramerica included North America, parts of Europe, Greenland, and part of Asia whereas Gondwana included Africa, parts of Europe, Antarctica, Australia, India, and South America. The oceanic plate also had several small landmasses on it (Miall, 2008).

During the Devonian, the ocean started to close by subduction beneath Euramerica and Gondwana. The Acadian Mountains started to form during the early Devonian. However, the most prominent events happened during the late Middle Devonian when the Avalonia Terrane collided with the proto-North America plate (Cook et al., 1979). The erosion of the Acadian Mountains carried a huge amount of sediments into the Appalachian Basin, causing basin subsidence and forming an enormous wedge of sediment called the Catskill Delta (Fig. 6). As a result, in Ohio, Kentucky, and Pennsylvania, organic-rich shales were interbedded with less organic-rich sediments (Harper and Kostelnik, 2010). During this period, the shallow marine portion of the basin accumulated carbonates during high sea level stands, and those sediments were eroded during low sea level stands.

An example of a tectonic delta complex, the Catskill Delta was an enormous wedge of sediment built westward into the Appalachian Basin as a result of sediments eroded from the
Acadian Mountain (Friedman and Johnson, 1966) (Fig. 6). The Catskill Delta extended from the Hudson River in the eastern New York west to Lake Erie, and from central New York southward to northern Virginia. During the Middle and Late Devonian, the Catskill Delta built westward into the Appalachian Basin. In Ohio, an unconformity separates the Olentangy shale into two parts: the lower part can be correlated to the Hamilton Group of New York and other eastern states; the upper part can also be correlated to the Java and West Falls Formations of New York. The Devonian rocks above the unconformity represent the lower part of the sequence formed during the Late Devonian and Mississippian transgression (Schwietering, 1979).

Oliver et al. (1967, 1971) described the Devonian rocks in the Appalachian Basin, summarized existing knowledge of these rocks on cross sections, and showed that the upper Devonian black shale sequences (Ohio Shale-Chattanooga Shale) in the western part of the Appalachian Basin are physically continuous with the Middle Devonian and the lower Upper Devonian black shale sequences in the east. Their interpretation suggests that only one major transgression of the sea occurred during the Devonian Period, and the distribution of black shale in the section represents a westward migration of the black shale lithofacies as the sea transgressed westward from the basin center onto the Cincinnati Arch.

**Regional Stratigraphy**

Ohio has been situated within the bounds of the North American Plate from Precambrian time to the present. Thus, since the end of the Precambrian, there has been no major deformation of the area in Ohio other than minor folding and faulting at the close of the Paleozoic Era (Coogan, 1996). Thus, deposition of the Devonian shales was closely related to the subsidence of the Appalachian Basin. The Acadian Orogeny is especially important in regional geological history because it controlled the subsidence of the Appalachian Basin (Shi, 1995).
At approximately 386 Ma, deposition of sediment in clear seas began in the Appalachian Basin underlying the Catskill Delta. Under those conditions, richly fossiliferous limestone started to deposit during the early Middle Devonian. The Columbus Limestone is an example of this interval because it has wide distribution in many states in northeast U. S. and in Ontario, Canada. In northeastern Ohio, the Columbus Limestone conformably overlies the Lucas Dolomite and directly underlies the Ohio Shale. However, in the northwest Ohio, the Columbus Limestone underlies the Delaware Limestone and Olentangy Shale. Also, it unconformably overlies other carbonate rocks in northwestern and southern Ohio (Hoover, 1960; Janssens, 1969) (Fig. 7).

The Delaware Limestone was deposited during Middle Devonian period. It conformably overlies the Columbus Limestone in eastern Ohio. In older research, authors described this unit as mostly limestone and called it “Blue Limestone” because it contains a thin, bluish-gray, fine-grained siltstone or silty limestone that indicate the start of the rise of Acadian Mountains. Until the mid-1950s, previous workers believed that streams and waves transported the silt into the western edge of the Appalachian Basin, for deposition with the Delaware Limestone. Several papers investigate the abundant fossils of the Delaware Limestone in more detail (Hoover, 1960; Coogan, 1996) (Fig. 7).

The Olentangy Shale Member is a gray to greenish shale with an average thickness of about 10 m. It is, in general, poorly fossiliferous (Hoover, 1960; Coogan, 1996). Most geologists spilt this unit in two parts with an intraformatinal unconformity between them (Fig. 7). The lower part of the Olentangy Shale was deposited during the late Middle Devonian, (382 Ma). The upper part of the Olentangy Shale, which unconformably overlies the lower Olentangy Shale, represents the first appearance of the late Devonian black shale sequence. It can be correlated to the Burket Shale Member of Harrell Formation of southwestern Pennsylvania, to
Figure 7  The generalized formations in west-central Ohio. This composite section represents about 330 meters of rock exposed across the area. This is not a scale but the thicknesses indicated are proportional (source: modified from Coogan, 1996)
Figure 8. Stratigraphic column and a correlation for Upper Devonian rock sequence in Northeastern USA representing the Ohio State strata and their equivalent in the Kentucky, Pennsylvania, New York, and West Virginia States. Sources: (Hoover, 1960; Coogan, 1969; Patchen, 1977; Schwietering, 1979; Milici and Swezey, 2006),
the Geneseo Shale Member of the Geneseo Formation in New York, and the Rhinestreet Shale Member of the West Falls Formation in West Virginia, New York, and northeastern Pennsylvania. In addition, it can be correlated to the lower Selmier Member of the New Albany Shale Formation in west Kentucky and to the Dowelltown Shale Member of the Chattanooga Shale in south Kentucky (Fig. 8).

**Ohio Shale**

The Ohio Shale is divided into three members. It ranges in thickness from less than 6 m to more than 200 m (ODNR, 2011). The Ohio Shale crops out from Cuyahoga County in northern Ohio to Pulaski County in southern Kentucky. The color of the Ohio Shale ranges from brown to brownish black and gray to greenish gray. It is laminated to thin bedded strata with fissile partings (Fig. 8). In general, it consists of shale cemented by carbonate (Hoover, 1960; Coogan, 1996).

In ascending order, the Huron Shale Member of the Ohio Shale is the most widespread of the black shales, and extends from Ohio and eastern Kentucky into western Pennsylvania and western West Virginia. It conformably overlies the upper Olentangy shale in most parts of Ohio except in north-central Ohio (Gray et al., 1982; Shi, 1995) (Fig. 7). Hoover (1960) and Shi (1995) reported that this member is hard to distinguish from the overlying and underlying members. Stout et al. (1943) reported its thickness is ~ 125 m. The Huron Shale Member is characterized as grayish black fissile shale. Hoover (1960) wrote that the fresh samples of this unit are bluish black and grayish black in color. He noticed that the Huron Shale Member commonly appear as thin fissile beds because of weathering; however, the unit is thick bedded and massive in the fresh outcrops (Broadhead and Potter, 1980).
In general, The Huron Shale Member underlies Chagrin Shale Member; however, in some areas, it underlies Cleveland Shale Member. In this case, it is hard to distinguish the Huron Shale Member from the Cleveland Shale Member. Hoover (1960) and Broadhead and Potter (1980) used two criteria to differentiate these two members. First, the percentage of clay minerals tends to be greater in the Huron Shale Member. Second, the diameter and thickness of calcareous concretion layers are large in the Huron Shale Member.

The Huron Shale Member can be correlated to the Lower Gassaway Member (the upper portion of the Chattanooga Shale) in south Kentucky and to the Selmier Shale Member (the upper part of the New Albany Formation in southern and western Kentucky) (Fig. 8). In addition, it can be correlated to the Hume Shale Member (the upper part of the Canadaway Formation in New York and northeastern Pennsylvania) and to the Dunkirk Shale Member (the middle part of the Perrysburg Formation in the Catskill Delta Group in West Virginia).

The Chagrin Shale Member of the Ohio Shale is a local unit that can be found in northern Ohio between the Huron Shale Member and Cleveland Shale Member. It conformably overlies the Huron Shale Member and underlies the Cleveland Shale Member (Fig. 7). The outcrop pattern is a narrow band north-south parallel to the Appalachian basin (Hoover, 1960; Shi, 1995). The Chagrin Shale Member consists of light to medium gray, noncarbonaceous shales (Coogan, 1996). It is not tough to distinguish Chagrin Shale Member from the overlying layer, Cleveland Shale Member, or the underlying layer, Huron Shale Member.

The Chagrin Shale Member is exposed in northeast Kentucky, and it can be correlated to the Middle Gassaway Shale Member (the middle part of the Chattanooga Formation in south Kentucky) and to the Lower Grassy Creek Member (the middle part of the New Albany Formation in western Kentucky). In addition, it is equivalent to the Chadakoin Shale Member.
(the middle part of the Conneaut Shale in northeastern Pennsylvania and New York) and to the Minnehaha Springs Member of the Scherr Formation (the upper part of Greenland Gap Group in West Virginia) (Fig. 8).

The upper part of the Ohio Shale is the Cleveland Shale Member, which is grayish- and greenish-gray in color (Hansen, 1994). It conformably overlies the Chagrin Shale Member and underlies the Late Devonian Bedford Shale (Fig. 7). It extended from northern Ohio to southeast Pennsylvania, northeast Kentucky, and West Virginia (Dennison et al., 1994). Its thickness ranges from about 5 -15 m, and it also has a narrow outcrop pattern of two bands starting east-westward from Ashtabula County to Erie County and then turning southward until Lawrence County. The Cleveland Shale Member of the Ohio Shale is mostly black shale but it also contains in the lower part many beds of bluish-gray or gray clay shale, some thin gray to brown siltstone beds, many small nodules and lumps of pyrite, and several thin siliceous limestone beds characterized by the cone-in-cone structures. Hoover (1960) reported that the fresh samples of the Cleveland Shale Member are bluish black to brownish black, but it turns to coffee brown when they are exposed to weather. In the fresh outcrops, the massive shales are compact. However, it becomes thinly fissile and brittle, after slight weathering. Upon extreme weathering, it turns to dark grey and breaks down into flaky pieces but does not acquire the real plasticity of clay shale. Primary and secondary deposits of pyrite are present in considerable quantities along the laminae as concretionary masses and /or as finely disseminated pyrite. When the shale is chipped, it gives off a gaseous or petroliferous odor that is indicative of its high carbonaceous (kerogen) content.

The Cleveland Shale Member also extends into Kentucky and Pennsylvania, and it can be correlated with the Upper Gassaway Member (the upper part of the Chattanooga Formation in
southern Kentucky) and to the Grassy Creek Member and Hannibal Member (the upper parts of the New Albany Formation in western Kentucky). It is also possible to correlate this unit with the Riceville Member (the upper part of the Conewango Formation in New York and northeastern Pennsylvania) and to the Cleveland Member (the upper part of the Catskill Delta Group in West Virginia) (Fig. 8).

Thus, in northern Ohio, black shale can be divided into two shale units, the Huron Shale Member and the overlying Cleveland Shale Member, only based on the local presence of the Chagrin Shale Member. Elsewhere, these two members are difficult to separate. Isopach contours of the Cleveland Shale Member delineate a northeast-southwest thick zone in the Cleveland vicinity that then turns abruptly south in western areas. The Cleveland Shale Member predominantly consists of fissile, quartz-pyrite-illite-chlorite shale and organic matter in the Cleveland region (Nelson, 1955).

The Bedford Shale Member overlies the Cleveland Shale Member, and it has a thickness of about 35 m. The color of this unit is originally gray, but it has a red look in many locations. Many geologists considered this particular unit with the overlying unit, Berea Sandstone, to be related to the Early Mississippian period in their age. However, these units have been assigned as parts of the late Upper Devonian just above the Ohio Shale. The Bedford Shale illustrates that the sediments were transferred to the western edge of the Appalachian Basin, especially the Ohio Sea, from uplands to the north in Canada and from the Catskill Delta to the east (Ohio History Central, 2012).
METHODS

Field Work

Outcrop Locations

Outcrop study of this research was conducted in three different locations in northeast Ohio, Cuyahoga County. There were total of 18 field trips taken over 34 days, to the three locations. One of the field trips was taken with Dr. Evans in August 2012, and another one was taken with AAPG, field trip in September 2012. While most of the Cleveland Shale Member outcrops were found along the Rocky River, the best exposures were found at Huntington Park, near Bay Village, west of the city of Cleveland. Figure 9 shows the locations of the three study areas.

A brief summary of the stratigraphic sections of the three location of the Cleveland Shale Member can be found in Table 1 while the detailed stratigraphic sections can be found in Appendix A. The stratigraphic section at Bay Village is 17 m thick and extends laterally 330 m (Appendix A-1). The stratigraphic section at Bedford, in the Cuyahoga Valley National Park, is one of the best exposures of the contact between the Chagrin Shale Member and the Cleveland Shale Member. At this location, the contact extends laterally for about 500 m. The Cleveland Shale Member is 16 m thick (Appendix A-2). The stratigraphic section at West Creek, a tributary of the Cuyahoga River in Brooklyn Heights Village Park, is 15 m thick and extends laterally for 450 m (Appendix A-3).

A total of 143 rock samples were collected from the three outcrops in addition to 18 samples that were collected from the well cores. The 161 samples were used to identify composition, grain size, and sedimentary structures. A total of 68 samples were used to make thin sections, and 12 samples were prepared for Scanning Electron Microscopy (SEM) analysis.
Table 1. A Summary of the three outcrops.

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinate</th>
<th>Approximate Total Thickness (m)</th>
<th>Approximate CSM* Thickness (m)</th>
<th>Samples Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Easting</td>
<td>Northing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huntington Park</td>
<td>422550</td>
<td>4593570</td>
<td>17.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Cleveland Metro Pkwy</td>
<td>454923</td>
<td>4581584</td>
<td>51.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Brooklyn Heights</td>
<td>443218</td>
<td>4584872</td>
<td>32.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

CSM* = Cleveland Shale Member
Figure 9 A map of the study area in Cleveland showing three locations for measured sections.
At each location, digital photographs were taken of the whole section, individual lithofacies, and the specific sedimentary structures. Photographs taken at the outcrops were converted to a photomosaic using the Panavue Image Assembler program. Because the three study areas have long exposures, multiple digital images were taken and manually stitched with specific points avoid any repetition in the photos. In addition, the coordinates of each location were calculated by Garmin GPS. Stratigraphic sections that measured in the three locations describing the changing of lithology, color, composition, grain size, and sedimentary structures. Appendix A contains the three sections from the three locations using the approach of Catuneanu (2006). The sections were produced in digital form using Adobe Illustrator version 6. At the locations, the beds are tilted; therefore, the measurements were calculated taking into consideration the tilting, and measurements were recorded perpendicular to the bedding plane. Some beds have thicknesses that change laterally, so the stratigraphic sections represent the mean thickness of each bed.

Paleocurrents data were collected from groove casts using a Brunton Compass. The paleocurrent measurements are summarized in Appendix D and are plotted on a rose diagram (Fig. 41). Vector statistics were evaluated to calculate the vector mean, vector magnitude, circular standard deviation, circular variance, and significance can be found in Appendix D. The equations used for the vector statistics are (Potter and Pettijohn, 1977):

\[
\text{Vector Mean} = \theta = \tan^{-1} \left[ \Sigma \text{nsin} \theta / \Sigma \text{nccos} \theta \right]
\]
\[
\text{Vector Magnitude} = R = (1/n) [\Sigma (\text{nsin} \theta)^2 + \Sigma (\text{nccos} \theta)^2]^{0.5}
\]
\[
\text{Circular Std. Deviation} = S = (180/ \pi)[2(1-1.0015R)]^{0.5}
\]
\[
\text{Circular Variance} = S^2
\]
\[
\text{Test of Significance} = p = e^{- (nR)^2 / n}
\]
Well Core Locations

In this research, five well cores were chosen from five different counties in northeast Ohio (Table 2). They are stored at the Horace R. Collins Core Laboratory of the Ohio Geological Survey at Alum Creek State Park in Columbus. The cores were chosen to represent the best available data for the Cleveland Shale Member in the region (fig. 10). The cores are held in boxes of 0.61 m (2 ft) long and 0.3 m (1 ft) wide showing the total about 3 m (10 ft) of core length per box. All the boxes were numbered in their length and marked if there are missing intervals. Because of the fissility in the shale, there was a problem cleaning the core fragments for study (i.e. the core absorbed water and disarticulated). Moreover, there are missing sections and some disarranged sections as a result of boxes that previously fell on the ground. Therefore, cores were cleaned by using a soft dry paintbrush and wiped with a damp towel (fig. 11). More details about core evaluations can be found in Appendix B.

The description of the cores included lithology, sedimentary structures, composition, and texture. The description was achieved by visual inspection using three hand lenses (x10, x20, and x60), and a binocular microscope which is provided in the core lab. A digital camera was used to take photographic for the specific interested lithology and sedimentary structures. Eighteen samples were collected from the cores for study using the petrographic microscopes and SEM analysis (Table 4).

Geophysical logs

The lithologies of any well can be presented by natural gamma-ray activity which can be drawn as the gamma ray log (GR). The spectral gamma ray log is used to provide an individual reading for each element so anomalies in concentration can be found and interpreted. The most common radioactive isotopes in sedimentary rocks are $^{40}$K, $^{238}$U, and $^{232}$Th. The most abundant
Table 2. A summary of the six well cores used in this study

<table>
<thead>
<tr>
<th>Well #</th>
<th>County</th>
<th>Owners</th>
<th>Coordinate</th>
<th>CSM* Thickness (ft)</th>
<th>CSM* Thickness (m)</th>
<th>Number of Sample Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Easting</td>
<td>Northing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2720</td>
<td>Ashtabula</td>
<td>N. American Exploration Inc.</td>
<td>502563</td>
<td>4610228</td>
<td>22</td>
<td>6.7</td>
</tr>
<tr>
<td>2721</td>
<td>Ashtabula</td>
<td>N. American Exploration Inc.</td>
<td>508084</td>
<td>4605481</td>
<td>11</td>
<td>3.3</td>
</tr>
<tr>
<td>2739</td>
<td>Erie</td>
<td>N. American Exploration Inc.</td>
<td>380854</td>
<td>4577489</td>
<td>48</td>
<td>14.6</td>
</tr>
<tr>
<td>2754</td>
<td>Huron</td>
<td>N. American Exploration Inc.</td>
<td>361251</td>
<td>4548968</td>
<td>40</td>
<td>12.2</td>
</tr>
<tr>
<td>2763</td>
<td>Lorain</td>
<td>N. American Exploration Inc.</td>
<td>395890</td>
<td>4583975</td>
<td>64</td>
<td>19.5</td>
</tr>
</tbody>
</table>

CSM* = Cleveland Shale Member
Figure 10. A map showing the locations of the five well cores used in this study.
Figure 11. Core sample photograph showing the form of the fissile shale. Because the core absorbed water and disarticulated, it had to be cleaned by a soft dry brush or cleaned with a moist towel.
source of radioactivity is $^{40}\text{K}$ which is found in clay minerals such as illite and chlorite, and also in micas or feldspars. In general, the highest GR readings are from shales. However, high percentages of K-feldspars or micas (in sandstones or shale) can also produce high gamma-ray responses (Asquith et al., 1982).

Each lithology has unique physical property, which can affect on the geophysical log responses. The gamma-ray logs and density logs were used to calibrate matching the logs to the core data in order to determine the lithology of subsurface. Mainly, the gamma-ray is the better indicator to differ mudrocks from sandstones because higher GR means mudrocks because they are rich in clay minerals. However, sandstones can also have high GR if they are rich in potassium feldspar or containing clay minerals or radioactive rock fragments (Reading, 1996). A potential source of errors in GR log in this study is the presence of feldspar and clay minerals cement. Therefore, larger GR values are interpreted as shales while low GR values are interpreted as high clay content sandstones.

The gamma-ray log curves can be divided to five different types based on their shapes: cylindrical-, irregular-, bell-, symmetrical-, and funnel-shaped curves. This is beneficial because it gives better understanding which means better interpretation of lithology and grain size trends. The cylindrical-shaped curve represents clean sandstones or carbonates which can be found in aeolian, braided fluvial, carbonate shelf, reef, or submarine canyon. The irregular-shaped curves can be interpreted as mixed clean and shaly deposit such as fluvial floodplain, carbonate or clastic slopes, tidal flat, or canyon depositional environments. The bell-shaped curve, which has abrupt base, represents a fining-upward sequence (including shale content) that may be showing fluvial to tidal point bars, deep-water channel, or transgressive shelf sand deposits. The symmetrical-shaped curve is usually rounded base and top and interpreted as a sandy offshore
bar or amalgamated coarsening-upward and fining-upward sedimentary environment. The last shape is the funnel-shaped curve, which has an abrupt top indicating coarsening-upward trend and suggesting crevasse splay, distributary mouth bar, barrier island, shallow-water sheet sand, carbonate shoaling-upward sequence, or submarine fan deposit (Cant, 1992).

The neutron-porosity (NP) shows the total amount of pore spaces in the rock by measuring the hydrogen content, which is correlated with the formation water. Usually, mudrocks have high porosity which means higher neutron-porosity responses while sandstones can show lower GR values and low NP responses because sandstone, in general, have low porosity. However, sandstones can be well cemented which can affect the NP responses. Based on porosity, tight reservoir rocks have high densities (Reading, 1996).

