SUBSURFACE FACIES ANALYSIS OF THE CAMBRIAN CONASAUGA FORMATION AND KERBEL FORMATION IN EAST-CENTRAL OHIO

Bharat Ban jade

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 2011

Committee:

James E. Evans, Advisor

Charles M. Onasch

Jeffrey Snyder
ABSTRACT

James E. Evans, advisor

This study presents a subsurface facies analysis of the Cambrian Conasauga Formation and Kerbel Formation using well core and geophysical logs. Well-2580, drilled in Seneca County (Ohio), was used for facies analysis, and the correlation of facies was based on the gamma-ray (GR) log for three wells from adjacent counties in Ohio (Well-20154 in Erie County, Well-20233 in Huron County, and Well-20148 in Marion County).

In Well-2580, the Conasauga Formation is 37-m thick and the Kerbel Formation is 23-m thick. Analysis of the core identified 18 lithofacies. Some of the lithofacies are siliciclastic rocks, including: massive, planar laminated, cross-bedded, and hummocky stratified sandstone with burrows; massive and planar-laminated siltstone; massive mudstone; heterolithic sandstone and silty mudstone with tidal rhythmites showing double mud drapes, flaser-, lenticular-, and wavy-beddings; and heterogeneous siltstone and silty mudstone with rhythmic planar-lamination. Other lithofacies are dolomitized carbonate rocks that originally were massive, oolitic, intraclastic, and fossiliferous limestones. In general, the Conasauga Formation is a mixed siliciclastic-carbonate depositional unit with abundant tidal sedimentary structures consistent with a shallow-marine depositional setting and the Kerbel Formation is a siliciclastic depositional unit consistent with a marginal-marine depositional setting.

The lower part of the Conasauga Formation consists of sandstone beds organized into a coarsening- and thickening-upward sequence of massive bedded, planar laminated, cross-bedded, and hummocky stratified sandstone. These beds are interbedded with beds having heterolithic tidal features such as flaser-bedding and wavy-bedding of heterogeneous
sandstone and silty mudstone. This section in the GR-log shows the irregular shaped pattern with no trend, and is interpreted as bay-head delta deposits.

This section is followed by a coarsening upward sequence of sandstone beds with planar-bedding, cross-bedding, and hummocky cross-stratification interbedded with minor tidalite beds. In the GR-log, this section is represented by a funnel-shaped pattern with abrupt tops suggesting a coarsening-upward trend. This sequence is interpreted as deposited in offshore transition zone from subtidal to lower intertidal flat deposits.

The overlying section, middle part of the Conasauga Formation, consists of dolomitized limestone, sandstone, and siltstone with planar-lamination, cross-bedding, hummocky-stratification alternating with beds rich in tidally-influenced structures such as flaser-, lenticular-, and wavy-beddings, and planar rhythmites of heterogeneous sandstone and siltymudstone. In GR-log this section is represented by an irregular pattern with no trend and is interpreted to be the part of intertidal deposits.

This section is followed by a funnel-shaped gamma-ray log pattern in upper part of the Conasauga Formation and whole section of the Kerbel Formation, suggesting an overall coarsening-upward trend. The upper part of the Conasauga Formation consists of very fine-grained sandstone with minor interbedded beds of thin mudstone. The Kerbel Formation consists of a coarsening-upward sequence, changing from fine-grained sandstone at the base to coarse-grained sandstone at top, that presents massive, parallel-laminated, and cross-bedded sandstone with carbonate intraclasts consisting of micrite, peloids, ooids, and bioclasts. These sandstone beds are interpreted as a barrier and/or overwash deposit.
A similar sequence of GR-log pattern is also found from logs of Well-20154 in Erie County, Well-20233 in Huron County, and Well-20148 in Marion County. The only difference between wells is the thickness of the various sections. The Kerbel Formation is thickest in the Seneca County with thickness of 23-m and the Conasauga Formation is thickest in the Marion County with thickness of 49-m. The matching of the general succession of lithofacies signature of the logs in four wells suggests that the depositional environment interpreted for Well-2580 is at least regional in character.

In summary, this study found that the Conasauga Formation sandstone beds of a bay-head delta system. These sandstones are reworked and overlain by tempestites, tidalites, and carbonates deposited in an offshore transition zone from subtidal to sand flat environments. These deposits are overlain by tidalite beds representing intertidal deposits in an estuarine or lagoonal depositional environment. The coarsening-upward trend of the strandplain (beach-barrier-overwash) of the Kerbel Formation above estuarine or lagoonal deposits suggests landward migration of the strandplain during transgression. As a whole, the sequences of the two units represent the late Cambrian marine transgression: landward migration of estuary, lagoonal, or tidal flat environments over a bay-head delta environment, and then landward migration of a barrier and/or overwash environment over estuarine, lagoonal, or tidal flat environments on a microtidal to mesotidal coast.
ACKNOWLEDGMENTS

My special thanks go to Dr. James E. Evans whose continuous support, direction, and encouragement made my research feasible and successful. I wish to thank the Ohio Geological Survey, especially Mr. Greg Schumacher, for access to the cores and logs at the Horace R. Collins Core Laboratory. I wish to thanks to Dr. Charles M. Onasch for his help in making thin-sections. Dr. Jeff Snyder helped me throughout my study in the department in this two years period with full care, which is hard to explain.

The data for this thesis is collected with the help of my friends Ahmmad, Joshua Thomas Maurer, Mike Moore, and Randy Williams. Without their help it would have been impossible to collect the data for this thesis.

Financially, my thesis work is supported by a graduate student grant- in- aid of research from the Geological Society of America and by the Fox Geophysical Scholarship in the Department of Geology at Bowling Green State University.

I am always indebted to my Father Parshuram Banjade, Mother Devkala Banjade, and Brother Dipak Banjade for their continuous support, desire, and strong will of my success in life.
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INTRODUCTION

A facies model is a general summary of a depositional environment presented in words or a diagram that shows the relationship between processes, geomorphologic features, and the deposits that eventually can be preserved in the ancient record (Walker, 1992). This model is then used for the interpretation of the environment, as a norm or standard for the basis of comparison, and also useful as a predictor to find economically important geologic resources. This research is focused on facies analysis of two Cambrian units in Ohio, the Conasauga Formation and the Kerbel Formation, in order to understand their depositional environments.

Both of these units are part of the Cambrian sequence in Ohio and are composed of different proportions of sandstone, siltstone, shale, and carbonate, and thus are considered to be part of a marginal-marine sequence. In Ohio, both rock units are in the subsurface. The units were named as the Conasauga Formation and Kerbel Formation by Janssens (1973). Subsequently, Ryder et al. (2008) proposed the Conasauga Group, to include both the Conasauga Formation and the underlying Rome Formation. Janssens (1973) considered the Conasauga Formation and Kerbel Formation to be deposited due to the progradation of a deltaic plain over the adjacent prodelta depositional environment, while Donaldson et al. (1975, 1988) interpreted both units to be part of a tidal environment. Because these two interpretations do not match with each other, this study was proposed. The study of these two rock units will also help further our understanding of the Cambrian history of Ohio.

The purpose of the proposed research is to: 1) conduct a subsurface facies analysis of the Conasauga Formation and Kerbel Formation to re-evaluate the older interpretations that
these units formed in a deltaic or tidal environment; 2) to look for the evidence of tidal structures or storm deposits (tempestites); 3) to consider the possibility that the two units are actually a prograding shoreline sequence; and 4) look for the evidence of lagoon or estuarine sedimentation, or barrier over wash deposits.

Well cores and geophysical logs are the main source of data used for subsurface studies. Well cores can be used to study sedimentary structures, lithology, and grain size distribution for fining- and coarsening-upward successions. Well logs provide information about lithology, composition, textures, and sedimentary structures that will be used to define lithofacies, which are the basis of interpretation of the depositional environment. Because only one well is available with complete core preservation, this study uses Well-2580, drilled in Seneca County, as the main well, and three wells from adjacent counties to extend the interpretation of the two units based on geophysical logs. In Well-2580, detailed lithological study allows recognition of lithofacies, which are correlated with the well logs (gamma-ray log and neutron porosity log) from the same well to make a log signature model, which can be used to correlate to the adjacent wells (Well-20154 from Erie County, Well-20233 from Huron County, and Well-20148 from Marion County) (Fig. 1). The cores and logs are available from the Ohio Geological Survey.

Previous subsurface facies analyses of the Mt. Simon Sandstone (Saeed, 2002) and Rose Run Sandstone (Chuks, 2008) will serve as case studies for this research. Both studies used well cores and well logs from certain wells in Ohio to obtain information from the subsurface. These studies divided the wells into a control well and an experiment well. In the control well, the author first identified lithofacies from drill cores and then correlated those facies with their log signatures from the same well. This was used to produce a subsurface facies model. That model was then tested by interpreting the geophysical logs from the
experimental well, and then it was verified by matching with cores from the same experimental well. Chuks (2008) even used two extra wells for interpretation and correlation of geophysical logs. These studies verified the applicability of well logs to interpret sedimentary patterns and trends, and to achieve subsurface correlation, which would not have been possible through traditional methods (Wylie and Wood, 2005).
Figure 1. (A) Geological map of Ohio showing the general location of the four wells used for the study, (B) East-west cross section of Ohio showing relationships of Precambrian rocks and the East Continent Rift Basin to overlying Paleozoic sedimentary rocks (Hansen, 1997).
GEOLOGIC BACKGROUND

The Precambrian basement rocks of Ohio consist of metamorphic and igneous rocks of the Grenville Province in eastern Ohio, sedimentary and igneous rocks of East Continent Rift Basin in western Ohio, and igneous rocks of the Granite-Rhyolite Province in western Ohio. The basement rocks were affected by the Grenville Orogeny, 1.1 billion years ago. The Precambrian rocks are unconformably overlain by a thick (> 1000 m) section of Paleozoic sedimentary rocks. These rocks were deformed during the late Paleozoic Appalachian orogeny.

Precambrian

Two major Precambrian terrenes, the Granite-Rhyolite Province and the Grenville Province, form the basement rocks of Ohio (McCormick, 1961; Janssens, 1973; Lidiak et al., 1966). The Granite-Rhyolite Province consists of igneous rocks approximately 1470 Ma in age. The Granite-Rhyolite Province was deformed by subsequent doming of the crust from uprising magma caused major faulting and subsidence of thin lithosphere, associated with the development of a complex rift system called the East Continent Rift Basin (Drahovzal et al., 1992) (Fig. 1). This basin filled with thick clastic sedimentary and volcanic rocks forming the Middle Run Formation (Shrake et al., 1990). The rift basin is more than 6096 m thick in areas adjacent to the Grenville Front (Drahovzal et al., 1992). The Grenville Front is the boundary between the two provinces (Bass, 1960), and extends from Brown County to Lucas County along the western portion of Ohio. Along the Grenville Front, the strongly deformed Grenville- age metamorphic and igneous rocks are juxtaposed with the gently deformed Granite-Rhyolite Province igneous rocks. The Grenville Front is a zone approximately 54-
km wide, north-south oriented and having east-dipping imbricated thrust slices. The Bowling Green Fault also correlates with the position of the Grenville Front (Onasch and Kahle, 1991; Baranoski and Wickstrom, 1991; Baranoski, 2002), and is considered active since the late Precambrian (Wickstrom et al., 1992; Onasch, 1995). The Grenville Province consists mainly of granitic igneous and metamorphic rocks, which are approximately 950-1,350 Ma (mostly from 1,000 to 1,100 Ma) from isotopic ages (Rankin et al., 1993). Lidiak et al. (1966) reported an $^{87}$Rb- $^{87}$Sr biotite age of 860 Ma from the granite, and a $^{40}$K- $^{40}$Ar whole rock granodiorite vein age of 850 Ma from gneiss.