**Laboratory Work**

**Petrology**

_Petrographic Microscope._ From the 161 hand samples and core samples that were collected from the study areas, 11 sandstone and 22 mudstone thin sections (Table 3) were prepared by Applied Petrographic Services, Incorporated. Those sandstones represent the horizontal and vertical aspects from the sandstone intervals from hyperpycnites, turbidities, or tempestites. In some cases, for the thick intervals, two slides were prepared representing the base and the top of the layer. The main aims for this method were to identify the mineral composition, to determine the change of grain size within each interval from the base to the top, to observe the sedimentary structures and microstructures, and to distinguish clay from silt. Following the Gazzi-Dickinson method (Ingersoll et al., 1984), 300 grains per thin section were point counted from three sandstone samples which are 13-SH-04, 13-SH-09, and 13-SH-29 (Table 3).
Table 3. Samples log for thin section analysis

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample No</th>
<th>Location</th>
<th>Lithology</th>
<th>description</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13-SA-01</td>
<td>H. Park*</td>
<td>Hyperpycnite</td>
<td>Upper surface</td>
<td>0.81 m</td>
</tr>
<tr>
<td>2</td>
<td>13-SA-03</td>
<td>H. Park*</td>
<td>Hyperpycnite</td>
<td>Y axis slide</td>
<td>2.35 m</td>
</tr>
<tr>
<td>3</td>
<td>13-SA-04</td>
<td>H. Park*</td>
<td>Tempestite</td>
<td>Upper surface</td>
<td>3.81 m</td>
</tr>
<tr>
<td>4</td>
<td>13-SA-05</td>
<td>H. Park*</td>
<td>Tempestite</td>
<td>Slide from a middle</td>
<td>3.81 m</td>
</tr>
<tr>
<td>5</td>
<td>13-SA-06</td>
<td>H. Park*</td>
<td>Tempestite</td>
<td>Lower surface</td>
<td>3.81 m</td>
</tr>
<tr>
<td>6</td>
<td>13-SA-08</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Upper surface</td>
<td>5.38 m</td>
</tr>
<tr>
<td>7</td>
<td>13-SA-09</td>
<td>H. Park*</td>
<td>Turbidite</td>
<td>Slide from a middle</td>
<td>9.62 m</td>
</tr>
<tr>
<td>8</td>
<td>13-SA-12</td>
<td>H. Park*</td>
<td>Turbidite</td>
<td>Y axis slide</td>
<td>9.62 m</td>
</tr>
<tr>
<td>9</td>
<td>13-SA-20</td>
<td>H. Park*</td>
<td>Siltstone</td>
<td>Upper surface</td>
<td>0.30 m</td>
</tr>
<tr>
<td>10</td>
<td>13-SA-23</td>
<td>H. Park*</td>
<td>Rhythmic Shale</td>
<td>Upper surface</td>
<td>3.32 m</td>
</tr>
<tr>
<td>11</td>
<td>13-SA-25</td>
<td>H. Park*</td>
<td>Rhythmic Shale</td>
<td>Upper surface</td>
<td>11.9 m</td>
</tr>
<tr>
<td>12</td>
<td>13-SA-29</td>
<td>H. Park*</td>
<td>Turbidite</td>
<td>Lower surface</td>
<td>12.02 m</td>
</tr>
<tr>
<td>13</td>
<td>13-SA-30</td>
<td>H. Park*</td>
<td>Siltstone</td>
<td>Upper surface</td>
<td>0.7 m</td>
</tr>
<tr>
<td>14</td>
<td>13-SA-35</td>
<td>H. Park*</td>
<td>Tempestite</td>
<td>Y axis slide</td>
<td>8.33 m</td>
</tr>
<tr>
<td>15</td>
<td>13-SA-36</td>
<td>H. Park*</td>
<td>Siltstone</td>
<td>Upper surface</td>
<td>6.00 m</td>
</tr>
<tr>
<td>16</td>
<td>13-SA-38</td>
<td>H. Park*</td>
<td>Claystone</td>
<td>Upper surface</td>
<td>1.42 m</td>
</tr>
<tr>
<td>17</td>
<td>13-SA-40</td>
<td>H. Park*</td>
<td>Clayshale</td>
<td>Upper surface</td>
<td>0.13 m</td>
</tr>
<tr>
<td>18</td>
<td>13-SA-42</td>
<td>H. Park*</td>
<td>Clayshale</td>
<td>Y axis slide</td>
<td>0.13 m</td>
</tr>
<tr>
<td>19</td>
<td>13-SA-45</td>
<td>Core 2720</td>
<td>Clayshale</td>
<td>Y axis slide</td>
<td>24.3 m</td>
</tr>
<tr>
<td>20</td>
<td>13-SA-47</td>
<td>Core 2721</td>
<td>Mudstone</td>
<td>Upper surface</td>
<td>23.2 m</td>
</tr>
<tr>
<td>21</td>
<td>13-SA-48</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Y axis slide</td>
<td>1.31 m</td>
</tr>
<tr>
<td>22</td>
<td>13-SA-52</td>
<td>H. Park*</td>
<td>Mudshale</td>
<td>Upper surface</td>
<td>6.60 m</td>
</tr>
<tr>
<td>23</td>
<td>13-SA-80</td>
<td>B. Park*</td>
<td>Siltstone</td>
<td>Y axis slide</td>
<td>0.9 m</td>
</tr>
<tr>
<td>24</td>
<td>13-SA-82</td>
<td>B. Park*</td>
<td>Rhythmic Shale</td>
<td>Y axis slide</td>
<td>4.55 m</td>
</tr>
<tr>
<td>25</td>
<td>13-SA-83</td>
<td>H. Park*</td>
<td>Rhythmic Shale</td>
<td>Y axis slide</td>
<td>11.91 m</td>
</tr>
<tr>
<td>26</td>
<td>13-SA-201</td>
<td>B. Park*</td>
<td>Siltstone</td>
<td>Y axis slide</td>
<td>6.31 m</td>
</tr>
<tr>
<td>27</td>
<td>13-SA-203</td>
<td>B. Park*</td>
<td>Claystone</td>
<td>Y axis slide</td>
<td>5.45 m</td>
</tr>
<tr>
<td>28</td>
<td>13-SA-207</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Y axis slide</td>
<td>3.02 m</td>
</tr>
<tr>
<td>29</td>
<td>13-SA-209</td>
<td>H. Park*</td>
<td>Mudshale</td>
<td>Y axis slide</td>
<td>7.81 m</td>
</tr>
<tr>
<td>30</td>
<td>13-SA-210</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Y axis slide</td>
<td>5.38 m</td>
</tr>
<tr>
<td>31</td>
<td>13-SA-215</td>
<td>H. Park*</td>
<td>Am. Tempestite</td>
<td>Upper surface</td>
<td>6.53 m</td>
</tr>
<tr>
<td>32</td>
<td>13-SA-216</td>
<td>H. Park*</td>
<td>Am. Tempestite</td>
<td>Y axis slide</td>
<td>6.53 m</td>
</tr>
<tr>
<td>33</td>
<td>13-SA-215</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Upper surface</td>
<td>1.31 m</td>
</tr>
</tbody>
</table>

Note. * H. Park = Huntington Beach Metropark, B. Park = Bedford Reservation Metropark.
Binocular Microscope. Some core samples that were collected from the Ohio Division of Geological Survey are too small to make into thin sections. Those samples were analyzed using LEICA MZ 12.5 binocular microscope in the Department of Geology at BGSU. The aim of using this method was to identify microlamination, micro-hummocky stratification, or microburrows that they are sufficient in order to distinguish lithology and use for lithofacies analysis. Four samples have chosen in this method, each one represent different lithofacies. Sample (13-SH-103 and 13-S-104), (13-SH-107), and (13-SH-105) were selected to represent turbidities, tempestites, and hyperpycnites, respectively. The results will be explained within the next section and can be found in figures (20, 21, and 22).

**Scanning Electron Microscopy (SEM) analysis**

From both outcrops and wells, 12 specimens (Table 4) were analyzed and imaged in the Department of Biology at BGSU using the Hitachi model S-2700 Scanning Electron Microscope. The specimens were chosen to represent the different textures and sedimentary microstructures in each mudstone lithofacies association or sandstone lithofacies association. In addition, plant debris and mottles were difficult to study using the two previous microscopes; therefore, two samples were prepared to examine these features.

Most of the specimens were prepared by cutting rock samples, in the Department of Geology, to be less than 1 cm$^3$ in size in order to fit within the stages apertures of the SEM microscope. Two types of stages were used, and they differ from each other in their capacity. One can hold four smaller specimens while the other stage can hold only one large specimen. The sandstone specimens were analyzed individually because of their large sizes ($>2$ cm$^3$). The most important point here is that the thickness of each specimen has to be less than 0.6 cm, to
avoid damaging the outermost lens due to the short working distance. Each specimen was fixed in a single stub and then (because the lower surface is not flat), graphite paint has used to mount the tube, which consist of conductive materials, to the specimen, which consist of non-conductive materials (Bozzola and Russell, 1999).

The specimens were prepared by drying and coating them using two different machines. The Samdri 780A Critical Point Dryer was used to dry the specimens using 100% ethanol with temperature 33-39 °C and under pressure of 1200 – 1500 psi. To coating the samples, the Hummer VI-A Sputter Coater machine was used with 10nm thick layer of gold-palladium (Bozzola and Russell, 1999).

Setting the SEM machine with the Qualitative Element software requires certain steps in a specific order and resulting waiting times between steps. The stage coordinates, X and Y, were set on 17 and 20 while the Z coordinate was set at EX (meaning the tilt was 0). Because all the specimens are geological samples, the settings of the SEM machine had to be set at specific numbers. The Hitachi microscope was used under an acceleration voltage of 20 kV, beam current (spot size) of 10-µA, and working distance of 8-12 mm ((Bozzola and Russell, 1999). After the image appeared on the screen, the screen had to be adjusted. With a magnification of X8000, the screen controls were used to adjust the coarse and fine adjustment knobs and the X- and Y-direction adjustment knobs. Initially, the gun aperture had to be adjusted on setting 2 to obtain SEM images, but was later changed to setting 3 to use the Qualitative Element Software (QES). Significantly, to get QES images, the magnification has to be more than X5000 and working distance has to be settled at 12 mm (Lyman et al., 1990).
Table 4. Sample log for SEM analysis

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Location</th>
<th>Lithology</th>
<th>Description</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-SA-101</td>
<td>Core 2720</td>
<td>Siltstone</td>
<td>Upper surface</td>
<td>23.0 m</td>
</tr>
<tr>
<td>13-SA-102</td>
<td>Core 2720</td>
<td>Hyperpycnite</td>
<td>Upper surface</td>
<td>23.3 m</td>
</tr>
<tr>
<td>13-SA-103</td>
<td>Core 2720</td>
<td>Turbidite</td>
<td>Upper surface</td>
<td>23.8 m</td>
</tr>
<tr>
<td>13-SA-104</td>
<td>Core 2720</td>
<td>Turbidite</td>
<td>Y axis slide</td>
<td>26.7 m</td>
</tr>
<tr>
<td>13-SA-105</td>
<td>Core 2721</td>
<td>Hyperpycnite</td>
<td>Lower surface</td>
<td>23.2 m</td>
</tr>
<tr>
<td>13-SA-106</td>
<td>Core 2739</td>
<td>Bioturbated mudstone</td>
<td>Y axis slide</td>
<td>35.1 m</td>
</tr>
<tr>
<td>13-SA-107</td>
<td>Core 2739</td>
<td>Tempestite</td>
<td>Upper surface</td>
<td>34.8 m</td>
</tr>
<tr>
<td>13-SA-108</td>
<td>Core 2739</td>
<td>Siltstone</td>
<td>Upper surface</td>
<td>37.5 m</td>
</tr>
<tr>
<td>13-SA-109</td>
<td>H. Park*</td>
<td>Mudstone</td>
<td>Upper surface</td>
<td>3.02 m</td>
</tr>
<tr>
<td>13-SA-110</td>
<td>H. Park*</td>
<td>Mudshale</td>
<td>Y axis slide</td>
<td>7.11 m</td>
</tr>
<tr>
<td>13-SA-111</td>
<td>H. Park*</td>
<td>Claystone</td>
<td>Upper surface</td>
<td>5.01 m</td>
</tr>
<tr>
<td>13-SA-112</td>
<td>H. Park*</td>
<td>Clayshale</td>
<td>Y axis slide</td>
<td>7.55 m</td>
</tr>
</tbody>
</table>

Note: H. Park = Huntington Beach Metropark.
The goal of this method is to gain a better examination of the microfacies. It is a nondestructive method to verify the identification of minerals using the qualitative element analysis program. Nine samples were used for SEM analysis, 3 samples from the Huntington Beach and 6 samples from the well cores (Table 4). After using the SEM/EDAX to determine the chemical composition of the clasts, an atlas of SEM images was used to identify the clay minerals.
RESULTS

Lithology analysis

The lithology of Cleveland Shale Member was studied using different methods such as hand samples, thin sections, and binocular and petrographic microscopes and SEM analysis. These methods were used to analyze the samples that were collected from the three sites and well cores. Three main lithologies were identified in the outcrop observation: sandstone, siltstone, and mudstone.

Sandstone

The sandstones of the Cleveland Shale Member are very fine- to fine-grained, poorly to moderate sorted, sub-angular to sub-rounded, quartz arenites or quartz wackes. The primary structures that found with the sandstones intervals include massive bedding, hummocky stratification, planar lamination, ripple lamination, sole marks, and normal grading. Sandstones can be found continuous beds, discontinuous beds, or lenses interbedded with mudstones. The importance of sandstones in the Cleveland Shale Member can be assessed in two ways: as interbedded sandstone intervals and as total sandstone percentage within the mudstone. The interbedded sandstone intervals were observed to make up 11.36% of the unit while, the total sandstone percentage in the mudstone lithofacies is 2.5%.

Because most sandstone intervals in the Cleveland Shale Member are very fine- to fine-grained, only three samples are chosen to make point count analysis. Point counts from these three intervals represent three different lithofacies which can be found in Figure 12 and summarized in Table 5. After counting more than 300 grains, the data were evaluated as percentages of QFL and Q_mFL_t (Fig. 12). The QFL diagram is a sandstone classification scheme.
Table 5. Summary of point count data with raw percentages using two different methods QFL and QmFL.

<table>
<thead>
<tr>
<th></th>
<th>Sample 1 (13-SH-29)</th>
<th>Sample 2 (13-SH-09)</th>
<th>Sample 3 (13-SH-04)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Row Count</td>
<td>Raw %</td>
<td>*QFL Class %</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocrytalline</td>
<td>213.0</td>
<td>59.8</td>
<td>81.6</td>
</tr>
<tr>
<td>Cryptocrystalline</td>
<td>31.0</td>
<td>8.0</td>
<td>92.9</td>
</tr>
<tr>
<td>Polycrytalline</td>
<td>1.0</td>
<td>0.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>3.0</td>
<td>0.8</td>
<td>6.7</td>
</tr>
<tr>
<td>Potassium</td>
<td>16.0</td>
<td>4.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Lithic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentary</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Volcanic</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Metamorphic</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Accessories</td>
<td>7.0</td>
<td>1.8</td>
<td>9.0</td>
</tr>
<tr>
<td>Voids</td>
<td>71.0</td>
<td>18.4</td>
<td>102.0</td>
</tr>
<tr>
<td>Cement</td>
<td>18.0</td>
<td>4.7</td>
<td>39.0</td>
</tr>
<tr>
<td>Matrix</td>
<td>7.0</td>
<td>1.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Total</td>
<td>386</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* The total point count of quartz, feldspar, and lithic for the three samples are 283, 282, and 280, respectively.
Figure 12. Sandstone classification of three sandstone thin sections from the Cleveland Shale Member representing three different lithofacies (After Folk, 1974). The red diamond represents figure 13A, the red circle represent figure 13B, and the rectangular represents figure 13C. Note the diamond represents sample 1 (13-SH-29), the circle represents sample 2 (13-SH-09), and the triangle represents sample 3 (13-SH-04).
based on quartz (monocrystalline, polycrystalline, and chert), feldspar (potassium and plagioclase), and lithics or rock fragments. The $Q_{m}FL_{t}$ diagram is a of sandstone classification scheme based on monocrystalline quartz, feldspar, and all rock fragments in addition to polycrystalline and chert. The Folk (1974) sandstone classification diagram was used to plot the data count and it has observed that all the samples plotted in this diagram are quartz arenites.

The massive interbedded sandstone (sample 13-SH-29) (Fig 13A) is found to be very-fine to medium-grained, poorly to moderate sorted, sub-angular to sub-rounded, quartz arenites. The cements are mostly clay minerals, while the sedimentary rock fragments are shale and chert clasts. The accessory minerals are mostly mica. The normally graded sandstone is found to be very fine-grained to medium-grained, poorly to moderate sorted, sub-angular to sub-rounded quartz arenites (sample 13-SH-09) (Fig. 13B). The sedimentary rock fragments are also abundant as shale and chert clasts. Shale, siltstone, and chert are the most common sedimentary fragment in sandstones and they are tough to recognize especially if they altered during burial diagenesis (Boggs, 2009). The third sample is observed to be very fine- to medium grained, very poorly to moderate sorted, sub-rounded, quartz arenite (sample 13-SH-04) (Fig 13C). The sample has calcite cement rather than clay minerals. Some of the grains were rotated or altered (change in clay minerals), due to physical and/or chemical, burial diagenesis.

The percentages of void spaces were calculated for each of the three samples in order to estimate the porosity of the samples. Voids range from 18 to 23% in the samples (Table 5). Those void spaces are patchy due to selected areas of cementation. Therefore, due to cementation and compaction, porosity of these three samples has been reduced considerably. Porosity in rocks can be found either as void spaces or internal to some grains. Boggs (2009) stated that
Figure 13. Photomicrograph of sandstone from Cleveland Shale Member. A) massive, very fine-to fine-grained quartz arenite (sample 13-SH-29). B) Normally graded, very fine- to fine-grained quartz arenite (sample 13-SH-09). C) Very fine- to medium grained quartz arenite (sample 13-SH-04). See Table 5 and Figure 12 For more details.
porosity in rocks can be primary (depositional) or secondary (post-depositional) which can be recognized based on the relationships of frameworks grains, fossils, clay minerals, and cements.

**Mudrocks**

The term mudrock is recently preferred name for all the fine-grained sediments that are <63 µm in diameter, rather than shale (Stow and Piper, 1984; Potter et al., 2005; Boggs, 2010). The mudrocks of the Cleveland Shale Member were studied from hand samples and core samples using the binocular and petrographic microscopes, and SEM analysis. Different sedimentary structures were observed in the mudrocks in the Cleveland Shale Member such as massive bedding, planar lamination, and graded bedding. Based on the clay percentage of each sample, and based on the primary sedimentary structure, each mudrock can be classified (Fig 14).

It can be tough to observe the primary structures of mudrocks in the field because of weathering. Therefore, using different microscopes can allow observing these structures in more detail. For instance, some what appears to be planar laminated mudrock in the field can be shown to be micro-cross-laminated siltstone. The sedimentary structures in the mudrocks need to be closely inspected using hand lenses or high magnification microscopes to determine if the lamination is truly laminated or micro cross-laminated (Stow, 2005).

Siltstone was mostly observed as planar laminated siltstone interbedded with claystone and clayshales, or as very thinly laminated siltstone within the sandstone intervals, or as lenses within mudstone or sandstone. In addition, it was found as massive to normally graded siltstone beds. Finally, some burrows within the mudstone intervals were infilled by marine siltstone.
<table>
<thead>
<tr>
<th>Percentage clay-size constituents</th>
<th>0–32</th>
<th>33–65</th>
<th>66–100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field adjective</td>
<td>Gritty</td>
<td>Loamy</td>
<td>Fat or slick</td>
</tr>
<tr>
<td>Nonindurated Beds Greater than 10 mm</td>
<td>Bedded silt</td>
<td>Bedded mud</td>
<td>Bedded claymud</td>
</tr>
<tr>
<td>Laminae Less than 10 mm</td>
<td>Laminated silt</td>
<td>Laminated mud</td>
<td>Laminated claymud</td>
</tr>
<tr>
<td>Indurated Beds Greater than 10 mm</td>
<td>Bedded siltstone</td>
<td>Mudstone</td>
<td>Claystone</td>
</tr>
<tr>
<td>Laminae Less than 10 mm</td>
<td>Laminated siltstone</td>
<td>Mudshale</td>
<td>Clayshale</td>
</tr>
</tbody>
</table>

Figure 14. Mudstone classification which is used in this study (Modified after Potter et al., 1980)
Siltstone interbedded with sandstone or mudstone made up of 65% of the Cleveland Shale Member.

The siltstones are planar laminated, very fine- to medium-grained, moderate to well-sorted, sub-angular to rounded, calcareous quartz siltstone. In thin section, the quartz siltstones can be observed with low percentages of potassium feldspar and sedimentary rock fragments. Alternatively, the siltstones are massive to normally graded, very-fine- to very coarse-grained, very poorly- to moderate-sorted, angular to sub-rounded, quartz siltstone. It was recognized that some of the burrows in mudstone intervals were infilled with poorly sorted siltstone, sub-angular to sub-rounded, and this can be interpreted as siltstone that infiltrated from adjacent environment. On contrast, some of the burrows in siltstone intervals were filled by mud which can be interpreted as sediment fallout from suspension.

The fabric of the mudstones, which refers to the particle-to-particle relationships and orientations, is irregular. The different of fabric in the mudstone can be attributed to three depositional and diagenesis mechanisms: physicochemical, bioorganic, and/or burial diagenesis (Bennett et al., 1991). In the Cleveland Shale Member, most of the mudrocks are fissility which means they can be splitting easily into very thin layers, <10mm, planar, and parallel surfaces along laminations. McKee and Weir (1953) classified mudrocks based on thickness of microfabric to papery, fissile, platy, flaggy, and slabby. The mudrocks in the Cleveland Shale Member are observed as papery, fissile, and platy which are < 10 mm.