The Precambrian basement rocks are buried by the Paleozoic sedimentary rocks in the eastern mid-continental portion of the United States, but reach the surface in the Adirondack Mountains of New York and Ontario, and are locally exposed in the Appalachian basin where there has been significant, post-Paleozoic erosion. These basement rocks form a homoclinal ramp that dips gradually from an interior craton to the external margin of the Appalachian fold-and-thrust belt. The basement ramp deepens gradually southeastward from about 914- m below MSL on the eastern flank of the Findlay Arch to about 7,162- m below MSL under the Allegheny structural front (Ryder et al., 2008). This gradual deepening is locally interrupted by a Middle Cambrian rift system, the Rome Trough, where the depth of basement falls to 7924- m below MSL.

**Paleozoic Tectonic Setting**

With respect to Paleozoic plate tectonics, the rocks of Ohio are considered as part of the Laurentia Plate between the late Precambrian to early Cambrian. The Laurentia Plate formed from the Canadian Shield and overlying platform. Both of these two components contained an important local structure called the transcontinental arch, which at times had topographic relief and affected sedimentation (Riley et al., 1993). During the early Paleozoic,
the eastern margin of Laurentia consisted of a continental slope, continental rise, and continental shelf in the area around Ohio and Pennsylvania. During the late Precambrian to early Cambrian, Laurentia faced the Iapetus Ocean, which formed from the rifting of the southern Baltic plate from the eastern Laurentian plate. This rifting event is associated with the subsidence of several fault-bounded crustal blocks, which have been interpreted as aulacogens. The Rome Trough is interpreted as one of them, and became the locus or depocenter that captured thick deposits of Cambrian sediments in Ohio, Kentucky, West Virginia, and Pennsylvania.

Baranoski (2002) argued that tectonic quiescence of the Grenville thrust faults in the eastern part of the Grenville Front Tectonic Zone during the early Cambrian affected the Iapetus Ocean and led to the formation of the Appalachian Basin. Subsidence of these Grenville faults during the Early Paleozoic created a series of structural terraces stepping toward the basin (Gray et al., 1982; Riley et al., 1993). During the Paleozoic, three depositional basins formed in or near Ohio: the Michigan basin to the north, the Appalachian basin to the east, and the Illinois basin to the west. These three basins are separated by the Cincinnati, Findlay, and Kankakee arches (Janssens, 1973; Shearrow, 1987). The structural relief of these arches is considered to be the product of differential subsidence, rather than uplift, because of the relatively stable character or slow subsidence rate of the arches during the history of the sedimentary basins (Droste and Shaver, 1983). The Ohio Platform (Summerson, 1962), and the early phases of the Illinois, Michigan, and Appalachian Basins are four major structural elements dating to “pre-Ordovician” age in Ohio.

It has been suggested that numerous structural features of the Paleozoic age rocks formed or were reformed by re-activated Precambrian structures related to the Grenville Province. For example, the Bowling Green fault (Onasch and Kahle, 1991; Wickstrom et al.,
1992) is related to the sedimentary and tectonic features in northwestern Ohio, and the Rome Trough was responsible for similar features in northern Kentucky and adjacent West Virginia (Baranoski, 2002).

**Early Paleozoic Geologic History of Ohio**

During the early Cambrian, a shallow warm tropical sea encroached upon the craton, including the study area (Hagadorn et al., 2002). The Mt. Simon Sandstone is the oldest Paleozoic unit in Ohio, and was deposited in a nearshore coastal environment (Ostrom, 1966; Saeed, 2002). As the result of the subsidence of the craton, the transgression of Cambrian sea from southeast and southwest created the blanket deposition of the Mt. Simon Sandstone over most of Ohio, except some basement monadnocks. The Mt. Simon Sandstone was overtopped by, from oldest to youngest, the Rome, Eau Claire, Conasauga, and Kerbel formations as part of the Late Cambrian transgression. Deposition of the overlying Late Cambrian Knox Group occurred in a shallow-marine carbonate environment, as the Ohio region was completely covered by shallow marine environments. According to Riley et al. (1993), Cambrian sandstones were deposited around the margin of the transcontinental arch, while carbonates were deposited in the adjacent shallow marine environments. Thus, the interfingering of Cambrian sandstone and carbonate resulted from fluctuations in sea level.

According to Rankin (1975), the rifting that created the Proto-Atlantic or Iapetus Ocean, continued through the Cambrian and into early Ordovician time. This rifting, together with the subsidence of the craton from east to west, created the Iapetan rift- and passive-marine sequence (Table 1). There were four stages of the development of this sequence: (1) The “Lower Iapetan Sequence”, which consists of the syn-rift deposition of texturally and compositionally immature, poorly sorted, feldspathic siliciclastic sedimentary rocks of Ocoee
Table 1. Sequences of the Iapetan rift- and –passive margin sequences with their stratigraphic units and depositional environments.

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<td>Knox Group</td>
<td>Carbonate Shelf</td>
</tr>
<tr>
<td></td>
<td>Pre- Knox Sequence</td>
<td>Kerbel Formation</td>
<td>Delta Plain</td>
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<tr>
<td></td>
<td></td>
<td>Conasauga Formation</td>
<td>Clastic Tidal Flat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rome Formation</td>
<td>Clastic Shelf</td>
</tr>
<tr>
<td></td>
<td>Carbonate Sequence</td>
<td>Mt. Simon Sandstone</td>
<td>Shoreface/Foreshore, Tidal Flat</td>
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<tr>
<td></td>
<td></td>
<td>Shady or Tomstown Dolomite</td>
<td>Carbonate Shelf</td>
</tr>
<tr>
<td>Lower Cambrian</td>
<td>Lower Iapetan Sequence</td>
<td>Erwin Formation</td>
<td>Shallow marine Shelf</td>
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<tr>
<td></td>
<td></td>
<td>Hampton Shale</td>
<td>Silt- and mud- dominated marine shelf</td>
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<tr>
<td></td>
<td>Proterozoic</td>
<td>Ocoee Supergroup</td>
<td>Deeper Water Turbidites</td>
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<tr>
<td></td>
<td></td>
<td>Great Smoky Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Walden Creek Group</td>
<td>Unstable Shelf Deposits</td>
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<tr>
<td></td>
<td></td>
<td>Snowbird Group</td>
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Subgroup, had sediment sources derived from erosion of basement rocks. Rifting and subsidence of the craton led to the transgression of the sea from east to west and the deposition of the more well sorted elastic rocks of the Hampton and Erwin Formations. (2) The “Carbonate Sequence”, including the Shady Formation and Tomstown Dolomite (Read, 1989a, b) were deposited with the continued transgression. (3) The Rome Formation of the “Pre-Knox Sequence” in filled the Rome Trough, which was formed due to renewed rifting, marginal uplift, arching and thinning of the crust within the interior of the continent (Sutton, 1981). The newer episode of rifting resulted in clastic deposition in the intercratonic grabens and carbonate deposition along the continental margin. Some carbonate was deposited during the middle Cambrian outside the graben areas, which was followed by the deposition of the Conasauga Group and Kerbel Formation during the Late Cambrian (Hansen, 1997). (4) The Knox Group, of the “Knox Sequence” was deposited after the Rome Formation along the eastern part of the Appalachian basin. The Knox Group carbonates were eventually deposited over the entire margin during the late Cambrian to early Ordovician. Finally, the Taconic Orogeny ended the Iapetan rift- and passive- marine sequence, and created a regional unconformity (Rodgers, 1971; Shanmugan and Lash, 1982).

Stratigraphy

The Mt. Simon Sandstone, Conasauga Group (which consist both Conasauga Formation and Rome Formation), and Kerbel Formation are part of the pre-Knox sequence, which lies below the Cambrian-Ordovician Knox Group (and the equivalent Gatesburg Formation in Pennsylvania and New York) (Fig. 2). These units extend from the northern Kentucky to Michigan and New York, with an increase in thickness in the Rome Trough. The deposits in the Pre-Knox sequence can be subdivided into: (1) deposits in the craton in
Figure 2. Stratigraphy of pre-Knox Group of Ohio (from Janssens, 1973) [MRS = Middle Run Sandstone].
northern Kentucky, Ohio, western Pennsylvania, western New York, and Ontario, (2) deposits in the Rome Trough, in central Kentucky, West Virginia, Pennsylvania, and southern New York, and (3) deposits between the Rome Trough and the Allegheny structural front (Ryder, 1992a) (Fig. 3). Harris (1975) interpreted the cratonic area to be the stable shelf, and Rome trough to be an unstable shelf province.

Thomas (1991) considered the Pre-Knox sequence in the Appalachian basin to represent a transgressive sequence, with the shoreline migrating in the northwesterly direction. The Precambrian basement rocks are overtopped by late Precambrian clastic and volcanic syn-rift rocks along the Appalachian Blue Ridge. These rift-fill successions and basement rocks are overlain by the sandstones including the Mt. Simon Sandstone of the transgressive sequence, which indicate the time of transition from an active rift to a passive margin along the Blue Ridge. The different proportion of sandstone, siltstone, carbonate, and shale of the Pre-Knox sequence indicate complexities of the resulting shallow marine environment (Harris and Baranoski, 1997).

Conasauga Group

The Conasauga Formation was first named as the Conasauga Shale, for the Conasauga Valley in northwestern Georgia (Hayes, 1892). In type locality, it is underlain by the Rome Formation and overlain by the Knox Dolomite. The Conasauga Formation can be traced from west-central Ohio to eastern Kentucky and can be correlated with the lower sandy member of the Gatesburg Formation (Wagner, 1966) in northwestern Pennsylvania. In Kentucky, the name Conasauga Formation was first used by Thomas (1960), who assigned previously undescribed shale and limestone to the formation.