The texture of the mudrock varies based on the clay percentage and sedimentary structures. Using Potter et al., (1980) classification, there are four types of mudrocks. The rock has a percentage of clay between 33 to 66; the rock can be mudstone when it is massive and
mudshale when it is laminated. On contrast, if the clays are more than 66%, the rock will be claystone when it is massive and clayshale when it is laminated.

**Results of SEM Analysis**

The SEM analysis shows that the mudrocks are composed of <5% sand, 5-65% silt, and 23-70% clay. Organic matter (including plant debris) ranges from 7% to 20% and the mean is 9.6%. The clay consists of quartz, chlorite, illite, with a low percentage (< 1%) of kaolinite. Chlorite is about 20 µm in diameter and can be found sub-perpendicular to perpendicular to the surface (Fig. 15 A). This mineral was found in most of the light gray mudstone lithofacies. Illite is the most common clay mineral in both dark and light gray mudstone with slightly increases in the dark lithofacies (Fig. 15B). Kaolinite is 7-30 µm in diameter and was mostly found in dark mudstone lithofacies (Fig 15C). The EDAX analysis shows the differences of the composition between these three minerals.

Many sandstones and siltstones in the Cleveland Shale Member containing black grains. In the SEM images, these grains were found to be plant fragments, probably derived from terrestrial plants, and brought into the depositional environments by floods or storms. No specific preferred orientation was observed, probably because plant materials float and gradually settle from suspension after becoming water saturated. Plant debris is most typical in the upper parts of turbidite and hyperpycnite sequences (Fig. 16).

Flocculation is a process of small particles joining together to form grain aggregates. In mudrocks, this process is can be the key of mudrock sedimentation (Boggs, 2009; Schieber et al., 2007). These variables in this phenomenon include settling velocity, floccule size, grain-size distribution, ion exchange behavior, and organic content. Flocculation in mudrocks can produce
Figure 15. Microphotograph of clay minerals. A) Chlorite was found in most of the light gray mudstone lithofacies. B) Illite was observed as the most common clay minerals in both dark and light gray mudstone, with slightly increases in the dark lithofacies. C) Kaolinite was observed as the least common clay minerals, and mostly found in dark mudstone lithofacies. The EDAX analysis is showing the chemical composition of the three minerals that the chlorite has high percentage of Al, and Fr. The illite and kaolinite have less Fe, and they differ from each other that illite has more Al while kaolinite has no K.
Figure 16. Photomicrograph of plant debris at the top surface of event deposit. A) SEM image showing pieces of organic materials in the upper surface of turbidite, and they interpreted as plant debris because EDAX analysis more carbon and oxygen. They seem to be deposited as fallout from suspension. B) SEM image showing a close-up from image A (red rectangle). C) SEM image showing a close-up from image B (red rectangle). D) SEM image from another example of an upper surface of hyperpycnites. Note: lengths are shorter and each leg is split into several parts.
variable thicknesses and low-angle ripples or downcurrent-dipping cross-strata, at the upper portions of the deposits (Schieber et al., 2007). In the Cleveland Shale Member, the mudrock samples, which are examined using SEM, do not show any evidence of flocculation as a result of compaction and lithification. In addition, the mudrocks in the Cleveland Shale Member may contain silt grains settling from suspension (Fig. 17 A and B). The micropores in most of the mudrock samples disappear because of illite fractions diminish (Fawad et al., 2010). Schneider et al. (2011) stated that compaction processes may contribute to reduce the pores in mudrocks and those pores can be interpreted as matrix-clast voids (Fig. 17C).

Many event layers in the Cleveland Shale Member show planar lamination in the hand samples. SEM examinations of these layers show the planar lamination represents two different lithofacies ripple laminated siltstone overlain by planar laminated mudstone (Fig 17D). This microstructure indicates that low-energy currents reworked on laminated siltstone to produce those ripples. EDAX analysis also show that a high percentages of organic matter is present on the laminated mudstone, while the siltstones are rich in silicon and oxygen. Moreover, examination of the upper portion of a hand sample shows what appears to be planar laminated mudstone. Within the resolution of the SEM, this can be shown to be rhythmites of low organic, medium gray clayshale alternating with high organic, very dark gray clayshale (Fig. 17E). The EDAX examination of each component demonstrates that the dark gray clayshale has more carbon and oxygen. SEM analysis also reveals vertical burrows in the claystone layer from the middle part of Cleveland Shale Member that was infill by mud (Fig. 17F)
Figure 17. A) SEM image of siltstone grain (red arrow) (50 µm in diameter) at the upper surface of claystone settling out from suspension. B) SEM image showing grains silt (red arrows). C) SEM image showing micropores which are affected and reduced by compaction process. Red arrows showing plant fragments D) SEM image of normally graded siltstone (lithofacies SSI) overlain by massive claystone showing sharp contact. E) SEM image of flood deposit showing high organic and low organic rhythmites. F) SEM image showing a vertical burrow in a claystone layer that was infilled by mud.
Lithofacies Analysis

The Cleveland Shale Member consists of interbedded sandstone, siltstone, claystone, and mudstone. This member has a variety of sedimentary structures including massive bedding, parallel lamination, lenticular lamination, ripple lamination, hummocky stratification, and bioturbation. Lithofacies are unique combinations of primary sedimentary structures, composition, texture, and lithology (Nichols, 1999; Boggs, 2001). The geological method to interpret the depositional environment includes a detailed description of each lithofacies, interpreting each lithofacies, identifying each lithofacies association (a group of related lithofacies), and finally interpreting each lithofacies associations. In the Cleveland Shale Member, from use of hand samples, core samples, and thin sections, fourteen individual lithofacies were recognized in the outcrop as well as well cores. Table 6 summarized the lithofacies and their textures, sedimentary structures, and interpretations.

Massive sandstone (lithofacies Sm)

Lithofacies Sm consists of massive, very fine-to medium-grained, moderately to poorly sorted, subangular- to subrounded, quartz arenite. This facies is usually found underlying planar laminated sandstone or hummocky stratification. The thickness of this lithofacies is variable from 0.5 cm to 12 cm (Fig. 18). Erosional features and small intraclasts of mudstone can be present. The shapes of these deposits can vary, but usually they are sheet-like and elongated parallel to the erosion surface and the laminated strata (Fig 18 B). At the top of some of these units, discontinuous fine-grained sandstone layers occur with wave ripples can be observed. The basal erosional surfaces often contain sole marks (Fig. 18C). These sole marks are groove casts that have a unique direction. These massive sandstones overlain mudstones which have
<table>
<thead>
<tr>
<th>Lithofacies code</th>
<th>Lithology</th>
<th>Sedimentary Structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm</td>
<td>Very fine- to medium-grained sandstone</td>
<td>Massive</td>
<td>Rapid deposits or homogeneous sediments</td>
</tr>
<tr>
<td>Simg</td>
<td>Very fine- to medium-grained sandstone</td>
<td>normally graded bedding</td>
<td>Fallout from suspension</td>
</tr>
<tr>
<td>Sl</td>
<td>Very fine- to medium-grained sandstone</td>
<td>Planar lamination</td>
<td>Upper plane bed</td>
</tr>
<tr>
<td>Sr</td>
<td>Very fine- to fine-grained sandstone</td>
<td>Rippled lamination</td>
<td>Low-flow regime</td>
</tr>
<tr>
<td>Sh</td>
<td>Fine- to medium-grained sandstone</td>
<td>Hummocky stratification</td>
<td>Storm deposits</td>
</tr>
<tr>
<td>SSg</td>
<td>Fine- to medium-grained siltstone</td>
<td>Normally graded bedding</td>
<td>Fallout from suspension</td>
</tr>
<tr>
<td>SSm</td>
<td>Fine- to medium-grained siltstone</td>
<td>Massive</td>
<td>Rapid deposits or homogeneous sediments</td>
</tr>
<tr>
<td>SSLI</td>
<td>Very fine- to fine-grained siltstone</td>
<td>Planar lamination</td>
<td>Fallout from suspension or oscillatory current deposits</td>
</tr>
<tr>
<td>SSCl</td>
<td>Siltstone/clayshale Rhythmites</td>
<td>Planar lamination</td>
<td>Tidal rhythmtes</td>
</tr>
<tr>
<td>Ml</td>
<td>Mudstone</td>
<td>Planar lamination</td>
<td>Fallout from suspension</td>
</tr>
<tr>
<td>Mm</td>
<td>Mudstone</td>
<td>Massive</td>
<td>Rapid deposits or homogeneous sediments</td>
</tr>
<tr>
<td>Mc</td>
<td>Mudstone</td>
<td>Concretion</td>
<td>Pre-compaction concretion</td>
</tr>
<tr>
<td>Cm</td>
<td>Claystone</td>
<td>Massive</td>
<td>Rapid deposits or homogeneous sediments</td>
</tr>
<tr>
<td>Cl</td>
<td>Claystone</td>
<td>Planar lamination</td>
<td>Fallout from suspension</td>
</tr>
</tbody>
</table>
Figure 18. Photomicrograph of core samples and photograph of outcrops of lithofacies Smg. A) photomicrograph of tempestite from core 2720 showing massive to normally graded sandstone (lithofacies Smg) overlain by planar laminated sandstone (lithofacies Sl), overlain by planar laminated mudshale (lithofacies Ml). B) Core sample examined by binocular microscope showing lithofacies Smg, lithofacies Sl, and lithofacies SSl. C) Groove casts found in the base of storm deposits, tempestite D) Field image showing casts of Trace fossils found in mudstone which underlying massive sandstone.
horizontal or vertical burrows of different lengths that were infilled by very fine-grained sands (Fig. 18D). Field observations indicate the unit is completely massive. However, thin section examinations show that some of these units are normal graded sandstone.

**Interpretation.** There are several different interpretations of sandstones with massive bedding. Many geologists believe that this type of sediments can be possibly interpreted as rapid deposition of homogeneous sediments that those layers were deposited under sufficient energy of a flow or a high density current (Stow & Tabrez 1998; Nakajima & Satoh 2001). Rapid deposits are good indicators of specific type of processes such as turbidity flows, mudflows, grain flows (Boggs, 2001) or tempestites (Nichols, 1999). The significant indicator is the erosional base with sole marks which can be found in a turbidite (Bouma, 1962) or tempestite (Dott and Bourgeois, 1982). Finally, massive beds can also develop where grain size is homogeneous.

**Normally graded sandstone (lithofacies Smg)**

Lithofacies Smg consists of normally grade, very fine- to medium-grained, moderately to poorly sorted, subangular or subrounded quartz arenite. This facies is usually found overlying massive sandstone (lithofacies Sm) and underlying planar sandstone or hummocky stratified sandstone (Fig. 18). The change in grain size is observed. For instance, planar laminated sandstone can be graded upward into siltstone, and hummocky stratified sandstone can be graded upward into planar laminated sandstone. In thin section, this lithofacies can contain very thin laminae of siltstone. The thickness of this lithofacies ranges between 2 mm to 7 cm (Fig 18 A and B).

**Interpretation.** There are many different interpretations of normally graded sandstones. Normally graded sandstone with a sharp base and small shale intraclasts can be interpreted as a
turbidite, specifically Division A of the Bouma Sequence (Mulder et al., 2003). Normally grading is due to variations of grain size and particle density. It can be observed using X-radiography (Hamblin, 1965) unless these primary structures are destroyed bioturbation (Selley, 2000). In other instances, massive to normal graded sandstone can be the lower part of a tempestite (Walker and Plint, 1992). In addition, the mudstone intraclasts that can be found in this lithofacies are a result of erosional process from the underlying strata, and can be interpreted as rip-up intraclasts (Flugel, 1982). The discontinuous sedimentary structures in this lithofacies are less common and they can be interpreted as sedimentary grains that are transported individually (Bourget et al., 2010).

**Planar laminated sandstone (lithofacies Sl)**

Lithofacies Sl consists of planar laminated, very fine- to fine-grained, moderately- to well sorted, subangular- to subrounded quartz arenite. This lithofacies often overlies normally graded sandstone (lithofacies Smg) or hummocky stratified sandstone (lithofacies Sh) with mostly abrupt contacts (Fig. 18 and 19), but the contacts can be gradational in thinner (0.25 cm thick) beds. Overlying lithofacies Sl, laminated siltstone (lithofacies SSI), planar laminated mudstone (lithofacies MI) or rippled laminated sandstone (lithofacies Sr) or can be observed (Fig. 18 and 19). This lithofacies did not show any evidence of bioturbation even in thin section.

**Interpretation.** Planar laminated sandstone intervals can result from three different depositional mechanisms. As a part of turbidites, this lithofacies can form as upper planar bed (Bouma, 1962). Cases of planar laminated sandstones above the lithofacies Smg are probably this type. The variable thicknesses may be related to the particle densities in the body of the flow. The alteration of well laminated to massive siltstone indicates fluctuations in flow strength
Figure 19. Photomicrograph and photograph of lithofacies Sl, lithofacies SSCI and lithofacies Sr.  

A) Planar laminated sandstone lithofacies Sl is observed overlain by rippled laminated sandstone, overlain by siltstone-clayshale rhythmites. Red arrows show asymmetrical ripples.  

B) Photomicrograph of core sample showing lithofacies Sl overlain by lithofacies Sr overlain by lithofacies SSCI.  

C) Photograph of outcrop from Huntington Beach outcrop showing storm deposits.
(Nichols, 1999; Boggs, 2001). It is often for the planar lamination to be controlled due to soft-sediment deformation of bedding surfaces from loading or slumping.

In addition, lithofacies Sl can also be found within storm deposits. In this case, it can be interpreted as deposits under oscillatory currents or during waning storms (Walker and Plint, 1992). Boggs (2001) interpreted this lithofacies as a result of settling process from suspension loads that this lithofacies is a part of hummocky intervals during storm processes. Thus, the combination of planar laminated sandstones overlying hummocky stratified sandstones represents storm horizons.

Finally, in recent studies show that planar laminated sandstones have been found as a part of flood deposits (Boggs, 2001; Mulder and Alexander, 2001; Bourget et al., 2010). The present of planar laminated, very fine-to fine-grained sandstones in shallow marine environment can be a result of introduced flood deposits that settle out from suspension loads (Boggs, 2001). In this case, planar laminated sandstone is interpreted as lower flow regime plane bed (Mulder and Alexander, 2001).

**Rippled laminated sandstone (lithofacies Sr)**

Lithofacies Sr consists of rippled laminated, very-fine- to fine-grained, poorly to moderate-sorted calcareous quartz arenite. This lithofacies are observed with symmetrical and asymmetrical current ripples (Fig 19A). In most cases, this lithofacies overlies planar laminated sandstone (lithofacies Sl) and underlies either planar laminated siltstone (lithofacies SSl) or laminated siltstone-clayshale rhythmites (lithofacies SSCl). It shows abrupt contacts with most of these lithofacies except with lithofacies Sl (Fig. 19C). The thickness of this lithofacies ranges from 0.2 cm to 6 cm. Lenses of siltstones and sandstone can be observed at the base and the
middle of this lithofacies, and the form of the lenses can be ripples giving a shape that allows calculation the ripple wavelength (Fig 19A).

**Interpretation.** Most of the rippled laminated sandstone consists of symmetric or wave ripples that develop as a result of bidirectional flows. Ripple marks are really hard to observe in the field because of lack of good exposure and weathering. The present of ripple lamination overlying planar laminated sandstone can be interpreted as the upper parts of storm deposits or parts of turbidites. In the case of storm deposits, the symmetrical ripples suggest depositions process by oscillatory flows due to orbital wave motion. The good preservation of these ripples indicate that the deposition process was under a low flow regime, with weak current activity, at deeper water depths (Hart and Plint, 1989). The present of rippled laminated sandstone overlying planar laminated sandstone could reflect waning energy condition (Walker and Plint, 1992). In turbidites, the presence of ripple laminated fine-grained sandstones over planar laminated sandstone represent a diminishing of flow velocity compared to the underlying strata, and the sedimentation rate is similar the migration rate which can form current ripples that is more common in turbidity currents (Nichols, 1999).

**Hummocky stratified sandstone lithofacies (Sh)**

Lithofacies Sh consists of hummocky stratified, fine- to medium-grained, sub-angular to sub-rounded, poorly to moderate-sorted quartz arenite. In the Cleveland Shale Member, this lithofacies always overlies massive to normally graded sandstone (lithofacies Smg) and underlies planar laminated sandstone (lithofacies Sl) (Fig. 19C). Lithofacies Sh is hummocky stratified with a scoured base and sharp contact. It is consists of multiple sets of undulating laminations
which are organized into concave-up swales and convex-up hummocks (Fig. 20). The thickness of this lithofacies ranges from 0.6 cm to 32 cm.

In general, individual hummocky stratified sandstone beds are commonly found with planar laminated sandstone, ripple laminated sandstone, and mudstone (Boggs, 2001). With an multiple storm events, amalgamated hummocky stratified sandstone form (Fig, 20C), and in this case, these amalgamated units can be called “swaly stratification” (Leckie and Walker, 1982). Within these strata, planar laminated sandstone (lithofacies Sl) overlies the hummocky stratified sandstone (lithofacies Sh).

**Interpretation.** It has been well known that sandstone with scoured base, and convex- and concave-upward hummocky stratification represents high-energy events such as storms or hurricanes. If these sandstones are discontinuous, this probably represents a low sediment supply of sand and increasing sediment supply of silt. The scouring of sand and mud indicates erosion, and both convex- and concave-upward stratification with or without the presence of escape burrows indicate high rate of deposition due to settling after a high-energy event such as a storm (Harms et al., 1975). Hummocky stratified sandstone can be found everywhere in shallow depositional environments just above storm weather wave base (SWWB) (Walker and Plint, 1992). Greenwood and Sherman (1986), in their study of cores from modern shallow marine environments, found that storm deposits are best preserved between storm weather wave base (SWWB) and fair weather wave base (FWWB).

Amalgamated hummocky stratified sandstones typically have a coarsening- and thickening-upward trend. These multistory sandstones may have interbedded with discontinuous mudstones. Amalgamated hummocky stratified sandstone may have completed or partial
Figure 20. Photomicrograph and photograph of storm deposits. A) Photomicrograph showing hummocky stratification (lithofacies Sh) overlain by lithofacies Sl overlain by lithofacies Sr. B) Photomicrograph of thin section showing hummocky stratified sandstone C) Amalgamated hummocky stratified sandstone found on the middle part of the Huntington Beach outcrop. D) Photograph of a large hand sample, ~ 60 cm, showing hummocky and swaly stratified sandstone. E) Photograph of a large hand sample, ~ 50 cm, showing hummocky and swaly stratified sandstone.
preservation of individual tempestites. When erosion reworks on individual storm deposits, the upper parts of the lower tempestite can be reworked to create new hummocks (Fig. 19 D and E). In this case, the lower tempestite can be observed as incomplete sequence, and the upper tempestite may contain very fine sandstones due to high-power waves and tides (Walker and Plint, 1992). Consequently, amalgamated hummocky stratifications can be observed at or above the FWWB.

**Normally graded siltstone (lithofacies SSg)**

Lithofacies SSg consists of normally graded, fine- to medium-grained, poorly to moderate sorted, subangular to subrounded quartz siltstone. This lithofacies can appear to be massive in the field; however, examination in the binocular microscopes indicates these layers are normally graded, poorly sorted, siltstone (Fig. 21A and B). The lithofacies is mostly observed above massive siltstones (lithofacies SSm) and below planar laminated siltstone (lithofacies SSl) or siltstone-clayshale rhythmites (lithofacies SSCl). Sometimes this sequence lacks the massive siltstones, and in this case, the graded siltstones have erosional scoured surface and mudstone clasts at the base. Mostly the contacts are sharp, but gradual contacts are occasionally observed. The thickness of this lithofacies ranges from 0.8 cm to 2 cm.

**Interpretation.** There are different possible interpretations of normally graded siltstones. This lithofacies can be deposited from episodic, high-energy events including distal turbidite currents, storm events, or flood deposits (Nichols, 1999). In general, normally graded siltstones tend to form from fallout from suspension mechanisms, mostly as a result of waning flow.

Markello and Read (1981) interpreted normally graded sandstone and siltstone as a result of erosion and re-deposition processes during storm events. Thus, high-energy storm waves will
produce a scoured surface overlain by fallout from suspension (Bowen et al., 1974). The presence of normally graded siltstone (lithofacies SSg) overlying by planar laminated siltstone (SSI) can be interpreted as deposits of suspended depositions under waning storm-energy conditions (Hamblin and Walker, 1979). Alternatively, this lithofacies could be interpreted as a part of classical Bouma type (turbidites deposited) under low-density currents (Lowe, 1982; Soyinka and Slatt, 2008). Incorporated mudstone intraclasts can be interpreted as rip-up clasts that brought from the underlying strata during erosional events.

**Homogeneous massive siltstone (lithofacies SSM)**

Lithofacies SSm consists of massive fine- to medium-grained, poorly- to well sorted, subangular to subrounded, quartz siltstone. It is observed associated with the normally graded siltstone (lithofacies SSg) in different thicknesses ranging from 0.7 cm to 2 cm (Fig. 21A). The contact relationships of lithofacies SSm with the upper strata are mostly sharp but it can be gradual in some cases. This lithofacies often shows scoured surfaces at the base with tiny angular mudstone clasts. This lithofacies may contain minor amount of sand and clay, and they can be found in sufficient concentrations to make these beds poorly to moderate sorted.