In eastern Tennessee, Rodgers (1953) used the term Conasauga Shale for shales which pass to the southeast into six units composed of alternating sequences of shale and
Figure 3. Major Structural features and tectonic provinces for the Cambrian pre-Knox Group play (from Harris, 1975).
limestone, altogether forming the Conasauga Group. The units in ascending order are the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale and Maynardville Limestone. In the Rome Trough, the Conasauga Group consists of the Maryville Limestone, Rogersville Shale, Rutledge Limestone, and Pumpkin Valley Shale. Rodgers (1953) considered the term “Conasauga Group” to be useful only when the lower limestone member of Maynardville Limestone can be found, while the term “Conasauga Formation” is better when only the upper dolomite member of the Maynardville Limestone can be found.

In Ohio, Janssens (1973) considered the Conasauga Formation and Rome Formation to be separate stratigraphic units, both of which later considered as Conasauga Group. Janssens (1973) described the composition of the Conasauga Formation as red and green shale with interbedded glauconitic siltstone, limestone, dolomite, and very fine-grained sandstone. He determined the lower contact (with the Rome Formation) and the upper contact (with the Kerbel Formation) to be gradational, and that the thickness of the unit varies from 13 to 137- m. From lithofacies analysis and evaluation of stratigraphic relationships of the post-Mt. Simon to pre-Knox strata in Ohio, Janssens (1973) interpreted the Kerbel Formation to be a deltaic deposit, which prograded over prodelta deposits of the Conasauga Formation (Fig. 4). This interpretation was based on the composition of the Conasauga Formation (shale with interbedded carbonate and fine-grained sandstone) and the coarsening-upward sandstone content of the Kerbel Formation.

Harris et al. (2004) considered the Rome Formation of Janssens (1973) in eastern and central Ohio to be an obsolete stratigraphic term and instead proposed that both the Conasauga Formation and Rome Formation can be merged into the Conasauga Group (Ryder et al., 2008). According to Ryder et al. (2008), the total thickness of the Conasauga Group
Fig 4. Proposed generalized paleogeography of Ohio and adjacent areas during late Middle Cambrian time (from Janssens, 1973, Beardsley and Cable, 1983, Lochman- Balk, 1970, and Baranoski, 2002). The “Kerbel delta” deposited sand on the prodelta mud of the Conasauga Formation to the SW, with muddy carbonate shelf deposits of the Conasauga Formation east of the delta and sandy shelf deposits of the Eau Claire Formation west of the delta. At this time, the Rome Trough was an area of thick sediment accumulation in eastern and southern Ohio. The edge of the Iapetus Ocean- Continental shelf was present on the western side of the Rome trough. Arrows indicate the direction of sediment transport. An important source of clastic sediment for the Kerbel delta was the Canadian Shield to the north.
(or its equivalents the Elbrook Formation and Trenton Limestone) range upward from 335-m on the eastern flank of the Findlay arch to 2468- m beneath the Allegheny structural front. In the Rome Trough, the Conasauga Group is typically between 457- m and 762- m thick and consists of the Maryville Limestone and the Nolichucky Shale (Ryder et al., 2008).

Donaldson et al. (1975, 1988) examined the depositional environment of the Rome Formation and Conasauga Formation from cores of two wells in West Virginia and interpreted that the carbonate and clastic facies were deposited in tidal-flat, tidal-channel, and shallow subtidal marine environments. Read (1989a, b) interpreted the depositional environment of both the Cambrian Conasauga Group and Ordovician Trenton Limestone as the deposits of a post-rift passive margin sequence. He also interpreted the Middle Ordovician Knox unconformity as due to continental-scale erosion resulting from eustatic sea level fall and/or tectonic uplift which followed the Taconic orogeny.

Schwimmer and Montante (2007) interpreted the Conasauga Formation as the product of inner-shelf and shelf-edge depositional environments that formed the Laurentian margin of the Cambrian Iapetus Ocean. In the Valley- and -Ridge Province of eastern Tennessee, the Conasuaga Group is interpreted as an intrashelf basin bounded by a high-relief carbonate shelf to the east and the craton to west (Rodgers, 1968; Palmer, 1971; Markello and Read, 1981). In the same province of east Tennessee, Hasson and Haase (1988) suggested three depositional environments for the Conasuaga Group: (1) shallow water, shale-dominated peritidal settings on the northwestern margin of the craton, (2) shelf margin, carbonate-dominated shoal and peritidal settings, and (3) mixed siliciclastic-carbonate shoal and peritidal settings. Cambrian polymerid trilobite zones (Table 2) with the *Ehmaniella* and *Bolaspidella* Biozones, found in the Conasauga Formation, suggest that the depositional
Table 2. Paleontology of the Conasauga Formation.