**Interpretation.** Siltstones are known as deposits in the transitional environment in between the mudstone and sandstone environments. In massive siltstones, the lack of sedimentary structures and absence of bioturbation can make the interpretation more difficult. Boggs (2001) stated that silts can be transported weather by wind or water, and that massive siltstones are considered to be deposited by the lack of traction transport during fallout from suspension, or as a result of sediment dispersion from high concentrated gravity flows, or as
Figure 21. Photomicrograph of core samples and thin sections. A) Core sample showing interbedded of siltstones, lithofacies SSg overlain by lithofacies SSI overlain by lithofacies SSm representing two different events. B) Photomicrograph of normal graded siltstone (lithofacies SSg). C) Photomicrograph of homogeneous massive siltstone (lithofacies SSm).
rapid deposition from storm events, or flood deposits (Walker and Plint, 1992; Stow and Tabrez; 1998; Nakajima, 2006). Thus, these sediments may be interpreted as homogeneous materials with lack of subsequent reworking.

**Planar laminated siltstone (lithofacies SSl)**

Lithofacies SSl consists of planar laminated, very-fine to fine-grained, moderately- to well-sorted, subrounded, quartz siltstone. This lithofacies is observed associated with massive siltstone (lithofacies SSm), or the normally graded siltstone (lithofacies SSG) as a part of what are interpreted as flood deposit sequences (Fig. 21A). It is also observed overlying hummocky stratified sandstone (lithofacies Sh) and rippled laminated sandstone (lithofacies Sr) as the upper part of storm deposit sequences. The individual beds of this lithofacies are 0.3 cm to 1.0 cm when it is found within the sandstone intervals. The slight percentages of sands and clays in some cases make this lithofacies moderately sorted. Mostly, the contact relationships are sharp. When interbedded with mudrocks, the planar laminated siltstones are more poorly sorted, containing up to 10-20% of clays. Typically, there is organic matter which ranges from 1% to 3%. Planar laminated siltstone (lithofacies SSl) is often interbedded with siltstone-clayshale rhythmites (lithofacies SSCI). The mean thickness of this lithofacies is 11 cm (Fig. 22A). The interbedded package of lithofacies SSI and lithofacies SSCI often overlie bundles of flood deposits, and terminated upward when hummocky stratified sandstones occur. Lithofacies SSI are laterally continuous, and typically have the same thickness in the three sites. In thin section, microlamination consisting of interbedded discontinuous claystone that is 0.1-1 mm thick can be observed. These may appear as lenses in the upper part of each SSI.
Figure 22. **A**) Outcrop photograph of interbedded of planar laminated siltstone (lithofacies SSI) and rhythmites consisting of planar laminated siltstone and clayshales (lithofacies SSCl). **B**) Photomicrograph of rhythmites consisting planar laminated siltstone and clayshales (lithofacies SSCl). Note: the arrows indicate higher organic matter content.
Interpretation. Lamination in siltstones can be interpreted due to energy fluctuations such as current flow and slackwater in tidal settling (Boggs, 2001). Moreover, laminated siltstone can be found in lacustrine or tidal environments. It can also be found in lower energy environments due to settling of fine-grained sediments. The presence of the very fine-grained sandstone and clay in the siltstone lithofacies suggests an influx of sediments due to storm events or settling of particles from suspension as a part of storm deposit sequences. Lithofacies SSI is interpreted as deposits of oscillatory currents or during the waning phase of a storm (Walker and Plint, 1992). Alternatively, the different thicknesses of the siltstone laminae may suggest fluctuations of suspended loads (Lowe, 1988).

As a part of a flood deposit sequence, planar laminated siltstone can be interpreted as a pulsed fallout process from plumes, and the different thickness suggest fluctuations in velocity and concentrations of the flow discharge (Zavala et al., 2006; Zavala, 2008). The presence of laminated siltstone in thick mudstone assemblages can be interpreted as settling from suspension loads. Nakajima (2006) interpreted discontinuous, rhythmically bedded layers as a result of erosional pulses in continuous aggradation.

Siltstone-clayshale rhythmites (lithofacies SSCI)

Lithofacies SSCI consists of planar laminated siltstone-clayshale rhythmites. In the Cleveland Shale Member, lithofacies SSCI has a total thickness of 133.35 cm. Each interval of rhythmites has a mean thickness of about 19 cm. There are seven intervals of lithofacies SSCI at Huntington Beach. This lithofacies can be divided into a lower part that is interbedded with lithofacies SSI, which has a combined mean thickness of 33.26 cm (Fig 22A), and an upper part where lithofacies SSCI is found interbedded with flood deposit sequences, which has a combined
mean thickness of 8.39 cm. In addition, the thickness of lithofacies SSCl is variable laterally when it is interbedded with flood sequences (Fig 23A).

The laminated siltstone portion of the rhythmite couplet consists of 70-80% silt, with less than 10% of very fine-grained sand and about 10-20% clay (Fig 23B). The thickness of the siltstone laminae varies between 0.5 cm and 2.5 cm. The clayshale portion of the rhythmites couplet consists of 70% clay, with minor amount of silt (Fig 23C). The thickness of the clayshale laminae ranges from 0.2 cm to 4 cm. The contact surfaces between siltstone and clayshale are always gradational. Organic matter (plant debris) is found in some layers ranging between 1% to 2%. As the sand increased to 10%, the microstructures that have observed in this lithofacies changes to planar lamination or climbing ripple lamination.

**Interpretation.** Siltstone-claystone rhythmites probably formed in lower energy water environments. The fact the sequence is interbedded many times with event deposits (including storm deposits and flood deposits) suggests deposition in deep-water environments. However, the presence of storm deposits with hummocky stratification indicates the water depth was above SWWB. The microstructures that formed with increase sand percentages suggest deposition in fairly shallow water that has affected by multiple strong shoaling waves (Schieber, 1990). The presence of planar to sub-planar laminated siltstone-clayshale rhythmites can be interpreted as suspension load deposits. This process may occur as multiple pulses of floodwater discharge, which has high percentages of suspended load, disperse in the ambient water.

**Laminated mudshale (lithofacies MI)**

Lithofacies MI consists of planar laminated mudstone. It ranges in thickness from 0.2 cm to 0.5 cm and may contain thin interbeds of very fine-grained sandstone. This lithofacies is
Figure 23. A) Outcrop photograph showing siltstone-claystone rhythmites having a total thickness of about 5 cm. Note, the red arrows represent claystone and the black arrows show siltstone. B) Photomicrograph of siltstone composed of 80% silt, 15% of clay, 3% of organic matter, and 2% of voids. C) Photomicrograph of clayshale composed of 70% of clay, 20% silt, and 10% of organic matter.
associated with planar laminated siltstone (lithofacies Sl) interbedded as the last part of the flood deposit sequences (Fig 24). The fine-scale lamination in the mudshale lithofacies indicate minimal bioturbation (Fig. 24 D and E).

When interbedded in with mudrocks, this lithofacies is moderately- to well sorted, and the composition of this lithofacies is a mixture of about 40% fine-grained siltstone, 50% of claystone, and <10% fine-grained sandstone, which is typically observed at the base. Intervals of lithofacies Mi are separated by thin claystones with the same geometry, and found association with lithofacies SSl and lithofacies Cl (Fig. 24 A). This lithofacies is observed in the field as laterally continuous beds. However, there can be discontinuous, very thin planar laminated mudshales where the silt percentage is more than the clay percentage. The contact surfaces are always gradational. This lithofacies can be bioturbated, with burrows infilled by silt and mud (Fig. 24D). The thickness of this lithofacies varies from 0.2 cm to 24 cm, and the mean thickness is 10 cm.

Interpretation. The deposition of fine-grained sediment suggests low-energy environment. The planar lamination suggests that the deposition was due to settling process in low-energy regime. In similar study, Howard and Reineck (1979) described similar laminated mudstones and interpreted them as offshore deposits. The occasional thin sand lamina could result from the influx sediments due to storm events and settling of particles from suspension.

**Massive carbonaceous mudstone (lithofacies Mm)**

Lithofacies Mm consists of carbonaceous massive mudstones. This lithofacies is mostly found in the upper part of the Cleveland Shale Member. This lithofacies is found associated with laminated mudshale lithofacies (Mi) and siltstone-clayshale rhythmites (lithofacies SScI).
Figure 24. A) Photograph of core sample showing lithofacies Ml overlain by lithofacies Cl (the upper red arrow) and underlain by lithofacies SSI (the lower red arrow). B) Photograph of core sample showing lithofacies Ml overlain by lithofacies Cl (red arrow). C) Photomicrograph showing lithofacies Ml underlain by lithofacies Mm (red arrow). D) Photomicrograph of burrow from lithofacies Ml showing infill by very fine-grained sand and silt. E) Photomicrograph of burrow from lithofacies Ml showing infill from the same sediment (mud).
Mm has a total thickness of 58.80 cm and individual intervals of lithofacies Mm have an average thickness of 8.40 cm. The texture in this lithofacies is about 1-2% very fine-grained sandstone, 35% siltstone, 40-50% clayshale (Fig. 24C). This lithofacies is rich in organic matter, which can reach 15%. The color in the fresh samples ranges from very dark blue-gray changes to medium dark blue-gray.

The primary sedimentary structure that has been identified in this lithofacies is massive bedding. In some cases, lithofacies Mm includes normally graded siltstone lamina. In addition, thin siltstone beds can be observed at the base of the same beds, and these range in thickness from 0.1 cm to 0.5 cm. Moreover, some burrows have seen in thin sections, which were infilled by mud (Fig. 25F). Typical burrows are about 7 mm long and 2 mm wide, and are found on the upper surface of the massive carbonaceous mudstones. The contacts with other strata are mostly sharp. Massive mudstone can also be found as intraclasts in other lithofacies.

**Interpretation.** Mudstones, in general, form under calm hydraulic conditions where fine-grained siliciclastic particles are allowed to settle out from suspension. Often these particles form thin mud drapes over previous deposits. In addition, the massive nature of lithofacies Mm may suggest the deposition of homogeneous mud in low-energy regime. The observation of mudstone beds between flood deposits or between storm deposits may show alternating events of transport and deposition of sand and mud. The stratigraphic position of lithofacies Mm above planar laminated siltstone or sandstone may indicate river flood or storm events (Walker, 1992). In addition, massive mudstone can result from floccules breaking down due to compaction and lithification.
Figure 25. A) Photomicrograph of massive carbonaceous concretionary mudstone showing the outer part of a concretionary sample. B) Photomicrograph of lithofacies Mc showing lateral move out of water which assist concretion to grow laterally. C) Photomicrograph of lithofacies Mc showing the inner part consisting of silt cemented by dolomite. D) Bioturbation found in the concretionary mudstone. E) Photomicrograph of two field samples showing different sizes of concretions which deposited around fossils remains. F) Photomicrograph of burrow showing bioturbation found in lithofacies Mm.
Concretionary massive mudstone (lithofacies Mc)

Lithofacies Mc consists of massive mudstone with carbonate concretions (Fig. 25). This lithofacies has a total thickness of 26.50 cm, mostly in the upper part of the Cleveland Shale Member. The concretion layers are interbedded with planar laminated mudshale (lithofacies Ml) and planar laminated clayshale (lithofacies Cl). Lithofacies Mc has texture of <1% fine-grained sandstone, 3-10% very fine-grained sandstone, 35-40% siltstone, and 40-50% clayshale (Fig. 25B). There are about 1% heavy minerals and 2-3% rock fragments. Organic matter can be abundant (20%) comparing with all the previous lithofacies (Fig. 25D).

Lithofacies Mc can be divided into three parts, lower, middle, and upper, to discuss the sedimentary structures. The lower part, which is about 0.5 mm thick, is massive showing some percentage of burrows that were infilled by silt (Fig. 25C). The middle part, which does not have any silt, is massive and can have two different colors light-brown and dark brown probably due to Fe. Organic matter in this portion is about 1-2%. The contacts between these two colors are sharp and they occur as continuous vertical fingers. The upper part is mostly organic matter which can cover 80% of this portion. The percentage of this matter is gradually increased upward. This lithofacies is rich in burrows which can be observed as vertical and sub-vertical burrows (Fig. 25D).

Interpretation. Most of the geologists who have studied the Cleveland Shale Member are interested in this lithofacies because the carbonate concretions distinguish the Cleveland Shale Member from the overlying Bedford Shale, and the underlying Chagrin Shale Member or Huron Shale Member (Cushing et al., 1931; Nelson, 1955; Hoover, 1960; Coogan, 1996; Criss et al., 1988). They interpreted the concretions in the Cleveland Shale Member as complex deposits that formed around fossil remains during early diagenetic growth in shallow water environments (Fig
As a result of early cementation, these deposits have a high porosity. It can be also interpreted as condensed section suggesting very slow net of sediment through very long time (Glenn and Garrison, ). The present of bioturbation suggests oxygenated environment which suggested by many workers as the upper half of Appellation Basin was oxygenated. In this case, fossils remains may be deposited on the ocean floor and the settling materials deposited around the fossils resulting condensed sections (Barth, 1975).

**Planar laminated clayshale (lithofacies Cl)**

Lithofacies Cl consists of planar laminated greenish-blue clayshale that are moderated- to well-sorted. Intervals of lithofacies Cl ranges from 0.2 cm to 0.5 cm thick. It typically forms the top of the flood deposits associated with planar laminated mudstone (lithofacies Ml) or siltstone-clayshale rhythmites (lithofacies SSCl). However, this lithofacies can be absent in many cases. Planar lamination can be discontinuous if interrupted by mottled silts. The contact surface with lithofacies Ml is sharp and relatively flat. If present, the siltstone, which appears as mottled areas, is found in the lowermost part of each bed. The dark color of this lithofacies is due to high (20%) organic matter content.

When interbedded with mudrocks, the planar laminated clayshales are observed in the middle and upper parts of the Cleveland Shale Member. The total thickness of the lithofacies is about 226 cm, and they are interbedded with laminated mudshale (lithofacies MI), concretionary massive mudstone (lithofacies MC), and massive claystone (lithofacies CM) (Fig. 26). The texture of lithofacies Cl is observed about 60-80% claystone, 20% siltstone, and 2-3% sandstone (Fig. 26 D). Heavy minerals and rock fragments are rare, typically 1-2%. Organic matter can be 10-30% in this lithofacies, and is concentrated in certain layers at the top of this lithofacies.
Figure 26. A) Photomicrographs of a core sample (core 2720) showing interbedded laminated clayshale (lithofacies Cl) and massive claystone (lithofacies Cm). This sample shows bioturbations (yellow arrows). B) Photomicrograph of a core sample showing lithofacies Ml. C) Outcrop photograph showing massive claystone (lithofacies Cm) overlain by laminated clayshale (lithofacies Cl) interbedded with flood deposits (red arrows). D) Photomicrograph of the texture of lithofacies Cl. Note dark layers are rich in organic matter. E) Photomicrograph of the massive claystone (lithofacies Cm) showing high organic matter (dark blebs).
In thin section, very thin (~ 0.1 – 0.2 mm) siltstone microlaminations can be distinguished (Fig. 26D). These microlaminations are found only where laminated clayshale (lithofacies Cl) and laminated mudshales (lithofacies Ml) are interbedded. In the outcrop views and thin sections, this lithofacies did not show any bioturbation; however, a core sample shows burrows <0.5 mm in diameter (Fig 26A). Similar features can be found in the Upper Devonian Chattanooga Shale, which is stratigraphically equivalent to the Cleveland Shale Member (Lobza & Schieber, 1990).

**Interpretation.** The fine-grained sediment indicates quiet-water deposition. However, the planar lamination in this lithofacies is the result of sediment settling out from suspension load and falling to the basin surface suggested low-energy environment (Breyer, 1992). The present of laminated clayshale in the flood deposit sequence can be interpreted as classical vertical stack of hemipelagite or pelagite deposit, which is known as Division Te in the Bouma sequence (background sedimentation) (Bouma, 1962). Fine-grained sediments that are deposited under settling process may occur within flood deposits that have low-sediment concentration (Parsons et al., 2001; Bhattacharya and MacEachern, 2009). Flood and storm deposits can also produce distinct laminated claystones with a lack of bioturbation, indicating much deposition from settling of clay from suspension loads (MacEachern et al., 2005).

**Massive claystone lithofacies (Cm)**

Lithofacies Cm consists of massive claystones. Lithofacies Cm is interbedded with planar laminated claystone (lithofacies Cl), and planar laminated mudshale (lithofacies Ml). In addition, massive claystones (lithofacies Cm) forms individual horizons that range from 4 cm to 19 cm thick, and it has an average thickness of 11 cm. The greenish-gray color does not change much laterally or vertically. Texturally, this lithofacies consists of 70-80% clayshale, 1-5% siltstone,
and the rest is 10-15% organic matter (Fig. 26E). Organic matter can be concentrated in certain areas, and some of it is elongated in shape (Fig. 26E). Lithofacies Cm is laterally continuous when they interbedded with laminated mudshale (lithofacies Ml). This lithofacies is lack of any primary or secondary sedimentary structures (Fig. 23B).

**Interpretation.** It has been well known that most of claystone deposits are a result of settle out from suspension loads in quiet environments. In addition, the absence of lamination may indicate that the sedimentation rates are very slow and the deposits are extensively bioturbated (Breyer, 1992) or it may mean that the environment was poorly oxygenated (Ekdale and Bromley, 1984). Moreover, the massive character of lithofacies Mm may suggest the deposition of homogeneous mud in a low-energy regime.

**Lithofacies Association**

Environmental interpretations cannot be based on individual lithofacies because many lithofacies can be produced in different environments, such as planar laminated sandstone or massive sandstone (Boggs, 2001). To avoid misinterpretations, lithofacies associations will be used to better identify each specific depositional environment (Walker and Plint, 1992; Boggs, 2001). A lithofacies association is a group of facies which occur together and reflect a specific depositional environment. In the Cleveland Shale Member, the following lithofacies association have been found: turbidites, tempestites, hyperpycnites, green-gray mudrocks, green-gray siltstone-mudshale rhythmites, dark blue-gray mudrocks, and blue-gray mudshale-clayshale rhythmites.
Turbidite lithofacies association

Both outcrops and cores hand specimens show that a sequence of lithofacies found in the Cleveland Shale Member are turbidites: massive to normally graded sandstone (lithofacies Smg), planar laminated sandstone (lithofacies Sl), rippled laminated sandstone (lithofacies Sr), and planar laminated siltstone (lithofacies SSl). Turbidites are the deposits of turbidity currents, which are a type of density currents (Bouma, 1962; Boggs, 2001). Turbidite can be subdivided into the well-known Bouma Sequence, which consists of five divisions (Divisions A-E), and can be abbreviated as T_{abcde}. The deposits are found in different thickness ranges from centimeters to few decimeters. Vertically, this lithofacies association shows the transition from medium-grained sandstone to siltstone with different sedimentary structures such as massive bedding, normally grading, planar laminations, and ripple laminations. In addition, this lithofacies association may present rip-up clasts and scoured surface at the base (Fig. 27A and B).

Complete turbidites (T_{abcde}) are rare in the outcrops and well cores in the Cleveland Shale Member. Typically, the finer-grained, upper portions of the Bouma Sequence (T_{cde} and T_{de}) are present (Fig 27) (Table 7). The mean thickness of turbidites in the Cleveland Shale Member ranges from 10 cm at the Huntington Beach, to 17 cm at Bedford Metropark, to 16 cm at Brooklyn Heights Metropark. The thinnest turbidite that is found in this study is 4 cm thick while the thickest turbidite is observed in Bedford Metropark and Brooklyn Heights Metropark was 40 cm thick (Fig. 27D). Over all, the mean thickness of all of the observed turbidites in the Cleveland Shale Member turbidites is 12.6 cm.

Thickness vibration in turbidites may reflect the topography of the basin, energy of the event, or proximal-distal relationships. In some depositional settings, certain beds may reflect
Figure 27. A) Core photograph and interpretation sketch ($A'$) of Bouma Division A and B ($T_{ab}$) in sample 13-SH-103. B) Core photograph and interpretation ($B'$) of Bouma Division C and D ($T_{cd}$) in sample (13-Sh-104). C) Ideal Bouma Sequence of turbidite showing complete turbidite sequence (modified after Bouma 1962). D) Field photograph of turbidite showing complete turbidite sequence ($T_{abcd}$) at Bedford Metropark (Scale bar of the whole image ~ 70 cm thick).
Table 7. Summary of turbidite thicknesses from the three outcrops.

<table>
<thead>
<tr>
<th>Turbidite Unit #</th>
<th>Site 1 Thickness</th>
<th>Site 2 Thickness</th>
<th>Site 3 Thickness</th>
<th>Average</th>
<th>Bouma Divisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidite 1</td>
<td>Not found</td>
<td>13.0</td>
<td>16.14</td>
<td>14.57</td>
<td>T_{bc}</td>
</tr>
<tr>
<td>Turbidite 2</td>
<td>Not found</td>
<td>12.0</td>
<td>10</td>
<td>11.00</td>
<td>T_{de}</td>
</tr>
<tr>
<td>Turbidite 3</td>
<td>7.68</td>
<td>9.0</td>
<td>8.09</td>
<td>8.26</td>
<td>T_{de}</td>
</tr>
<tr>
<td>Turbidite 4</td>
<td>Not found</td>
<td>32.0</td>
<td>Not found</td>
<td>32.00</td>
<td>T_{bcde}</td>
</tr>
<tr>
<td>Turbidite 5</td>
<td>14.59</td>
<td>42.0</td>
<td>39.58</td>
<td>32.06</td>
<td>T_{abcd}</td>
</tr>
<tr>
<td>Turbidite 7</td>
<td>8.67</td>
<td>Not found</td>
<td>14.14</td>
<td>11.41</td>
<td>T_{cde}</td>
</tr>
<tr>
<td>Turbidite 8</td>
<td>Not found</td>
<td>13.0</td>
<td>9.22</td>
<td>11.11</td>
<td>T_{bed}</td>
</tr>
<tr>
<td>Turbidite 9</td>
<td>4.48</td>
<td>6.0</td>
<td>13.73</td>
<td>8.07</td>
<td>T_{cd}</td>
</tr>
<tr>
<td>Turbidite 10</td>
<td>15.22</td>
<td>11.0</td>
<td>4.61</td>
<td>10.28</td>
<td>T_{cde}</td>
</tr>
<tr>
<td>Average per site</td>
<td>10.13</td>
<td>17.25</td>
<td>14.44</td>
<td>14.5 = Total Average</td>
<td></td>
</tr>
</tbody>
</table>

Site 1 = Huntington Beach in Bay Village, Site 2 = Cleveland Metro Pkwy in Bedford Metropark, Site 3 = Brooklyn Heights Metropark.
Table 8. Summary of the turbidite lithofacies association in the Cleveland Shale Member.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies Lithology</th>
<th>Thickness</th>
<th>Sedimentary Structures</th>
<th>Bouma Division</th>
<th>Interpretations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smg</td>
<td>sandstone</td>
<td>0-25 cm</td>
<td>Massive, normal fining upgrading, load structures, sole marks rip-up clasts, erosional surfaces</td>
<td>$T_a$</td>
<td>Rapid settling from suspension of sandy low-density turbidity currents, powerful and turbulent flows (Bouma, 1962; Mutti and Ricci Lucchi, 1972; Lowe, 1982)</td>
</tr>
<tr>
<td>Sl</td>
<td>sandstone</td>
<td>0-12 cm</td>
<td>Planar laminated with discontinuous silty laminae</td>
<td>$T_b$</td>
<td>Rapid mass deposition to traction movement in low-density turbidity currents (Bouma, 1962; Stow, 1977, 1984; Paola et al., 1989)</td>
</tr>
<tr>
<td>Sr</td>
<td>sandstone</td>
<td>0-3 cm</td>
<td>Ripple to climbing ripple lamination</td>
<td>$T_c$</td>
<td>Traction movement with fallout processes from waning turbidity currents (Bouma, 1962; Stow, 1977, 1984; Mulder and Alexander, 2001)</td>
</tr>
<tr>
<td>SSl</td>
<td>siltstone</td>
<td>0-2 cm</td>
<td>Planar lamination</td>
<td>$T_d$</td>
<td>Deposition from suspension processes during weak turbulent motion in low-density turbidity currents (Bouma 1962; Stow and Dean, 1984)</td>
</tr>
</tbody>
</table>
high-discharge events, and as a result, the thickness of individual bed may reflect the magnitude of the event (Sinclair and Cowie, 2003). Thin-bedded turbidites are common in the Cleveland Shale Member and are interpreted as distal turbidites (combination of $T_{cd}$ and $T_{de}$) (Table 7). Distal turbidite deposits are often with distal tempestites. The examined samples show that they were probably deposited below mean fair weather wave base (FWWB). The environment was oxic, as burrows can be found and the oxygen can be inferred by the presence of the turbidity current (Potter et al., 1982; Grimm & Follmi, 1994). Table 8 shows the occurrence of turbidite lithofacies that are observed in the Cleveland Shale Member and their interpretations.

**Tempestite lithofacies association**

The idealized sequence of a tempestite consists of massive to normally graded sandstone (lithofacies Sg) with scoured base, overlain by hummocky stratified sandstone (lithofacies Sh), overlain by planar laminated sandstone (lithofacies Sl), overlain by ripple laminated sandstone (lithofacies Sr), and ending with pelagic or hemipelagic massive or laminated mudstone (lithofacies Mm or lithofacies Ml) (Fig. 28C). The idealized sequence may not be completely preserved due to erosion or bioturbation (Walker and Plint 1992; Einsele, 2000). It has been shown that tempestites represent storm events (Ager, 1974). From outcrop and core samples, a sequence of four lithofacies was recognized as tempestite in the Cleveland Shale Member: 1) massive to normal graded sandstone (lithofacies Smg), hummocky stratified sandstones (lithofacies Sh), planar laminated sandstone (lithofacies Sl), and ripple laminated sandstone (lithofacies Sr). Figure 28 A shows a core sample (left side) with an interpretative drawing A’ (right side) to show clearly the lithofacies and the sedimentary structures found in a typical tempestite in the Cleveland Shale Member.
Figure 28. A) Core photograph from and interpretative sketch (A’) from sample 13-SH-107 showing the complete sequence of beds in a tempestite (storm deposits). B) Idealized tempestite sequence (modified after Dott and Bourgeois, 1982). C) Outcrop photograph showing amalgamated tempestite at Huntington Beach (scale of whole image ~1 m thick). D) Outcrop photograph showing thick (~32 cm) tempestite found at Bedford Metropark (scale of whole image ~1.5 m thick).
Tempestites in the Cleveland Shale Member have a mean thickness of 11 cm at the Huntington Beach, 13 cm at the Bedford Metropark, and 15 cm at the Brooklyn Heights Metropark. These tempestites are mostly thin-bedded sandstones (4-21 cm); however, like situations with turbidites, thick tempestites (40 cm and 30 cm thick) were observed at both Brooklyn Heights and Bedford Metroparks (Fig. 28 E and F). In the cores, tempestites were observed in all the 5 cores, and the mean thickness is ~ 5 cm.

Hummocky stratification is an indicator of high-energy waves in shallow water environments (Einsele, 2000). The shape of deposits (hummocks and swales) shows the original depositional geometry that was preserved. The thicknesses of the tempestites decrease distally as sediment supply decreases offshore. The intraclasts that are found at the base of the tempestites indicate erosion of the pre-storm substrate (Fig 28A). Many of these sandstone units contain trace fossils representing the Skolithos ichnofacies.

Amalgamated tempestites consist of two or more superimposed tempestites. In the Cleveland Shale Member, these occur in several places where two tempestites are separated by very thin massive mudstones. These amalgamated tempestites are found in the upper part of the Cleveland Shale Member with a mean thickness of 12 cm (Fig 28). The presence of amalgamated hummocky stratification indicates a storm-dominated offshore transition environment. High-energy offshore transitions environments can be recognized by thick and/or amalgamation of tempestite sequences (swaly stratification) which can be interbedded with thin silty mudstone beds (McCubbin 1982, Walker and Plint 1992).
Table 9. Summary of the tempestite lithofacies association in the Cleveland Shale Member.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies Lithology</th>
<th>Thickness</th>
<th>Sedimentary Structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sg</td>
<td>Sandstone</td>
<td>1-9 cm</td>
<td>Normal upgrading sandstone siltstone with erosional surface at the base and sole marks, groove casts</td>
<td>Fallout from suspension as a production of waning flow, storm events (Ager, 1974; Brenner and Davies, 1973)</td>
</tr>
<tr>
<td>Sh</td>
<td>Sandstone</td>
<td>7-15 cm</td>
<td>Hummocky stratification (convex-upward)</td>
<td>Storm deposits are effected by the combination of oscillatory and unidirectional flows. (Ager, 1974; Harms et al., 1975)</td>
</tr>
<tr>
<td>Sl</td>
<td>Sandstone</td>
<td>2-5 cm</td>
<td>Parallel lamination</td>
<td>As a part of tempestite, it is depositions by oscillatory currents or from waning storm (Walker and Plint, 1992)</td>
</tr>
<tr>
<td>Sr</td>
<td>Sandstone</td>
<td>1-2 cm</td>
<td>Low-angle cross lamination and with ripple mark at the top</td>
<td>As a part of storm deposits, unidirectional migration of small dunes and ripples (Friedman et al, 1992; Walker and Plint, 1992)</td>
</tr>
</tbody>
</table>
Over all, sequences and structures indicate that deposition occurred on a clastic marine shelf at water depths above storm weather wave base (SWWB). Because the typical tempestite in the Cleveland Shale Member is thin and typically an incomplete sequence, the deposits can be interpreted as distal tempestites. However, the local occurrence of thick amalgamated tempestites may reflect proximal tempestites were deposited close by.

**Hyperpycnite (Flood deposits) lithofacies association,**

When flood waters flow into oceans or lakes, the density contrast between the effluent and ambient waters can initiate hypopycnites or hyperpycnites. The idealized sequence of the hyperpycnites are still being debated, because there are different deposits formed, based on the variable factors such as sediment concentration, flow energy, basin topography, and density contrasts (Mulder et al., 2003; Soyinka and Slatt, 2008; Bhattacharya and MacEachern, 2009).

In the Cleveland Shale Member, hyperpycnites are recognized from an association of six lithofacies. That are not necessarily present in all instances, for instance, as some have only four lithofacies while others have three lithofacies (Fig 29). In ascending order, the lithofacies are: massive to normally graded sandstone (lithofacies Smg), overlain by planar laminated sandstone (lithofacies Sl) overlain by rippled laminated sandstone (lithofacies Sr), overlain by planar laminated siltstone (lithofacies SSl), overlain by siltstone and claystone rhythmites (lithofacies SSCI), and/or covered by planar laminated clayshale (lithofacies Ml) (Table 13). Lithofacies Smg is observed in all the samples, while it is overlain by either lithofacies Sl or lithofacies SSl. If lithofacies Sl occurs, it is overlain by ripple laminated sandstone (lithofacies Sr) and then planar laminated mudstone (lithofacies Ml). Otherwise, lithofacies SSl is overlain by siltstone-
Figure 29. A) Photomicrograph of core sample and interpretative sketch (A’) from 13-SH-105 showing four lithofacies: massive sandstone (lithofacies Sg) with erosional base and rip-up clasts, overlain by normal grading sandstone (lithofacies Sg), overlain by laminated siltstone/mudstone rhythmites (lithofacies SSCl), and copped by planar laminated claystone (lithofacies Cl). B) Outcrop photograph showing hyperpynmites at Bedford Metropark (scale of whole image ~3 m thick). C) Outcrop photograph showing hyperpynmites at Huntington Beach.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies Lithology</th>
<th>Thickness</th>
<th>Sedimentary Structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smg</td>
<td>sandstone</td>
<td>2-12 mm</td>
<td>Massive to normally grading with erosional surface at the base and rip-up intraclasts</td>
<td>Rapid settling from suspension of sandy low-density hyperpycnal currents (Bouma, 1962; Mutti &amp; Ricci Lucchi, 1972; Lowe, 1982)</td>
</tr>
<tr>
<td>Sl</td>
<td>Sandstone</td>
<td>1-7 mm</td>
<td>Planar lamination</td>
<td>Rapid deposition to traction movement in low-density turbidity currents (Bouma, 1962; Stow, 1977, 1984; Paola et al., 1989)</td>
</tr>
<tr>
<td>Sr</td>
<td>Sandstone</td>
<td>1-2 mm</td>
<td>Asymmetrical and symmetrical rippled lamination</td>
<td>Traction movement with fallout processes from waning hyperpycnal currents (Bouma, 1962; Stow, 1977, 1984, Mulder and Alexander, 2001)</td>
</tr>
<tr>
<td>SSI</td>
<td>Siltstone</td>
<td>0.5-3 mm</td>
<td>Planar lamination</td>
<td>Deposition from suspension processes during weak turbulent motion in low-density hyperpycnal currents (Bouma 1962; Stow &amp; Dean, 1984)</td>
</tr>
<tr>
<td>SSCl</td>
<td>Siltstone-claystone rhythmites</td>
<td>0.5-3 mm</td>
<td>Rhythmites</td>
<td>Deposition from high concentrated flow census (Bouma, 1962; Mulder and Alexander, 2001)</td>
</tr>
<tr>
<td>Cl</td>
<td>Clayshale</td>
<td>0.5-2 mm</td>
<td>Planar lamination</td>
<td>Deposition of high suspension settling sediment (Stow and Bowen, 1978; Bourget et al., 2010)</td>
</tr>
</tbody>
</table>
claystone rhythmites (lithofacies SSCI) or by planar laminated clayshale (lithofacies Cl) (Fig. 29). At the top, most of the samples show laminated clayshale at the top of the sequence. This lithofacies association is probably deposited below the mean storm weather wave base (SWWB).

The contact surfaces with the other lithofacies are sharp. Massive sandstones have been observed below the normal graded sandstone. At the top of the massive deposits, a planar and cross-laminations of poorly mixed sandstone can be found. Then, the siltstone and clayshale rhythmic lithofacies is associated with planar laminated sandstone or siltstone. A top of that, planar laminated clayshales are observed, and these clayshales can have plant fragment, which can be seen as a line at the top of the silt. The upper surface can show preferred grain orientation, but this is rare at the bottom of the hyperpycnites. Hyperpycnites are found 24 times in different thickness, but the average is 1.74 cm. Most of the hyperpycnites occur in lower and upper parts of the Cleveland Shale Member.

The diagnostic features that indicate these deposits are hyperpycnites and not turbidite are the following: constant thicknesses of all the hyperpycnites, land (continental) fragments, consisting of siltstone-clayshale rhythmites. The occurrence of very fine- to fine-grained sandstone indicates a distal environment. Nakajima (2006) characterized the distal deposits by relatively simple upward fine-grained deposits. He noticed that since the flows tend to migrate to the head of the current because of high velocity of the flows.

**Green-gray mudrock lithofacies association**

The green-gray mudrock lithofacies association is observed in the lower part of the Cleveland Shale Member. From outcrop and core samples, this lithofacies association consists of a sequence of three lithofacies: light green-gray planar laminated siltstone (lithofacies SSI),
Figure 30. A) Outcrop photograph showing interbedded of planar laminated siltstone (lithofacies SSI) overlain by massive claystone (lithofacies Cm), overlain by planar laminated clayshale. B) Photomicrograph of lithofacies SSI showing planar laminated siltstone having very thin laminae (0.1 mm) clayshale (Cl). C) Photomicrograph of lithofacies Cl showing planar lamination having high organic and low organic laminae. D) Photomicrograph of lithofacies Cm showing massive claystone with very low percentage of silt (<10%). E) Photomicrograph of lithofacies Cm having high percentage of blebs of organic matter.
overlain by dark green-gray massive claystone (lithofacies Cm), and ending with medium green-gray planar laminated clayshale (lithofacies Cl) (Fig. 30). The mean thickness of this lithofacies association is 51 cm. This lithofacies association is often interbedded with the hyperpycnites.

This lithofacies association is distinguished by thick claystone, which represent about 60% of the unit. Where there is interbedded planar laminated siltstone (lithofacies SSI), this lithofacies shows normal grading. The massive claystone consists a high percentage of organic matter (Fig 30 E).

One common idea about fine-grained sediments is that most mudstones are deposited in quiet environments. However, the coexistence of sandstone tempestite intervals suggests that paleo-water depth was about SWWB. The percentage of event horizons increases upward in this lithofacies association, indicating either increasing energy or shallowing paleowater depth. Aside from the sandy event layers, however, the ratio of clay to silt increases upward. The interbedded hyperpycnites may have provided very fine-grained sands to this lower-energy environment, as well as explain the presence of muddy rip-up intraclasts at the base of certain event layers.

Planar laminated, fine-grained deposits typically form from suspension fallout, and the thicknesses of the lamination represents the time and the rate of deposition (Bouma, 1962; Stow, 1984; Mulder and Alexander, 2001). In addition, the dark color of the mudrocks in this lithofacies association indicate more organic matter, while the light color in the lithofacies SSI suggest more quartz silts (Fig. 28B). The presence of burrows shows that bottom water were oxic. Lithofacies Cm is massive which indicates rapid deposition in short time. Over all, the green-gray mudrocks lithofacies association is a result of normal pelagic sedimentation interrupted by episodes of hyperpycnite deposition.
implying pulses of water entering the lake with high-discharge fine-grained sediments. The burrows that are observed in the massive claystone may destroy the lamination. These phenomena explain that the environment was volatile at or slightly above the storm weather wave base (SWWB).

**Green-gray siltstone-mudshale rhythmites lithofacies association**

The bluish-gray siltstone-mudshale rhythmites lithofacies association is mostly occurs in the middle and upper parts of the Cleveland Shale Member. It consists of light green-gray planar laminated siltstone (lithofacies SSl) and dark green-gray planar laminated mudshale (Lithofacies Ml) (Fig 31). The average thickness of each unit of this lithofacies association is 19 cm, but the mean thickness of each silt-mud couplet is 1.5 cm. Moreover, the thickness of each silt/mud couplet decreases upward. This lithofacies association was described early by Lewis (1988) and showing that this lithofacies association may comprise most of the upper part of the Cleveland Shale Member. In addition, this lithofacies association is not interbedded with event deposits.

This lithofacies association is initiated above a bundle of flood deposits and ended with the occurrence of hummocky stratification. The color of lithofacies SSl is constant, but the dark green-gray color of lithofacies Ml changes slightly from dark green-gray at the base to medium green-gray at the top, representing either increase of silt percent or decrease of organic matter. The contact relationships between the two lithofacies are mainly sharp, but in some instances it can be hard to distinguish the contact at the last silt/mud couplet.
Figure 31. A) Outcrop photograph of lithofacies association showing rhythms consisting of planar laminated siltstone and planar laminated mudshale. Yellow lines represent one unit of rhythms. B) Core photograph showing three cycles of lithofacies association. Note: each number represents one cycle (silt-mud couplet).
This lithofacies association is interpreted as high tidal deposits that. It can understood that the increase of silt upward and changed of color may represent the power of tides. They both planar laminated siltstone (lithofacies SSl) and planar laminated mudshale (lithofacies Ml) are the results of fallout of suspension in deep-water environment. The density contrast of particles may allow silts to be deposited before the low-density clay particles. The mud deposits is interpreted as background sediments while the silt deposits are provide by tides from rivers indicating high-energy environment. The presence of silt/mud couplet following by tempestites at the top suggests that the paleo-water depth was at FWWB.

**Dark blue-gray mudrock lithofacies association**

The dark blue-gray mudrock lithofacies association is found at the middle and upper parts of the Cleveland Shale Member. This lithofacies association is consists of medium blue-gray planar laminated mudshales (lithofacies Ml), overlain by concretionary massive mudstone (lithofacies Mc), and ending with dark blue-gray planar laminated clayshales (lithofacies Cl). The average thickness of this lithofacies association is 52 cm thick. Vertically, the thickness of each mud/mud/clay triplet is increased from a thickness of 42 cm at the base to 79 cm at the top.

This lithofacies association can be easily distinguished in two aspects. First, it has concretionary massive mudstone, and it is ending by thick planar laminated clayshale (lithofacies Cl). The contact relationship between lithofacies Ml and the underlying strata is always sharp. Also, the contacts between lithofacies Ml, Mc, and Cl are sharp due to unconformity deposits. Moreover, the change of color from medium blue at the base to dark blue at the top is due to the decrease of the silt percentage upward and increase of organic matter. This lithofacies association can be characterized as condensed sections present between two sandy event
Figure 32. Outcrop photograph showing lithofacies association MMC represented planar laminated mudshale (lithofacies MI), overlain by massive concretionary carbonaceous mudstone, and copping by laminated clayshale (lithofacies CI).
deposits. Each unit is observed between turbidite-hyperpycnite, tempestite-tempestite, or hyperpycnite-hyperpycnite. Bioturbation are also recognized in this lithofacies association, which can be vertical and horizontal.

Based on the interpretation of the concretionary massive mudstone by many geologists, the interpretation of this lithofacies association is that the mudshale deposits are the background deposits indicating low-energy environment, then the carbonate concretionary mudstone are deposits falling out from suspension around fossils remains represent very low rate of sediment during long time. After that, the rests of suspended particles of silt and clay are deposit (Stow, 1984; Mulder and Alexander, 2001). The coexistences of event deposits below and above each mud/mud/clay triplet suggest deep-water environment. However, the occurrence of amalgamated tempestite underlying this lithofacies association suggests offshore transition.

Blue-gray mudshale-clayshale rhythmites lithofacies association

The mudshale-clayshale rhythmites are only observed in the uppermost part of the Cleveland Shale Member. This lithofacies association consists of medium blue-gray planar laminated mudshale (lithofacies Ml) and dark blue-gray planar laminated clayshale (lithofacies Cl) (Fig. 33). The average thickness of these rhythmites is 23 cm. These rhythmites are interbedded with hyperpycnites and turbidites. Moreover, the color of lithofacies Ml changes upward from medium blue-gray to light blue-gray. The contact relationships are mostly sharp, but gradual contacts are also observed. This lithofacies association typically consists of event deposits, followed by thin laminated mudshale, which is 5 cm thick, overlain by thick laminated clayshale, which is 18 cm thick.
Figure 33. Outcrop photograph at Huntington Beach of lithofacies association CM showing rhythms consisting of planar laminated mudshale (lithofacies MI) and planar laminated clayshale (lithofacies CI). Note: The two mudshale/clayshale rhythms are separated by thin (~1 cm) hyperpycnite.
Because planar laminated clayshale is abundant of organic matter, this lithofacies association is observed darker than the other associations (Fig. 33).

This lithofacies association is similar to the dark blue-gray mudrock lithofacies association. The only difference is the absence of condensed section. This lithofacies association is interpreted as a result of fallout from suspension in low-energy environment. The present in mudshale and clayshale, which have the same color, suggests background deposits. The hyperpycnal and turbidity intervals may provide more suspensions. Thus, fine-grained planar laminated mudshale and clayshale are a result of fallout from suspensions (Bouma, 1962; Stow, 1984; Mulder and Alexander, 2001). In addition, the dark color of this lithofacies may represent more organic matter in lithofacies Cl.