<table>
<thead>
<tr>
<th>Ehmaniella Zone</th>
<th>Bolaspidella Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trilobita</strong></td>
<td></td>
</tr>
<tr>
<td>Glyphaspis capella</td>
<td>Elrathia antiquata</td>
</tr>
<tr>
<td>Naraoia compacta</td>
<td>Asaphiscus gregarious</td>
</tr>
<tr>
<td>Asaphiscus sp.</td>
<td>Alokistocare americanum</td>
</tr>
<tr>
<td>Bolaspis cf. B. labrosa</td>
<td>Peronopsis sp.</td>
</tr>
<tr>
<td>Tonkinella sp.</td>
<td>Solenopleurella (?) sp.</td>
</tr>
<tr>
<td>Olenoides sp.</td>
<td>Bolaspidella sp.</td>
</tr>
<tr>
<td>Solenopleurella sp.</td>
<td>Olenoids sp.</td>
</tr>
<tr>
<td>Peronopsis sp.</td>
<td></td>
</tr>
<tr>
<td><strong>Brachiopoda</strong></td>
<td></td>
</tr>
<tr>
<td>Wimanella aurialis</td>
<td>Acrothyra sp.</td>
</tr>
<tr>
<td>Acrothyra sp.</td>
<td>Lingulella sp.</td>
</tr>
<tr>
<td>Lingulella sp.</td>
<td>Paterina sp.</td>
</tr>
<tr>
<td>Micromitra sp.</td>
<td></td>
</tr>
<tr>
<td><strong>Hyolithida</strong></td>
<td></td>
</tr>
<tr>
<td>Hyolithida, gen. &amp; sp. Indet.</td>
<td></td>
</tr>
<tr>
<td><strong>Porifera</strong></td>
<td></td>
</tr>
<tr>
<td>Leptomitus cf. L. zitteli</td>
<td>Leptomitus cf. L. zitteli</td>
</tr>
<tr>
<td>cf. Choia sp.</td>
<td>Eiffelia cf. E. globosa</td>
</tr>
<tr>
<td>Hexactinellida, gen. &amp; sp. Indet.</td>
<td>? Brooksella alternate</td>
</tr>
<tr>
<td>(= BrookSELLA alternate spicules?)</td>
<td></td>
</tr>
<tr>
<td><strong>Rhodophyta</strong></td>
<td></td>
</tr>
<tr>
<td>Dalyia racemata</td>
<td>Dalyia racemata</td>
</tr>
<tr>
<td><strong>Chlorophyta</strong></td>
<td></td>
</tr>
<tr>
<td>Chlorophyta, gen. &amp; sp. Indet.</td>
<td>cf. Ottoia prolific</td>
</tr>
<tr>
<td><strong>Ichnotaxa</strong></td>
<td></td>
</tr>
<tr>
<td>Dactyloidites sp.</td>
<td></td>
</tr>
<tr>
<td>(? = Brooksella alternate: Hexactinellida)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Walcott, 1916; Resser, 1938; Schwimmer and Robinson, 1990; Schwimmer and Montante, 2007; field observations.
environment of Cambrian inner-shelf (*Ehmaniella*) and mid- to- outer Shelf (*Bolaspidella*) (Schwimmer and Montante, 2007).

**Kerbel Formation**

According to Janssens (1973), the Kerbel Formation is 50- m thick and composed of coarsening- upward, fine- to coarse-grained sandstone. Sandstones assigned to Kerbel Formation in Ohio were previously reported as the Dresbach Formation or Franconia Formation (Cohee, 1945; Fettke, 1948), and both the formations were traced from eastern Wisconsin through northeastern Illinois and northern Indiana into northwestern Ohio and south-eastern Michigan (Cohee, 1945). The Kerbel Formation can be correlated to the Galesville and Ironton Formations in Illinois and both the Kerbel Formation and Conasauga Formation in eastern Ohio are equivalent to the Eau Claire Formation in western Ohio (Janssens, 1973). Rodgers (1953) included the Kerbel Formation in his Conasauga Group in eastern Tennessee. Rocks correlative with the Kerbel Formation in eastern Kentucky are mapped as the basal Knox Group by McGuire and Howell (1963) (Fig. 5) and occupy the same stratigraphic position of the Maynardville Limestone. Wagner (1966) correlated the Kerbel Formation with the upper part of the lower sandy member of the Gatesburg Formation in northwestern Pennsylvania. In eastern Ohio, the Kerbel Formation becomes dolomitic, and gradually thins and pinches out into Knox Dolomite (Ryder et al., 2008).

Janssens (1973) suggested that the source of sand in the Kerbel Formation was to the north because of the northward thickening of the Kerbel Formation (Fig. 4). He interpreted the Kerbel Formation as progradational unit, forming a coarsening- upward sequence, with very fine- and fine- grained sandstone at the base changing to medium- and coarse- grained sandstone at the top. Janssens (1973) argued that the Kerbel Formation was deposited in a
Figure 5. Correlation of the Conasauga Formation and Kerbel Formation with other stratigraphic units (Conasauga Group, Maryville Limestone, Rogersville Shale, Rutledge Limestone, Pupkin Valley Shale, Rome Formation, Shady Tomstown Dolomite, Warrior Formation, Pleasant Hill Formation, and Warrior Formation) (modified from Janssens, 1973; Bailey Geological Sevices Ltd. & Cochrane, 1984; Milici & Dewitt, 1988; Ryder, 1992a; and Riley et al., 1993). LSM= Lower Sandy Member, Gatesburg Formation, PHF= Pleasant Hill Formation, BS= Basal Sandstone.
local transgression and that progradation during transgression was accomplished due to the abundant supply of the sand relative to change in sea level.

**Importance of the Study**

In Ohio, the Cambrian Conasauga Formation and Kerbel Formation, have not been studied extensively. Most of the previously published information about these units was based on either a brief study of the two units or references to the work of Janssens (1973). Results of Janssens (1973) needs to be update with the use of more recent information or understandings about storm deposits, tidalites, and sequence stratigraphy.

The two previous interpretation about the depositional environment of the two units, by Janssens (1973) and Donaldson et al. (1975, 1988) are controversial. This study will attempt to solve the inconsistencies between the two interpretations with the use of facies analysis technique. This study will help to establish the Cambrian geological history of Ohio, which will be helpful for further research and will improve the correlation of Cambrian rocks of Ohio to rocks with adjacent counties.

This study will create a log facies model for the lithological successions of the two units, which can be utilized for the wells of adjacent counties where core is missing and only the geophysical logs are available.