**Stratigraphy**

**Outcrop Analysis**

**Huntington Metropark.** The stratigraphic section at Bay Village is 17 m thick and extends laterally 330 m (Fig. 34). At this location, the Cleveland Shale Member has a thickness of about 13.3 m and is overlain by the Bedford Shale (Fig. 37). This outcrop is composed of sandstones, siltstones, mudstones, and claystones. Most of the field analysis was taken from this outcrop because it is less rugged and easy to obtain weathered and fresh samples rather than the other two outcrops. Dividing this outcrop to three parts, the thickness of the mudrock units thins upward until the middle of the outcrop and then thickens upward. The average thickness of the mudrock units in the lower part is about 13 cm while it is about 9 cm at the middle part, and about 18 cm in the upper part of the Cleveland Shale Member. The sand percentage within the mudrock units is calculated to be about 2.5%.
Figure 34. A) Photographic of the Cleveland Shale Member at the Huntington Beach, Bay Village, West of the city of Cleveland showing a total thickness of 13.3 m. Note: green arrows represent hyperpycnites, red arrows represent tempestite, and red arrows represent turbidites. B) Photographic of the Cleveland Shale Member showing the outcrop extends ~ 13.3 m vertically and 300 m laterally.
Figure 35. Stratigraphic section of the outcrop at Huntington Beach. The total thickness of Huntington Beach is 13.30 m.
Cleveland Metro Pkwy in Bedford. This site is located southeast of the first site and the city of Cleveland. Corbett and Manner (1987) described the contacts of the Cleveland Shale Member with the overlying and underlying members. This site was chosen to identify the contacts and to compare the lithofacies. This outcrop has one of the best contact between the Chagrin Shale Member and the Cleveland Shale Member. At this location, the contact is exposed laterally for 500 m. The Cleveland Shale Member is about 16 m thick (Fig. 36). Therefore, this area has the same lithology as described at Huntington Park with some fundamental differences. This site is rugged and requires working with different tools to get fresh samples.

There is an increase in the number of sandstone intervals comparing to Huntington Beach. More than 30 hyperpycnite sandstones can be observed (Fig. 29 B). Some of them are very high that they cannot be reached, but they are recognized using digital binoculars. Also, the thickness of turbidites on the cliff increased at this site, including one bed ~ 40 cm thick containing Divisions A, B, C, and D (T_{abcd}) (Fig. 36). In addition, two tempestites are recognized with thicknesses of ~ 30 cm. Finally, mudrocks have higher the silt percentages than which is observed at Huntington Park.

Brooklyn Heights Village Metropark. The stratigraphic section at West Creek, a tributary of the Cuyahoga River in Brooklyn Heights Village Park, is 15 m thick and extends laterally for 450 m (Fig. 37). This site was visited as a part of an AAPG field trip in September 2012. Turbidites and tempestites have the similar thicknesses at this site as at the Bedford Park outcrop. However, the thickness and frequency of the hyperpycnites are decreased. This site has the best contact surface between Chagrín Shale Member and the Cleveland Shale Member (Fig. 36). Finally, at some location, large pyrite nodules were observed at the contact these two members.
Figure 36. A) Outcrop photograph of the Cleveland Shale Member at Bedford Metropark, southeast of the city of Cleveland. The thickness of this outcrop is ~ 16 m. The Turbidites are extended to more than 40 cm. Note: labels on the right side represent event-dominated deposits. B) Outcrop photograph of the Cleveland Shale Member at Bedford Metropark showing interbedded of tempestite, turbidite, and amalgamated tempestite. (Scale of whole image ~ 4 m).
Figure 37. A) Outcrop photograph and of the Cleveland Shale Member at Brooklyn Heights Metropark, southeast of the city of Cleveland. A’) Outcrop photograph showing interpretative image of A showing the contact between the Cleveland Shale Member and Chagrin Shale Member overlain by siltstone mudrocks lithofacies association.
Well Core Analysis

Five well cores were examined at the Ohio Department of Natural Resources, in the Horace R. Collins Core Laboratory (HRCL), in Columbus. These five cores were chosen based on core recovery and distribution across northeast Ohio. The lithofacies codes that used in in this analysis are the same as used in the previous analysis. The thickness, lithology, and the geophysical logs of the Cleveland Shale Member in these five cores can be found in Appendix C.

Core 2720. This core is located in Ashtabula County, extends from the surface to 109 ft (33.2 m) depth. In this core, the Cleveland Shale Member extends for ~ 6.7 m, (22 ft) m and shows most of the features that found in the Bay Village outcrop, Huntington Beach (Fig. 40). The distance between this core and the Huntington Beach outcrop is about 60 mi (97 km). Some burrows that were infilled by clays can be observed in this core, which is really hard to find in outcrops.

Core 2721. This core is located just couple hundred meters southeast of core 2720. The core has the same length of core 2720. However, the Cleveland Shale Member is extended for about 3.3 m (11 ft). The geological features that are described in core 2720 are observed in this core. Burrows infilled by siltstone are also in this core. These burrows are lens or elongated in shape. In addition, plant debris is also observed in this core.

Core 2739. This core is located east of I-80/90, between the cities of Huron and Vermilion. It extends from ~ 24 m (80 ft) to 164 m (540 ft) depth. The thickness of the Cleveland Shale Member is about 14.8 m (40 ft). Appendix B shows a summary of the event layers that can be observed in this core. Compared to the Huntington Beach outcrop, the number of event deposits is decreased suggesting change from proximal to distal environments.
Core 2754. This core is located in Huron County, just few kilometers northeast of the city of Willard. It extends from ~ 10.7 m (35 ft) to ~ 76 m (249 ft) depth. The thickness of the Cleveland Shale Member 12.2 m (40 ft). The numbers of event deposits are slightly different than core 2739 that only few sandstone intervals are missing. As this core is just 40 km south of core 2739, decrease in event layers may suggest that the topography may play an important role of sediment distribution.

Core 2763. This core is located in the middle of Lorain County, just between the I-80/90 and the city of Amherst. This thickness of this core is ~ 162.5 m (533.1 ft). The thickness of the Cleveland Shale Member is 19.5m (64 ft). This core is the closest core to the outcrop at Huntington Beach. Most of the geological features that have found in core 2739 are identified in this core (Appendix B).

Outcrop Correlation

For this study, event layers can be used to make correlation between the three outcrops. The lower parts of the three sites are dominated by individual tempestites and hyperpycnites, but it can be hard to make correlation based on hyperpycnites because they are very thin (mean thickness is 1.73 cm). The middle part is dominated by turbidites, individual tempestites, and amalgamated tempestites. In addition, the upper parts of the three outcrops are also dominated by turbidites. Therefore, the middle and upper parts can be correlated to each other based on tempestite-dominated and turbidite-dominated (Fig. 38).

The lower part in the three sites is dominated by two individual tempestites. The thickness of the lower tempestite is the same in the three locations, but the upper tempestite decreased from 14 at Bedford Metropark to 9 cm at Huntington Beach (Fig. 38). The mudrock
Figure 38. Outcrop correlation from the three sits based on tempestite-dominated (mellow yellow) and turbidite-dominated (brown).
units between these tempestites are different that the Brooklyn Metropark has only mud shale and siltstone while the other sites have also clayshale.

The middle parts of the three locations are observed in three zones. The first zone is tempestite-dominated, the second zone is turbidite-dominated, and the third zone is tempestite amalgamated-dominated. The thickness of the tempestites in the first zone is the same in the lower tempestite, but the thickness of the upper tempestite changes from 5 cm at Huntington Beach to 12 cm at Brooklyn Metropark to 19 cm at Bedford Metropark (Fig 38). The number of hyperpycnites also changes from 2 hyperpycnites at Huntington Beach to 4 hyperpycnites at Bedford Beach. The second zone is dominated by turbidites, which are found in three locations. The thickness of this lower turbidite changes from 14 cm at Huntington Beach to 31 cm at Brooklyn Metropark to 40 cm at Bedford Metropark while the upper turbidite is stable. The third zone is dominated by individual tempestites and amalgamated tempestites. The two amalgamated tempestites are observed in the three locations. However, between these amalgamated tempestites, Huntington Beach has only one individual tempestite while the other two locations have three individual tempestites. The thickness of the low amalgamated tempestite has the same thickness while the thickness of the upper amalgamated tempestite changes from 17 cm at Huntington Beach to 32 cm at Brooklyn Metropark to 41 cm at Bedford Metropark.

The upper part is dominated by turbidites. Two turbidites are observed separated by mud-clay rhythms. The thickness of the lower turbidite changes from 8 cm at Huntington Beach to 13 cm at Brooklyn Metropark to 14 cm at Bedford Metropark (Fig. 38). The upper turbidite changes from 5 cm thick at Huntington Beach to 13 cm at Brooklyn Metropark to 17 cm at Bedford Metropark. Rhythmite thickness between these turbidites changes from 26 cm at Huntington Beach to 41 at Brooklyn Metropark to 51 cm at Bedford Metropark.
Subsurface Analysis

Geophysical log analysis

In this study, because the three outcrops are in Cuyahoga County, the nearest core to the outcrops (core 2763) will be used for comparison to the lithologic changes observed. The GR and density logs were used to identifying the lithology in core 2763. Then the GR log from core 2763 was used to correlate with cores, 2754 and 2739, which are located further west. Finally, the core logs was used to correlate to the stratigraphy column at Huntington Beach. One problem with this approach is matching the thin sandstone intervals seen in outcrop and core to the Gamma-ray log. To solve this, intervals of thin sandstones were matching to intervals of low GR values. In summary, low GR values are interpreted as sandstones while high gamma-ray values are interpreted as mudrocks. In addition, high-density values are interpreted as mudrocks, and low values are interpreted as high porosity sandstones.

Log shape analysis

This method is used to better identifying subsurface analysis and interpret textural trends, in the sequence of the logs. This issue may provide insights of facies assemblages and allow for better depositional environment interpretations. The log pattern in core 2763 is divided into seven sections from the bottom of the Cleveland Shale Member to the top (Fig. 39). The section between 132 ft to 126 ft presents a cylindrical shaped pattern. The GR log response varies between 30 to 70 APT units shows no uniform response. Between 126 ft to 110 ft presents an irregular shaped GR log pattern indicating mixing of shale and sandstone intervals. The GR log response fluctuates between 30 and 90 API units. In the section between 110 ft to 100 ft, the GR log pattern is funnel. Overall, the GR response drops from 90 API units at the base to 45 API
Figure 39. Attempt to correlate the core from 2763 to the geophysical logs from the same well.

Yellow color represents low GR values (sand) while gray color represents high GR values (shale). The sand units are highlighted (mellow yellow) based on the low gamma ray with each group of event deposits. Key to symbols, C = Cylindrical, I = Irregular, F = Funnel, B = Bell, S = symmetrical.
units at the top indicating a fining upward trend. The section between 100 ft to 74 ft shows another an irregular shaped GR log pattern. The Gr log response fluctuates between 35 and 70 API units. Between 74 ft to 70 ft, the GR log shows a bell shaped pattern because the GR values increases from 35 to 60 API units suggesting coursing upward trend. The section between 70 ft to 62 ft is symmetrical shaped pattern that the GR response decreases from 60 API to 30 API units before it increases back to 60 API units. Finally, the section between 62 ft to 57 ft shows another funnel shaped pattern. The GR response changes from 60 API units at the bottom to 40 API units at the top indicating fining upward pattern.

**Subsurface correlations**

For this study, the geophysical logs were used from three wells: 2739, 2754, and 2763. These wells are speed approximately 15 km apart. Correlation were used based on the gamma-ray logs from the three cores using pattern matching technique, based on log shapes allowing for variations in lithology, thickness, and completeness of section (Fig. 40). Because the sandstone is rich in feldspar and mica, the low values are interpreted as sandstones, while the high values can be high organic mudstone.

This study uses the gamma ray log as the basis for interpreting the log patterns in the three Wells, and they are correlated with the stratigraphic section from the Huntington Beach outcrop. The sandstone intervals are very thin that the low gamma ray values cannot be matched with each interval. Instead of that, each package of the adjacent sandstone intervals can be matched with the low gamma ray values that are very close to each other. In addition, log shapes as discussed above were used to match the cores to each other. In general, well logs from the three well cores show good patterns.
Figure 40. Gamma ray logs and the Huntington Beach outcrop correlation. Yellow color in GR represents low GR values (sand) while gray color represents high GR values (shale). The sand units are highlighted (mellow yellow) based on the low gamma ray with each group of event deposits.
The section of the GR between 132 m to 126 m in the log is correlated with the first two meters in the Huntington Beach outcrop (Fig. 39). Well cores 2763 and 2754 are well matching with this section. The coexistence of many hyperpycnites, which is rich in sandstones that are cemented by clay minerals, may influence in the GR response. The geophysical log between 126 m and 110 m corresponds to the outcrop section between 2 m to 4.5 m. The coexistence of thick tempestites, which are well cemented by clay minerals, gives low GR log reading in all of the three cores. On contrast, the thick laminated clayshale shows high values in the GR log. The GR log between 110 and 100 m is matched with the 4.5 m to 6 m in the outcrop section. The GR log responses in the section are variable suggestion different thickness of the planar laminated clayshales (lithofacies Cl). The geophysical log response between 100 m to 74 m is correlated to the section from 6m to 10 m. All of the three cores give well matching except a turbidite layer. This layer if observed in Bedford Metropark in thickness of 40 cm while it is 14 cm at Huntington Beach. Thus, the thickness decreases westward, and this turbidite is not observed in the core suggest environment change from proximal to distal. This section is interpreted as a paleo-water depth above SWWB but below FWWB.

The GR log response in core 2763 between 74 m to 70 m is matching the outcrop section from 10 m to 12 m. The thick high organic clayshales show high values of gamma ray (~ 70 API) in all of the three cores. The very thin hyperpycnites (1.7 cm) may be absent or their thicknesses do not give well responses in the GR log. The section of gamma ray log between the 70 m and 64 m is corresponds to the section of outcrop from 12 m to 13 m. This section has thick turbidite intervals that show well response of GR log (Fig. 40). The GR log response between 64 m to 57 m is correlated to the upper part of the Cleveland Shale Member. The funnel shaped pattern is supported by the presence of lithofacies association MC, normal grading from sand in
turbidite to silt in lithofacies MI to clay in lithofacies CI at the top. This section can be interpreted as a paleo-water depth below FWWB. Thus, from the seven sections, it can be clear that the depositional environment is limited below FWWB and above SWWB, which means in the offshore transitional and/or offshore environments.

**Depositional Environment**

The Cleveland Shale Member can be divided into the lower, middle, and upper parts, based on important aspects of the deposits. These aspects are tempestites, condensed sections, turbidites, and hyperpycnites. Overall, the Cleveland Shale Member can be understood as part of a clastic shelf depositional environment.

The lower part of the Cleveland Shale Member is dominated by claystone units interrupted by hyperpycnites and tempestites. The length of this portion is about 5 m thick starting above the Chagrin Shale Member (Fig. 35). The average thickness of hyperpycnites in this portion is 1.7 cm. In the lower part, hyperpycnites can be found in two groups, at the lower portion and at the upper portion. The middle portion does not have any hyperpycnites, but it is dominated by tempestites, which is separated by thick planar laminated clayshale (lithofacies CI). The trend of hyperpycnites is changed in thickness upward suggesting increase in activity power of discharge percentages. The lower part of the Cleveland Shale Member is also dominated by lithofacies association SSL. The trend of this lithofacies association decreases upward in the lower portion, and then increases in the middle portion (Fig. 35).

The middle part of the Cleveland Shale Member will be divided into three portions, lower middle, and upper. The lower portion is dominated by hyperpycnites, tempestites, and siltstone-mudshale rhythmites lithofacies association (Fig. 35). This portion has multistory of same
deposits: tempestites at the base, overlain by lithofacies SSI, overlain by two hyperpycnites, which is separated by lithofacies Mm. The trend of each deposit decreases upward. The muddle portion is dominated by turbidite and hyperpycnites. Three turbidites are observed in this portion separated by a bundle of hyperpycnites. The trend of turbidite decreases upward from 14 cm to 4 cm while the hyperpycnites increases upward from 1.3 cm to 2.1 cm. These turbidites are observed very thick (30-40) at Bedford Metropark and Brooklyn Metropark. The upper portion of the middle part of the Cleveland Shale Member is dominated by amalgamated tempestites and mudrock lithofacies association. This portion can be distinguished by repetition deposits of tempestites or amalgamated tempestites overlain by thick clayshale units. In addition, the trend of mudrock lithofacies association increases upward (Fig. 35).

The upper part of the Cleveland Shale Member can be divided into two parts, lower and upper portions. The lower portion is dominated by mudshale-clayshale rhythmites lithofacies association and hyperpycnites (Fig. 35). This portion has a multistory of hyperpycnite follows by planar laminated mudshale and planar laminated clayshale. The trend of hyperpycnites decreases upward from 2.1 cm to 1.2 cm, and the trend of mudshale-clayshale rhythmites lithofacies association decreases from 88 cm to 41 cm. The upper portion of the upper part of the Cleveland Shale Member is dominated by turbidite and mudshale-clayshale rhythmites lithofacies association. The same story of the lower portion occurs that each turbidite overlays by a mudshale-clayshale couplet. However, the trend of turbidite decreases upward from 8 cm to 4 cm while the trend of couplet is almost stable (Fig. 35).

Over all, analyzing of event deposits indicates that hyperpycnites is found in all of the parts of the Cleveland Shale Member, but they can found as bundles in specific portions. The transitions from lower to middle to upper parts indicate that the trend of hyperpycnites increases
upward from the lower part to the middle, but it decreases from them the middle to the upper parts. In addition, as the same of hyperpycnite situation, the trend of tempestites increases upward from the lower part to the middle, but they are not observed at the upper part. The amalgamated tempestites are found only in the middle part of the Cleveland Shale Member. Moreover, the trend of turbidite intervals increase upward from the middle part to the upper part and they did not observed within the lower part (Fig. 35). The condensed sections are observed only in the middle part associated with tempestite and amalgamated tempestites.

Analyzing of muddy units shows that the Cleveland Shale Member is interbedded of silts, mud, and clays. The Cleveland Shale Member can be divided into three parts based on the mudrock dominations. The lower part is dominated by clay, the second part is dominated by silt in the lower portion and mud in the upper portion, while the upper part is dominated by clay (Fig 35). Over all, the lower and upper parts are interpreted as distal environment slightly above SWWB (deepening), while the middle part, which is dominated by storm deposits, is interpreted as distal environment below FWWB (shallowing).

**Paleontology**

Two trace fossils were observed in the Cleveland Shale Member in Huntington Beach. The first trace fossil is *Neonereites* which was found in a base of a turbidite interval. This trace fossil is observed in 2 cm long and 0.7 cm wide, and it has horizontal orientation. This trace fossil is usually found at the base of sandstone intervals (Benton and Harper, 1997; Ekdale et al. 1984). Seilacher (1960) describe this type of trace fossils, as usually, they composed of sinuous to irregular lengths, and they have smooth walls. *Neonereites* in the Cleveland Shale Member (Figure 41A) shows differences from the ideal *Neonereites* which is in figure 41B.
Figure 41. Photomicrograph and outcrop photograph of trace fossils. **A)** *Neonereites* found at the base of a turbidite in Cleveland Shale Member at Huntington Beach. **B)** Ideal *Neonereites*, Source of image: (Hantzschel, 1962). **C)** *Chagrinichnites* observed at the lower face of a tempestites in the Cleveland Shale Member at Huntington Beach. **D)** Ideal *Chagrinichnites*. Source of image: (Hannibal and Feldmann, 1983)
*Chagrinichnites* is interpreted as a fish fossil. It was found at the base of one of the tempestites in the Cleveland Shale Member at Huntington Beach (Fig. 41C). This fish fossil has a horizontal orientation and was found in 10 cm long and about 7 cm wide. Hannibal and Feldmann (1983) described *Chagrinichnites* from the Chagrin Shale Member. The example in the Cleveland Shale Member also include the fossilized remains of 60% of the lower body of a fish fossil.

**Paleocurrent Analysis**

Paleocurrent data are measurements of primary sedimentary structures that can be found in the upper, middle, and/or in the lower face of a stratum indicating paleoflow direction. Any primary structures that formed on a bedding surface due to erosion or deposition can be measured to indicate the paleoflow direction (Potter et al., 1980). The primary structures that occur in the Cleveland Shale Member are ripple marks, cross bedding, and groove casts. These sedimentary structures are observed within all the sandstone intervals. Groove casts is the only one that is well observed in the field at the base of tempestites (Fig. 42A).

With a Brunton compass, 56 measurements of groove casts were collected at Huntington Beach to determine the paleoflow. The bedding tilts less than 10°; therefore, these measurements do not need any tilt corrections. In the lab, these data were plotted in a rose diagram (Fig. 42B). The rose diagram indicates a unimodal paleocurrent pattern, from northeast to southwest. A summary of the measurements and vector statistics can be found in Table 11.
Figure 42. A) Outcrop photograph of the sole marks of a tempestite bed at Huntington Beach showing groove casts. B) Rose diagram showing NE to SW paleoflow direction at this location.
Table 11. Paleocurrent data and vector statistics for the groove casts.

<table>
<thead>
<tr>
<th>Class</th>
<th>Midpoint</th>
<th>sin θ</th>
<th>cos θ</th>
<th>n</th>
<th>n sin θ</th>
<th>n cos θ</th>
<th>(n sin θ)²</th>
<th>(n cos θ)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>000-030</td>
<td>15</td>
<td>0.259</td>
<td>0.996</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>030-060</td>
<td>45</td>
<td>0.707</td>
<td>0.707</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>060-090</td>
<td>75</td>
<td>0.966</td>
<td>0.259</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>090-120</td>
<td>105</td>
<td>0.966</td>
<td>-0.259</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>120-150</td>
<td>135</td>
<td>0.707</td>
<td>-0.707</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>150-180</td>
<td>165</td>
<td>0.259</td>
<td>-0.966</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>180-210</td>
<td>195</td>
<td>-0.259</td>
<td>-0.996</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>210-240</td>
<td>225</td>
<td>-0.707</td>
<td>-0.707</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>240-270</td>
<td>255</td>
<td>-0.966</td>
<td>-0.259</td>
<td>48</td>
<td>-46.368</td>
<td>-12.432</td>
<td>2149.991</td>
<td>154.555</td>
</tr>
<tr>
<td>270-300</td>
<td>285</td>
<td>-0.996</td>
<td>0.259</td>
<td>8</td>
<td>-7.968</td>
<td>2.072</td>
<td>63.489</td>
<td>4.293</td>
</tr>
<tr>
<td>300-330</td>
<td>315</td>
<td>-0.707</td>
<td>0.707</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>330-360</td>
<td>245</td>
<td>-0.259</td>
<td>0.966</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>56</strong></td>
<td><strong>-54.336</strong></td>
<td><strong>-10.360</strong></td>
<td><strong>2213.480</strong></td>
<td><strong>158.848</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Vector Statistics**

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vector Mean</td>
<td>θ = tan-1[Σ nsin θ / Σ ncos θ]</td>
<td>79.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vector Magnitude</td>
<td>R = (1/n) [Σ (nsin θ)^2 + Σ (ncos θ)^2]^{0.5}</td>
<td>0.06666</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular Std. Deviation</td>
<td>S = (180/π)[2(1-1.0015R)]^{0.5}</td>
<td>78.2456</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular Variance</td>
<td>S^2 =</td>
<td>6122.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test of Significance</td>
<td>p = exp [- (nR^2 / n)] =</td>
<td>0.77971</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DISCUSSION

Depositional Environment

General

The Cleveland Shale Member of the Ohio Shale is dominated by mudrocks, but also contains three sandstone lithofacies associations (turbidites, tempestites, and hyperpycnites). Accordingly, the Cleveland Shale Member can be understood as muddy shelf depositional environment. Variations of lithology percentages and different sedimentary structures allow the muddy shelf depositional environment to be divided into two parts: inner shelf, which is dominated by waves and currents, and outer shelf, which is dominated by surface and subsurface currents.

Outer Shelf Environment

The outer shelf environment is dominated by offshore mudstones and condensed section interbedded with turbidite and hyperpycnite event horizons. In most of the shelf mudstones, siltstones and mudrocks are found either massive or planar laminated. The thin laminated, and in some cases normal graded siltstones, mudstones are mostly observed with sharp contacts deposited by waning storm. Nichols (1999) suggested that very strong storms are able to reach offshore zone and produce sedimentary structures like very thin sandstone laminae overlapping with mudstones. Walker and Plint (1992) and Walker (1992) stated that most of the thin sandstone intervals in the outer shelf environment, which have an erosional base and may have sole marks, can be interpreted as turbidites. Moreover, most of the deposits in offshore environments are distinguished by monotonous interbeds of sandstones and mudstones extending in different thickness (Walker, 1992).
The Cleveland Shale Member is observed in the lower and upper parts as mudstones interbedded with turbidites, single individual tempestite, and hyperpycnites (Fig 43). In the lower part, these thick mudstone deposits contain lithofacies SSl, Cm, Cl and overlie the Chagrin Shale Member. In the upper part, the thick mudstone deposits contain lithofacies Mc, Ml, and Cl and underlie the Bedford Shale. As mentioned early, both lower and upper parts are dominated by clay and clay units are more common (Fig. 35). The interbedded sandstones are different. In the lower part, they are dominated by hyperpycnites and distal tempestites, while in the upper part, they are dominated by hyperpycnites and distal turbidities.

The lithofacies associations SSC and MC, which are dominated by clays, suggest subaqueous deposition in a unique offshore environment. Different mudstones with various settings are mostly deposited in interchannels or lakes and interflooded basins (Gordon and Bridge, 1987; Collinson, 1986). These two studies explain the depositional environments of both mudstones and sandstones can be observed in offshore environments. The sharing of sedimentary structures such as planar lamination suggests a low-energy offshore environment with moderate sediment rate. Occurrence of planar laminated siltstone in mudstone strata can be evidence of pulsations in current flow in shallow offshore environment. In addition, the absence of sands may also suggest offshore or offshore transition environments.

The normal background deposit in the Cleveland Shale Member is changed through the time of deposition. The lower part normal background deposits in the lower part is green-gray claystone changed through time to blue-gray claystone. Because the middle part of the Cleveland Shale Member is dominated by event horizons, the deposits are variable between siltstone, mudstone, and claystone. It can be understood that the background sedimentation in the lower
Figure 43. Stratigraphic Section showing the outer muddy shelf deposits which is dominated by hyperpycnites, individual turbidite, and individual tempestite.
and upper parts are continuous, but in the middle part which is interrupted by many event deposits, the background sediment was absent or minimal.

**Inner Shelf and Offshore Transition Environments.**

This zone can be characterized by higher energy waves (Collinson, 1986), while Boggs (2001) reported that the sediment in this zone vary from very fine- to fine sands, silts, and mud. Sedimentary structures that can be found in this zone include oscillation and current ripples and planar laminations. Interbedded with the fine-grained sediment are hummocky stratified, very fine- to medium-grained sandstone. These may form during storm events, and these storm deposits may contain mud intraclasts overlain by thin ripple laminated sand (Reading and Collinson, 1996). The transition between outer shelf and inner shelf can be indicated by increases of sand content and occurrence of hummocky stratification (Walker and Plint, 1992).

The presence of hummocky stratified sandstone and planar laminated siltstone interbedded with lithofacies Ml suggests a lower part of shoreface environment as silts increase upward. In the Cleveland Shale Member, these lithofacies are mostly found in the middle part, which is dominated by silts and mud (Fig. 44). The sedimentary structures which can be recognized in offshore transition sedimentary environments can be small wave ripples, and convolute bedding, while bioturbation is more common (Reineck and Singh, 1980). The occurrence of mud- and sand-filled bioturbation in the lithofacies Ml is observed suggesting an offshore transition environment. Both lithofacies Sl and SSl have lenses and very thin silts indicate verbal weak currents beside storm effects.

The offshore transition zone is defined as the accumulated space that is located between the mean weather wave base (MWWB) and the fair weather wave base (FWWB). This zone is
Figure 44. Stratigraphic section showing the inner muddy shelf deposits which is dominated by hyperpynmites, turbidites, and amalgamated tempestites.
characterized by the deposition of sandstone, siltstone, and mudstone due to deposition of the suspended load (McCubbin, 1982). The middle part of the Cleveland Shale Member is dominated by hummocks, silts, and mud. During fair weather conditions, the deeper wave base causes erosion followed by deposition of extensive sheets of hummocky stratified and planar laminated sand (Harms et al., 1975). Most tempestite, as well as amalgamated tempestites, beds are preserved between the storm weather wave base and fair weather wave base. Below SWWB, there may be no wave activity and the depth of wave base is commonly on the order of 10-m, but it can be significantly deeper (up to 200 m) during extreme storms (Boggs, 2001).

The inner shelf is the best place to develop tempestites, but tempestites can be observed as far as 40-km from the coast (Reineck and Singh, 1980). In this zone, storms offer obvious beds and sedimentary structures that can be easily distinguished from other strata, as they are limited by storm-influenced deposits (Dott and Bourgeois, 1982). The sediments that have hummocks are known as tempestites, which are observed in the middle part of the Cleveland Shale Member (Fig. 44). However, storm deposits can produce hummocky and swaley stratifications either in upper or middle shoreface (Ainsworth et al., 2008). Thus, the presence of tempestites and amalgamated tempestites interbedded with mudstones with high percentages of silt and no much sand suggests offshore transition sediment that are deposited on inner shelf environment, below FWWB.

**Event Horizons**

**Turbidites**

Turbidites are considered as gravity flow that can be found in different thickness in the Cleveland Shale Member. They can be found either proximal or distal based on the distance of
the source. The long distance can be effected by different factors such as flow energy, basin slopes or basin topography (basin controls), and rheology of unsteady flow (Sinclair and Cowie, 2003). Therefore, it has been known that many features may help to distinguish proximal turbidites from distal turbidites.

Sinclair and Cowie (2003) examined two sandstone formations in the Alpine foreland basin, Switzerland, and observed that the numbers of beds separating two turbidites are different in proximal and distal areas because of the high power of the initial flow to remove the thin beds in the proximal areas. Experimental analysis of waning turbidity currents shows lithological criteria to differentiate proximal from distal turbidites because the lower Bouma divisions may be missing (Walker and Mutti, 1973). In the Cleveland Shale Member, Bouma division A (T_a) is observed only at Bedford Metropark and Brooklyn Metropark. The same bed at Huntington Beach does not show this division. Moreover, Bouma division B (T_b) is also observed in two thick beds (40 cm) at Bedford and Brooklyn Metroparks, but only found in one bed at Huntington Beach. This may explain the relationship of proximal to distal turbidites between these three locations that it is moving from proximal (east) to distal (west). Moving from proximal to distal sides in the same basin can decrease the turbidity lithofacies.

The turbidite thickness changes, through T_a to T_c, and may also reflect proximal to distal trends (Seilacher, 1967; Mortimore, 1979). In the Cleveland Shale Member, the thickness of turbidites between the three sites indicates such a trend. The mean thickness of turbidite units at the Huntington Beach outcrop is 10 cm while it is almost 17 cm at the Bedford Metropark and Brooklyn Metropark outcrops (Table 7). One of the turbidites at Bedford Metropark is about 40 cm thick decreasing to 30 cm at the Brooklyn Metropark outcrop and about 14 cm at the Huntington Beach outcrop.
The diagnosis of the turbidite interval features are different based on channel and basin plain (Walker, 1978; Stow, 1984). Facies succession, lithology, sedimentary structures, unit geometry, texture, unit frequency, unit thickness, and vertical and lateral changes are the important geological features to analyze turbidite intervals to be diagnosed (Walker, 1978; Pickering 1981). These features are very important issues in order to indicate the depositional environment and turbidity model. The base cut-off with well-preserved strata underneath the turbidites, the absence of most Bouma divisions in most intervals, and the interval thicknesses can be different between proximal and distal turbidites (Walker and Mutti, 1973; Stow, 1984). The turbidite intervals in Cleveland Shale Member, which have observed in northeast Ohio, are similar to those distal turbidites that were examined by Bouma (1962), Lowe (1982), Stow and Dean (1984), and Mulder and Alexander (2001). Examined these features on the three outcrops suggest proximal (east) to distal (west) relationship.

In addition, the number of turbidite intervals decreases from east to west (Table 7). This decrease may suggest proximal-distal relationship. Another point, the turbidites vary in erosional power along the transect. At the Bedford and Brooklyn Metroparks, mudshales and clayshales (lithofacies Ml and Cl) may be missed partly or completely but can be observed in the other two locations. This may be interpreted to reflect the flow power and/or basin topography.

Finally, the presence of turbidites, in the middle part and the upper part of the Cleveland Shale Member, may indicate that the source area was not stable. Turbidites are usually initiated on subaqueous slopes as a result of earthquakes, pressure effects by waves, and/or over-steepening effects (Kneller, 2003).
**Tempestites**

It has been known that tempestites are generated by periodic storms which can provide and rework on sediment on shallow marine environment (Ager, 1974; Swift et al., 1986; Stow, 1984). The tempestites in the Cleveland Shale Member show variations in lithofacies and thickness.

The normal grading lithofacies is shown in few samples only in the outcrops because it is difficult to find in within the core samples, as the sole marks are absent. It thickes from 1-9 cm adding the thick groove casts (Fig. 37) Observation of this lithofacies was based on field examination and thin section that show massive change upward to be normal sandstones and siltstones. Hummocky stratified sandstone and siltstones are the most apparent sequence in tempestite lithofacies association (Leckie and Walker 1982). This lithofacies are recognized in all the outcrop samples while it is also hard to identify it in the small width core samples. The thicknesses of lithofacies (Sh) vary in period of ~ 7-15 cm. Analyzing of this facies was based on very thin curved thickening or thinning surfaces. The spacing areas between the crests of the curved surfaces were filled by suspension represent parallel laminated sandstones. The laminated siltstones (lithofacies SSI) were observed in all the samples while the ripple siltstones claystones were observed in only four samples. Thus, the tempestite sequences are changed laterally from site to another and vertically from the base to the top of each site. This may indicate the power of storms as well as sediment supply may change through time.

As with turbidites, the number of tempestites decreases eastward. This makes sense because distal turbidite deposits are often associated with distal tempestites (Walker, 1992). Distal tempestites are fine-grained and provide the same sedimentary structures as distal turbidites with exceptions of faunal characteristics and facies trend (Einsele and Seilacher, 1991).
The tempestites in the Cleveland Shale Member have a mean thickness of 12 cm and contain fine-grained sandstone. Thus, they are interpreted as distal tempestites that are deposited in the western edge of the Appalachian Basin.

By dividing the Huntington Beach outcrop to three parts, lower, middle, and upper, tempestite are observed in three groups. The lower part of the Cleveland Shale Member contains two tempestites separated by lithofacies SSI. The middle part consists of two groups of tempestites separated of a bundle of distal turbidites and hyperpycnites. Two tempestite are observed at Bedford and Brooklyn Metroparks and are missing at Huntington Beach. This may suggest proximal-distal relationship.

Amalgamated tempestite is consist of two interbedded tempestite unites separated by sheet-like of mudstone. Stacked sediment couplets, amalgamated tempestites, may form due to repeatedly occurring storm events on nearshore to transitional offshore environments between FWWB and SWWB (Blomeier, et al, 2011). The first unit, lower, is consists of the four lithofacies, Smg, Sh, Sl, and Sr, while the upper unit starts with lithofacies Sh overlain by lithofacies Sl and coped by lithofacies Sr at the top. The sheet-like mudstone, which is separated the two unites, is more likely to be the massive mudstone (Mm) which is identified in the ideal tempestite model by (Ager, 1974; Johnson and Baldwin, 1986). These two amalgamations can be interpreted as a production of shallow water storm deposits as a result of combination of oscillatory and unidirectional flows. The presence of planar laminated sandstone (lithofacies Sl) just above the hummocky stratifications is considered as a result of the waning storm deposits and wave deposits. The thickness of this lithofacies in most of the samples suggests either low strength of waves or increase of water depth. The low angle cross lamination with ripples at the top in lithofacies Sr just above lithofacies Sl is interpreted as suspended load deposits effected by
oscillatory and unidirectional flows. The preservation of these deposits indicates storm deposits at or above storm-weather wave base.

**Hyperpycnites**

Hyperpycnal flow is a thin stable layer of suspended load plumes that occur during flood event as high discharges from fluvial sediments at the river mouth enter ambient standing body of water (Mulder *et al.*, 1997). Hyperpycnal flow is realized a negatively active flow which inflows for long distances just above the seabed owning to the density contrast of the suspended current with the surrounding water (Mulder and Syvitski, 1995). This means that only finer grain sediments will be transported for long distances. These high discharge sediments can enter any basin in three forms. They can get in basin as sinking deposits just above the lake floor. In addition, the plumes can swim of the water surface or in the middle, based on the density or temperature differences between the incoming flow and basin water, and then they can sink to the basin surface. Moreover, if there are high density or temperature differences, the flow will sink directly above the water floor. In all of these three forms, the result will be hyperpycnal flow and hyperpycnite sediments (Heimsund, 2007).

Hyperpycnites are very thin strata and they may not possible to identify these lithofacies in the field work. In addition, it is more common to observe the whole lithofacies Smg, Sl, Sr, SSL, MI, and CI, in a hyperpycnal unit (Zavala *et al.*, 2006). In this study, these lithofacies, which are not in most of hyperpycnal case studies, are found in most hyperpycnal intervals. However, the six lithofacies are not observed in one single unit. Normal graded sandstones is the most obvious part of the hyperpycnal sequence (Nakajima, 2006). It was observed on core samples
with an erosional base, while in the hand samples that examined in light and electron microscopes, there are some elongated siltstone clasts just above the erosional clasts.

By dividing the Cleveland Shale Member into three parts, the most hyperpycnites are observed in the lower and middle parts. The lower part has one group of hyperpycnites while the middle part has three bundles of hyperpycnites separated by turbidites. The others are distributing in different depths. Thus, the distribution of hyperpycnites is not symmetrical. The coexistence of many hyperpycnites suggests wet, poorly drained floodplains, and a humid, tropical to subtropical climate (Mulder and Syvitski, 1995; Bhattacharya and MacEachern, 2009).

Turbulent flow, which can generate hyperpycnal flow at the end of its processing, can be generated as a result of four mechanisms: 1) slide transformation with river concentration flow, 2) river discharge that sends large amounts of both suspended and bed loads, 3) the density sequences of the nepheloid layer, 4) and finally muddy concentration fluids during storms in the offshore (Wilson and Roberts, 1995; Mulder and Syvitski, 1995; Kneller and Buckee, 2000). In addition, Mulder et al. (2003) added that turbulent flows could result condensing of the nepheloid layer or at a storm conditions when fine-suspensions take time to deposit. Bhattacharya and MacEachern (2009) stated a new source that speedy flocculation of very fine-grained associated with sediment settling might exist causing it to be low concentration hyperpycnal plumes.

Hyperpycnites are very fine-grained sands or fine-grained mud sediments, and they differ from turbidites. Soyinka and Slatt (2008) classified them based on their compositions that hyperpycnal flows are generated by non-ignitive processes, which mean a combination of fresh water with a high percentage of mud. However, the high percentage of bottom flows is a mixture
of seawater and sedimentary materials representing turbidity flows. Likewise, Mulder et al. (2003) distinguished these two sediments depending on the dynamic of generation. In subaqueous environments, river discharge of suspended and bed loads can create hyperpycnal flows based on different densities with different salinities while ignitive transformation generates turbulent flow that creates turbidity flows. Hence, when they proceed to the marine environments, these flows move downslope above the seabed because of very high-suspended loads and variable intensity between the flows and the ambient seawater. However, hyperpycnites can move for very long distance over all the basin topography, while in turbidity case, topography can effect on turbidity speed. The other factors that can affect these processes are the differences of temperatures and salinities between the ambient seawater and the flows (Yoshida et al., 2009; Haughton et al., 2010; Bourget et al., 2010).

Hyperpycnites can be divided into two parts based on distance between the depositional areas and the river’s mouth; distal and proximal hyperpycnites. These distances can be hundreds of meters up to hundreds of kilometers. Nakajima (2006) characterized the distal deposits by relatively simple upward fine-grained deposits. He noticed that since the flows tend to migrate to the head of the current because of high velocity of the flows. Nakajima also reported that the hyperpycnites traveled as far as 700 km from the river mouth with almost the same thickness. It seems that he is not alone. Ducassou et al. (2008) concurred with Nakajima analyzing the Mediterranean Sea hyperpycnites and noticed that the strata have the same thickness along the sea. From the well core analysis, they found that the hyperpycnites were deposited on the shallow sea floor and the upper continental slope. These two studies were stated based on the gravity force and the force of slope of the sea floor.
It is not reasonable to think that the slope will be steady from the river mouth to the distal areas. So there are other forces might help to deliver these sediments for hundreds of kilometers. Zavala et al. (2011) documented that the moving of hyperpycnal flows for a long distance is not necessary demand high slope as new facies of hyperpycnites can be explored in distal areas driving under the continues high-density river discharge. Therefore, the distance is based on the power of the sediment pumping to the basin and the time of the flood. Therefore, the hyperpycnal plumes can transfer the sediments, based on those three forces, to the deep environments because of geological events such as sea level fall or earthquakes. Thus, the hyperpycnites in the Cleveland Shale Member seem to be deposited as a result of hyperpycnal flows in distal areas.

The change of thickness, grain size, and sedimentary structures from place to another indicates a different basin beside the distal environments. Zavala et al. (2006) analyzed the Rayoso Formation from west-central Argentina. They characterized the strata within this area as low-angel cross-stratification, medium- to coarse-grained sandstones representing proximal environments. The hyperpycnal system has a large power, and the large grains will be deposited near the river mouth. In Rayoso Formation, there would be hyperpycnal plumes that have 2 m thick in some locations representing proximal environment. Furthermore, Heimsund (2007) added more explanation from his laboratory experiments in the University of Bergen, Norway. He stated that the main power of the flow was located on the channel axis. Therefore, most medium and large grains will still be located within the channel axis where the turbidite sediments will be restricted. These experiments elucidate the fluvial and the hyperpycnal systems and facilitate the interpretation of Holocene hyperpycnites.
Existing of plant debris of the upper surface of a hyperpycnites is a result of continental plant debris indicating the provenance of the hyperpycnites from land environments (Mortimore, 1979; Soyinka and Slatt, 2008). Hyperpycnites are abundant of land materials and continental debris such as leaves, plant fragments, and coal fragments (Soyinka and Slatt, 2008). Plant debris can be transferred together with very fine-grained (Zavala et al., 2007) and deposits by fallout with silt and clay from pro-delta plumes (Zavala et al., 2006).