The two rock units are members of “the pre-Knox Play”, which means that these units are also important as petroleum resources. Currently the two units are not proved to have petroleum potential, but both are considered important targets for future petroleum exploration. Thus, the results of this study will be helpful for petroleum exploration in Ohio.
METHODOLOGY

Drill Core

Core Analysis

This research is partly based on the study of drill core sections and includes a study of both lithology and sedimentary structures through hand samples and thin-sections. Overall 30 rock chip samples were collected for petrographic study, and thin-sections were made in the laboratory of the Department of Geology of Bowling Green State University. Thin-sections were particularly helpful in recognizing the modified carbonate textures in dolostone and arenaceous dolostones. Petrography gave the information about the intraclasts and glauconites which were hard to identify in cores. Altogether 11 sandstone thin-sections were point counted for provenance analysis using the Gazzi-Dickinson method (Dickinson, 1970; Gazzi, 1966). More than 200 grains per sample was counted per slide and the results are given in Appendix B. Sandstone mineral composition (as quartz, feldspar, and lithic fragments) obtained from point counts were plotted on the ternary diagrams (QFL and QmFLt plots) using the methods of Dickinson and Suczek (1979) and Dickinson et al. (1983).

Well Locations

According to Wickstrom et al. (1985), Well-2580 was drilled in 1985, in Liberty Township, Seneca County, by the Division of Geological Survey of the Ohio Department of Natural Resources. The purpose of drilling this well was to investigate the general geology, stratigraphy, geological structure, mineral presence, and hydrocarbon potential of Lower Paleozoic rocks in north-central Ohio. The drilling site has an altitude of 212- m above sea level. Well coring was done with a Model B-61 Pacemaker truck-mounted drill rig, manufactured by Mobile Drilling Company. Rotary drilling was performed until bedrock
found which was at 9-m, then NQ core bit and NCQ drill rods were utilized to drill up to 124-m depth, and BQ core bits and BCQ drill rods were utilized to drill the rest of the well, which had a length of 874-m. The NCQ drill rods were used for the intermediate casing string after drilling up to 124-m to block the inflow from the overlying freshwater aquifers. The core is stored in the Horace R. Collins Laboratory of the Ohio Geological Survey at Alum Creek State Park, Ohio. The cores were put in boxes and each box contains cores of about 3-m length. There was full preservation of the cores from the top of Kerbel Formation to bottom of Conasauga Formation, except for poor preservation of the Kerbel Formation between 692- to 697-m core lengths.

**Geophysical Logs**

**Gamma-ray log**

The gamma-ray (GR) log is based on the natural gamma-ray activity present in lithologies in the well. The gamma-ray log response is related to the presence of radioactive minerals as $^{40}$K, $^{238}$U, and $^{232}$Th (Table 3). The GR log is considered as a sensitive indicator of shale content and useful for correlation and facies studies (Miall, 1985). Generally, low GR-log responses are found in sandstones and carbonates, and high gamma-ray responses are found with increasing proportions of shale. However, sometimes because of the presence of potassium feldspars, micas, or glauconite, sandstone with low shale content can give a high gamma-ray response (Asquith and Gibson, 1982). In particular, diageneric clays in pores, presence of illite-rich shale partings, or higher amounts of K-feldspar in sandstone are problematic for GR log analysis, and in this case the spectralog can be beneficial. The spectralog works by using activation energy to divide the total natural radioactivity into thorium, potassium, and uranium spectral peaks, showing relative abundance. Thus if a zone
Table 3: Presence of radioactive isotopes in different minerals.

<table>
<thead>
<tr>
<th>Radioactive isotope</th>
<th>Minerals that contains these isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>illite, sylvite, K- feldspar, Biotite, muscovite, hornblende, glauconite.</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>organic matter, apatite, zircon, sphene, ore minerals.</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>organic matter, apatite, zircon, sphene, ore minerals.</td>
</tr>
</tbody>
</table>

has both high potassium content and high GR- log response, then the spectral log could recognize the importance of feldspar, glauconite, or mica (Asquith and Gibson, 1982).

Assuming that the GR- log response is due to the shale content, the following gamma log trends can be distinguished (Fig 6). GR- log patterns can be cylindrical, funnel- shaped, bell- shaped, symmetrical, or irregular depending upon the lithological sequence. Cylindrical log patterns lack any trend in the log shape and suggest the presence of “clean” sandstones or carbonates. These can be found in aeolian, braided fluvial, carbonate shelf, reef, or submarine canyon- fill depositional environments. Funnel- shaped log patterns indicate a coarsening- upward trend with an abrupt top. This suggests crevasse splay, distributary mouth bar, barrier island, shallow marine sheet sandstone, carbonate shoaling- upward sequence, or submarine fan lobe depositional environment. Bell- shaped log curve patterns have fining- upward trends and an abrupt base. This suggests fluvial point bar, tidal point bar, deep sea channel, or some transgressive shelf sands depositional environments. Symmetrical log curve patterns have a rounded base and top. This suggests sandy offshore bar, transgressive shelf sands, or amalgamated coarsening- upward and fining- upward units. Irregular log curve patterns indicate no particular grain-size trend. This can be interpreted as fluvial floodplain, carbonate slope, clastic slope, tidal flat, or canyon- fill depositional environments (Cant, 1992).