**Condensed Sections**

Concretionary mudstones are observed at five places in the upper part of the Cleveland Shale member. The presence of condensed carbonaceous mudstone implies slow net sediments through very long of time (Glenn and Garrison). Very low of sedimentation may cause extensive bioturbation in an oxygenated environment. It was suggests that the carbonaceous concretions may formed after deposition but before compression and they have different form as a result of the shape of fossils remains (Barth, 1975).

Condensations can be identified from the geophysical logs as these deposits reflect high gamma ray, low resistivity values, and high-density peaks (Mitchum et al, 1993; Vail and Wornardt, 1991). Jennifer et al (2000) examined condensed sections from the Gulf of Mexico and found the carbonate-rich condensed section is characterized by low gamma-ray and low density response (similar to sand) while the shale-rich condensed section is characterized by high gamma-ray and high density log (similar to shale). The condensations in the Cleveland Shale Member are carbonaceous concretionary mudshale, which are cemented by calcite or dolomite. Therefore, from the gamma-ray correlation in figure 40 that the five condensations, which are
surrounded by tempestites and hyperpycnites, are identified as high gamma ray values and high density responses.

Many geologists who have studied this interested concretionary mudstone found it as one of the most significant indicator to differ the Cleveland Shale Member from the overlying and underlying shales. The Chagrin Shale Member, The Cleveland Shale Member, and the Bedford Shale may contain condensations scattered throughout the formation (Hoover, 1960; Coogan, 1996). The concretions in the Chagrin Shale Member and Bedford Shale contain calcareous ferruginous concretions that can reach 9 inches in diameter (Cushing, 1912) while in the Cleveland Shale Member they are more flat and less diameter (Hoover, 1960).

The concretionary carbonaceous deposits seem to be deposited as a result of recrystallization of nucleus of organisms or plant remains. The overgrowth of concretions is interpreted as a secondary growth of crystals as water circulated in horizontal paths routes until compaction process started to remove it out suggesting physical rather than chemical processes (Hansen, 1994). These concretions started to form around decaying organic matter just above water floor and sedimentary minerals, could be calcite or dolomite, started to fill in voids and cemented grains (Criss et al., 1988).

The concretionary carbonaceous mudstones have sharp contact with other strata that they are underlain by laminated mudshale and overlain by clayshale. These three units represent lithofacies association MMC that is observed, in general, overlying hyperpycnite. The thick clayshales, which overlies concretions, show slow net sedimentation suggesting more and mixed organic matter can be found (Criss et al., 1988).
Paleogeography

The paleocurrent in the Cleveland Shale Member can be indicated by present of groove casts as a primary sedimentary structure. These groove casts are observed in the base of two tempestites located in the middle part of the Cleveland Shale Member at Huntington Beach.

The examination of this structure indicates northeast to southwest paleocurrent direction. The examination of siltstone and sandstone intervals in the Cleveland Shale Member in northeast Ohio suggests uniformly paleocurrents oriented from east side of the Appalachian Basin and can be observed perpendicular to the black shale Isopach (Potter et al., 1979). The paleocurrent directions of the Cleveland Shale Member turned southwest forward to the west margin of the Appalachian Basin (Lewis, 1988).

The paleogeographic setting of the depositional environment was performed by west paleoslope of a distal environment that shallowing westward of the Appalachian Basin. The observations of the change of gain size, thickness of intervals, and lithological unit absent westward may suggest proximal-distal relationship. The prograding shelf of the basin represents local paleogeographic setting showing shallowing westward distal basin (Lewis, 1988). The clastic sediments were transported to the west edge of the Appalachian Basin which is supported by a large river system in the same direction (Potter et al., 1979).

The present of different thicknesses of the turbidite intervals in the Cleveland Shale Member may suggest basin topographic controls and proximal-distal relationship. The sandstone intervals are observed as normal grading and planar lamination in western Cleveland area showing thick intervals in the west and thin intervals in the east (Lewis, 1988). The frequency of the turbidite combinations changes eastward in the Cleveland Shale Member northwest Ohio (Broadhead et al., 1982). Mausser (1982) suggested that the sandstone intervals were derived
from a large river system from northeast to southeast representing distal environment. The occurrence of unidirectional groove casts and symmetrical ripples suggested a large river system. The high stable organization of deposition and unidirectional paleocurrent indicate one large river system which was oriented to the late Devonian environment (Potter et al, 1979).

**Stratigraphic Trends**

The detailed stratigraphic section of the Cleveland Shale Member shows a general coarsening and thickening upward sequence of sand bodies. However, the mudstone unites in the same stratigraphic section can be observed as coarsening and thinning upward in the lower half while they are observed as fining and thickening upward in the upper half (Fig. 45). The sedimentary succession can be interpreted in three important aspects. The shallowing upward sequence at the base represents deepwater offshore mudstones at or slightly above FWWB. This sequence is overlain by offshore transition deposits which can be proved by occurrences of individual tempestites, turbidites, and hyperpycnites. The sequence is interpreted as a paleo-water depth between FWWB and SWWB. The presence of amalgamated hummocks is short period is interpreted as a paleo-water depth at or slightly below FWWB. The amalgamated tempestites are observed as thicker than the other tempestites and rippled sandstone (lithofacies Sr) are thicker (~ 5 cm) than the other tempestites. Finally, the last important aspect is the occurrence of shallowing upward sequence representing deepwater offshore mudstones at or slightly above SWWB.

A total of six prograding muddy shelf sequences have been identified in the Cleveland Shale Member (Fig. 45). These prograding sequences are classified into 1) prograding offshore influenced by hyperpycnites and turbidites (BD) 2) prograding storm-dominated offshore (BS);
Figure 45. Sequence stratigraphic interpretation of the stratigraphic section at Huntington Beach.

Key to symbols: PS = Prograding storm-dominated lower offshore transition; PD = Prograding offshore influenced by delta; PT = Prograding storm-dominated upper offshore transition.
3) prograding storm-dominated transition offshore (amalgamated tempestites) (BT). The major sets of the offshore sequences are 1) fine-grained claystone dominated offshore interbedded with individual distal turbidite and hyperpycnites sequence interpreted as offshore deposits; 2) individual distal tempestite, individual distal turbidite, hyperpycnites, and siltstone dominated offshore interpreted as offshore deposits between FWWB and SWWB; 3) amalgamated tempestites and mudstone dominated offshore sequence interpreted as offshore transition deposits.

Prograding offshore influenced by hyperpycnites and turbidites are recognized at the base and the upper most part of the Cleveland Shale Member. These two parts are dominated by turbidite and hyperpycnites which are intercalated with thick claystone deposits (Fig 45). Prograding storm-dominated offshore is observed by thin siltstones and mudshales interbedded with individual event deposits in the lower and middle parts of the Cleveland Shale Member. Prograding storm-dominated transition offshore is recognized by amalgamated tempestites and hyperpycnites interbedded with thick mudshales in the middle part.

Over time, the sediments were changed from clay to silt to mud and finally clay. The trend of sediment supply also has changed over time. The lower and upper parts are influenced by high sediment rate represents thick clayshales. The middle part is influenced by low sediment which can be interpreted the event deposits may erode those much silt and clay. This issue can be proved by the decreases of mudrocks through the three sites. In other words, many mudrock unites have observed at Bedford and Brooklyn Metroparks and not observed, or observed as very thin, at Huntington Beach.
SUMMARY AND CONCLUSIONS

There has long been a long debate about whether the Devonian Cleveland Shale Member as a part of the Ohio Shale was deposited in shallow-water or deepwater depositional environments. This study looked at the Cleveland Shale Member at three stratigraphic sections and five well cores from four counties in northeastern Ohio. The Cleveland Shale Member consists mostly of interbedded mudstones and sandstones. By studying the sedimentary structures, microstructures, and texture from the outcrops and the cores using different methods, the Cleveland Shale Member consists of 14 lithofacies, which are classified into four mudstone lithofacies associations and three sandstone lithofacies associations. The mudstone lithofacies are green-gray mudrocks lithofacies association, green-gray siltstone and mudshale rhythmites, dark blue-gray mudrock, and blue-gray mudshale and clayshale rhythmites. In addition, the sandstones lithofacies associations are turbidites, storm deposits (tempestites), and flood deposits (hyperpycnites).

Three types of event layers are interbedded with the mudstones lithofacies associations. The storm deposits, tempestites, is consisting of four lithofacies: massive to normally graded sandstones (lithofacies Smg), overlain by hummocky stratified fine-grained sandstones (lithofacies Sh), overlain by planar laminated very fine-grained sandstones (lithofacies Sl) overlain by ripple laminated very fine-grained sandstone (lithofacies Sr). This lithofacies is observed with a mean thickness of 13 cm. Turbidites lithofacies association is identified with a mean thickness of 14 cm containing four lithofacies: massive to normally graded sandstones (lithofacies Smg), overlain by planar laminated sandstone (lithofacies Sl), overlain by rippled laminated claystones (lithofacies Sr), overlain by planar laminated siltstone (lithofacies SSl). The last lithofacies association is flood deposits, which is known as hyperpycnites. They consists of
massive to normally graded sandstone (lithofacies Smg), overlying by planar laminated sandstone (lithofacies Sl) overlying by rippled laminated sandstone (lithofacies Sr), overlying by planar laminated siltstone (lithofacies SSl), overlying by siltstone and claystone rhythmites (lithofacies SSCl), and/or topped by planar laminated clayshale (lithofacies Mi). This lithofacies association has a mean thickness of 1.74 cm.

Green-gray mudrocks lithofacies association SSC is observed mostly in the lower part of Cleveland Shale Member interbedded with hyperpycnites and tempestites, and it consists of light green-gray planar laminated siltstone (lithofacies SSl), medium green-gray planar laminated clayshale (lithofacies Cl), dark green-gray massive claystone (lithofacies Cm). This lithofacies association is abundant of clay, and has a mean thickness of 51 cm. The green-gray siltstone and mudshales rhythmites lithofacies association SSM is observed in the middle part starting after bundle of hyperpycnites consists of light green-gray planar laminated siltstone (lithofacies SSl) and dark green-gray planar laminated mudshale (lithofacies Mi) and has a mean thickness of 19 cm. The dark blue-gray mudrock lithofacies association is found at the middle and upper parts of the Cleveland Shale Member consisting of medium blue-gray planar laminated mudshales (lithofacies Mi), overlain by 2) concretionary massive mudstone (lithofacies Mc) dark blue-gray planar laminated clayshales (lithofacies Cl). This association is recognized in mean thickness of 52 cm. The mudshale and clayshale rhythmites, which is the last lithofacies association, is only found in the uppermost part of the Cleveland Shale Member consisting of medium blue-gray planar laminated mudshale (lithofacies Mi) and dark blue-gray planar laminated clayshale. This mud/clay couplet has a mean thickness of 23 cm interbedded with hyperpycnites and turbidites.

The examination of 143 hand samples and 18 core samples using different methods indicate to several sedimentary structures such as parallel laminations, hummocky stratification,
massive to normal fining upgrading, and symmetrical and asymmetrical ripples. The color of the mudstones is changes from greenish-gray at the base to medium green-gray at the middle, and to dark blue-gray at the top. The Cleveland Shale Member is dominated by thick clayshales at the base, thin laminated siltstone and mudshale at the middle, and thick clayshales at the upper part.

A total of 56 measurements of sole marks, groove casts, which underlie some tempestite intervals indicate transport directions NE-SW. On the base of a turbidite, a trace fossil (Neonereites) was observed, while a Chagrinichnites (a trace fossil of fish) was observed at the base of a tempestites in Cleveland Shale Member at Huntington Beach. The presence of bioturbations in lithofacies suggests benthic life and there was some oxygen in offshore environment in the Appalachian Basin. It seems that this intermittent oxygenation was provided by the event deposits.

In summary, the observations of the sedimentary structures and lithology suggest the sediments were deposited on inner and outer muddy shelf environments. These muddy shelf environments were effected by different events such as floods, storms, turbidites, and turbid currents. The middle part of the Cleveland Shale Member is affected by all of these events. The lower part of the Cleveland Shale Member is affected by floods, tempestites, and turbidite currents while the upper part is only affected by turbidites and turbid currents. The paleo-water depth has fluctuated in offshore transition and offshore environments. The occurrence of siltstone and claystone rhythmtes and laminated siltstone are interpreted as they are deposited under high influence of turbid water, which has high concentration of suspended materials. All of these deposits are interpreted as depositions occur below FWWB. However, the presence of hummocky stratifications with ripples suggest depositional environment in the offshore transition, above SWWB.


APPENDIX A: STRATIGRAPHIC SECTIONS

Figure A1. Stratigraphic section of the Cleveland Shale Member at Bedford Metropark.
Figure A2. Stratigraphic section of the Cleveland Shale Member at Brooklyn Metropark.
Figure B1. Photomicrographs of turbidites in Cleveland Shale Member. A) Photomosaic showing cycles of multiple turbidites. It can be seen that each cycle starts with massive normal fining graded sandstone follows by micro-lamination sandstone, overlain by high organic laminated clayshale. B) Turbidite C and D (T_{cd}) distinguish by ripples, wavy or convoluted lamination overlain by parallel micro-lamination of siltstone and claystone. C) Turbidite D (T_d) planar laminated siltstone. D) Turbidite A (T_a) normal graded, fine- to very fine-grained sandstone.
Figure B1. Photomicrograph of thin section of tempestite intervals. A) Photomosaic showing tempestite lithofacies: Hummocky Stratification (lithofacies SSh), overlain by laminated sandstone (lithofacies Sl), overlain by ripple sandstone (Sr). B) Photomicrograph showing Planolite (burrow) at the top of a tempestite interval.
Figure B3. Photomicrograph of thin sections of hyperpycnites, A) Photomosaic of 5 photomicrographs showing three cycles of hyperpycnites. B) Close-up photomicrograph of the lower part of a upper hyperpycnites showing very fine-grained sandstone. C) close-up of the lower part of the lower hyperpycnites showing fine-grained sandstone. The three hyperpycnites indicate fining grading upward overall. D) Photomicrograph of the upper surface of a hyperpycnites shows the planar and wavy lamination at the top.
### APPENDIX C: WELL CORE DATA

Table C1. Showing the summery of cores 2739, 2754, and 2763

<table>
<thead>
<tr>
<th>Core #</th>
<th>Depth (ft)</th>
<th>Depth (m)</th>
<th>interval</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 2739</td>
<td>93.7</td>
<td>28.56</td>
<td>Hyperpycnite</td>
<td>1.5</td>
</tr>
<tr>
<td>Core 2739</td>
<td>96.4</td>
<td>29.38</td>
<td>Tempestite</td>
<td>3.2</td>
</tr>
<tr>
<td>Core 2739</td>
<td>96.9</td>
<td>29.54</td>
<td>Hyperpycnite</td>
<td>0.9</td>
</tr>
<tr>
<td>Core 2739</td>
<td>100.5</td>
<td>30.63</td>
<td>Turbidite</td>
<td>10.3</td>
</tr>
<tr>
<td>Core 2739</td>
<td>104.4</td>
<td>31.82</td>
<td>Tempestite</td>
<td>6.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>107.7</td>
<td>32.83</td>
<td>Turbidite</td>
<td>6.3</td>
</tr>
<tr>
<td>Core 2739</td>
<td>107.7</td>
<td>32.83</td>
<td>Bioturbation</td>
<td>0.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>111.2</td>
<td>33.89</td>
<td>Hyperpycnite</td>
<td>1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>114.3</td>
<td>34.84</td>
<td>Turbidite</td>
<td>9.6</td>
</tr>
<tr>
<td>Core 2739</td>
<td>116.2</td>
<td>35.42</td>
<td>Hyperpycnite</td>
<td>1.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>139.7</td>
<td>42.58</td>
<td>Hyperpycnite</td>
<td>1.3</td>
</tr>
<tr>
<td>Core 2739</td>
<td>191.3</td>
<td>58.31</td>
<td>Turbidite</td>
<td>3.4</td>
</tr>
<tr>
<td>Core 2739</td>
<td>197.7</td>
<td>60.26</td>
<td>Tempestite</td>
<td>5.5</td>
</tr>
<tr>
<td>Core 2739</td>
<td>199.8</td>
<td>60.90</td>
<td>Turbidite</td>
<td>7.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>208.4</td>
<td>63.52</td>
<td>Tempestite</td>
<td>5.2</td>
</tr>
<tr>
<td>Core 2739</td>
<td>208.4</td>
<td>63.52</td>
<td>Bioturbation</td>
<td>0.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>211.8</td>
<td>64.56</td>
<td>Turbidite</td>
<td>7.6</td>
</tr>
<tr>
<td>Core 2739</td>
<td>218.4</td>
<td>66.57</td>
<td>Hyperpycnite</td>
<td>0.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>218.9</td>
<td>66.72</td>
<td>Hyperpycnite</td>
<td>0.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>220.1</td>
<td>67.09</td>
<td>Hyperpycnite</td>
<td>1.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>223.6</td>
<td>68.15</td>
<td>Tempestite</td>
<td>3.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>56.0</td>
<td>17.07</td>
<td>Hyperpycnite</td>
<td>1.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>56.8</td>
<td>17.31</td>
<td>Tempestite</td>
<td>4.7</td>
</tr>
<tr>
<td>Core 2739</td>
<td>58.6</td>
<td>17.86</td>
<td>Hyperpycnite</td>
<td>0.9</td>
</tr>
<tr>
<td>Core 2739</td>
<td>60.3</td>
<td>18.38</td>
<td>Turbidite</td>
<td>13.2</td>
</tr>
<tr>
<td>Core 2739</td>
<td>64.3</td>
<td>19.60</td>
<td>Tempestite</td>
<td>5.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>66.6</td>
<td>20.30</td>
<td>Turbidite</td>
<td>6.5</td>
</tr>
<tr>
<td>Core 2739</td>
<td>66.6</td>
<td>20.30</td>
<td>Bioturbation</td>
<td>0.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>71.2</td>
<td>21.70</td>
<td>Hyperpycnite</td>
<td>1.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>73.7</td>
<td>22.46</td>
<td>Hyperpycnite</td>
<td>1.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>74.2</td>
<td>22.62</td>
<td>Turbidite</td>
<td>10.8</td>
</tr>
<tr>
<td>Core 2739</td>
<td>76.4</td>
<td>23.29</td>
<td>Hyperpycnite</td>
<td>1.0</td>
</tr>
<tr>
<td>Core 2739</td>
<td>82.3</td>
<td>25.09</td>
<td>Turbidite</td>
<td>9.6</td>
</tr>
<tr>
<td>Core 2739</td>
<td>97.9</td>
<td>29.84</td>
<td>Hyperpycnite</td>
<td>0.9</td>
</tr>
<tr>
<td>Core 2739</td>
<td>102.8</td>
<td>31.33</td>
<td>Hyperpycnite</td>
<td>1.1</td>
</tr>
<tr>
<td>Core 2739</td>
<td>108.2</td>
<td>32.98</td>
<td>Hyperpycnite</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Figure C1. Geophysical logs from core 2720 showing the Cleveland Shale Member underlain by Chagrin Shale Member and overlain by Bedford Shale and Berea Sandstone. The Cleveland Shale Member represents high GR values.
Figure C2. Geophysical logs from core 2721 showing the Cleveland Shale Member underlain by Chagrin Shale Member and overlain by Bedford Shale and Berea Sandstone. The Cleveland Shale Member represents high GR values.
Figure C2. Geophysical logs from core 2739 showing the Cleveland Shale Member underlain by Chagrin Shale Member and overlain by Bedford Shale and Berea Sandstone. The Cleveland Shale Member represents high GR values.
Figure C4. Geophysical logs from core 2754 showing the Cleveland Shale Member underlain by Chagrin Shale Member and overlain by Bedford Shale and Berea Sandstone. The Cleveland Shale Member represents high GR values.
Figure C5. Geophysical logs from core 2763 showing the Cleveland Shale Member underlain by Chagrin Shale Member and overlain by Bedford Shale and Berea Sandstone. The Cleveland Shale Member represents high GR values.
APPENDIX D: SEM DATA

Figure D1. SEM image showing magnified image tree legs found in the upper surface of hyperpycnites. The EDAX analysis showing high carbon and oxygen values.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>21.08</td>
</tr>
<tr>
<td>N K</td>
<td>04.92</td>
</tr>
<tr>
<td>O K</td>
<td>22.80</td>
</tr>
<tr>
<td>SiK</td>
<td>47.71</td>
</tr>
<tr>
<td>PbK</td>
<td>03.49</td>
</tr>
</tbody>
</table>
Figure D2. SEM image of sandstone grain (180 µm) at the upper surface of claystone showing evidence of flocculation. EDAX analysis showing high Si and Al values which can be interpreted as kaolinite clay minerals.
Figure D3. SEM image of normally graded siltstone (lithofacies SSI) overlain by massive claystone showing sharp contact in lithofacies association SSC. EDAX analysis can be found in figure D4.
Figure D4. EDAX analysis showing the two different lithologies in figure D3. A) EDAX analysis showing high Si and Al values which interpreted as claystone (kaolinite). B) EDAX analysis showing high Si and O values which interpreted as siltstone.
Figure D5. SEM image of planar laminated mudshale from flood deposit showing high organic and low organic subplanar lamination. EDAX analysis can be found in figure D6.
Figure D6. EDAX analysis showing the two different lithologies in figure D5. A) EDAX analysis showing high organic clayshale. B) EDAX analysis showing low organic clayshale.
Figure D7. SEM image showing well organized quartz from a base of turbidite representing coarse sands. EXAD analysis showing high value of oxygen.