Neutron porosity logs

The neutron- porosity (NP) log uses a neutron source to measure hydrogen ion concentration in the lithology, which is directly related to water content and thus indicates porosity. In this logging method, neutrons from an energy source are backscattered by collision with hydrogen atoms. The amount of backscattering is proportional to the water content. Neutrons are produced with a specific energy level from a radioactive source (e.g., a mixture of americium and beryllium) present in the logging tool, and the energy of the
Fig 6. Generalized gamma-ray response curves. The GR-log pattern can be interpreted for different environments (modified from Cant, 1992). See text for discussion.
backscattered neutrons are measured. The greatest loss of energy will be when neutrons collide with hydrogen atoms because they have equal mass. Thus the hydrogen content in the formation gives an estimate of the porosity in the rock unit. Especially in shale-free lithologies, the NP-log is useful to measure liquid-filled porosity (Asquith and Gibson, 1982). NP-logs can be used with the GR-logs for correlation, sequence analysis, or microfacies analysis (Fig. 7). GR-logs depend upon the radioactivity present in the rocks while NP-logs depend on the pore spaces present in the rock, so the response can be entirely opposite. For example, in coarse-grained sandstones, the GR-log may be low, but the NP-log may be high, indicating high porosity.
Figure 7. Neutron-porosity and Gamma-ray log response to different microfacies in a sequential vertical trend (modified from Rider, 1996).
RESULTS

Stratigraphy of Well- 2580 Core

The measured section of the Well- 2580 includes a portion of Rome Formation, all of the section of the Conasauga Formation and Kerbel Formation, and a portion of the Knox Dolomite (Fig. 8 and Appendix A).

Conasauga Group

In Ohio, the Conasauga Group is divided into two stratigraphic units, the Rome Formation and Conasauga Formation (Janssens, 1973). The Rome Formation consists of dolomite in eastern Ohio and sandstone in central Ohio. The Conasauga Formation consist of red and green shales with interbedded glauconitic siltstone, limestone, dolomite, and very fine- grained sandstone, with thickness ranging from 12-m to 137-m (Janssens, 1973).

In Well- 2580 drilled in Seneca County, the measured section of the Rome Formation consists of greater than 2.7-m of monotonous beds of massive bedded, intraclastic dolostone. The Conasauga Formation consists of mixed siliciclastic and carbonate sequences. The siliciclastic sequences consist of siltstone, heterogeneous siltstone-mudstone, very fine- to medium- grained sandstone, and heterogeneous sandstone and silty mudstone. The carbonate sequences consist of micritic dolostone and fossiliferous limestone. The Conasauga Formation is recognized from the Kerbel Formation and Rome Formation based on the presence of very fine- grained sandstone and mudstone, while the Kerbel Formation consists of fine- to medium- grained sandstone, and the Rome Formation consists almost entirely of dolostone. The overall thickness of the Conasauga Formation in Well- 2580 is 37-m.
Figure 8. Core stratigraphy of Well-2580 including the Conasauga Formation and Kerbel Formation (Wickstrom et al., 1985).
The lower part of the Conasauga Formation consists of a coarsening and thickening-upward sequence of massive bedded, planar- laminated, cross- bedded, and herringbone cross- bedded sandstone with some tidalites of flaser-, wavy-, and lenticular bedded sandstone and silty mudstone. The middle part of the Conasauga Formation consists of tempestite and tidalite beds. The tempestite beds consist of hummocky stratified sandstone, cross- bedded sandstone, massive sandstone and planar laminated sandstone. The tidalite beds consists of the flaser-, lenticular-, wavy-, and rhythmic planar- beds of the siliciclastic composition. Glauconite intraclasts are concentrated in both the siliciclastic and carbonate lithofacies. The upper part of the Conasauga Formation is composed of thick beds of parallel-laminated sandstone, and minor beds of massive sandstone, and flaser- bedded and rhythmic planar- bedded heterogeneous sandstone and silty mudstone, shale, mudstone, and parallel laminated siltstone. Sandstone is the dominant lithology of the Conasauga Formation, with grain size ranging from very fine- grained to medium- grained, but very- fine grained sandstone is the most abundant.

**Contact between Conasauga Group and Kerbel Formation**

The contact between the Conasauga Formation and the Kerbel Formation is recognized by the change of grain size. The upper part of the Conasauga Formation is composed of the interbedded very fine- grained sandstone and mudstone, which passes upward into an interbedded sequence of fine- grained sandstone and very fine- grained sandstone into the fine- grained sandstone of the Kerbel Formation (Fig. 9). The interbedded interval is taken as the contact between the Conasauga Formation and Kerbel Formation. Janssens (1973) also pointed out that the Conasauga Formation grades conformably into the overlying Kerbel Formation.
Figure 9. Stratigraphic section showing the gradational contact between Conasauga Formation and the Kerbel Formation in Well-2580.
**Kerbel Formation**

The Kerbel Formation consists of a coarsening-upward sequence of massive bedded, parallel-laminated, cross-bedded, and hummocky-stratified, fine- to coarse-grained, poorly to well sorted, calcareous quartz arenite with thickness up to 52-m (Janssens, 1973). In Well-2580, the Kerbel Formation consists of a coarsening-upward sequence of fine-grained sandstone grading upward into medium-grained sandstone in the middle part of the Kerbel Formation, and coarse-grained sandstone in upper part of the Kerbel Formation. The lithology of the Formation is a monotonous sequence of fine- to coarse-grained, poorly to well sorted, light gray, dolomitic quartz arenite and quartz wacke with subtle changes in grain size. The overall thickness of the Kerbel Formation in Well-2580 is of 24-m. Fine-grained sandstone consists of 15-m of the section. The overlying medium-grained sandstone is of 7-m, and the coarse-grained sandstone is of 2-m thick. About 5-m of section is missing in the fine grained sequence. The missing section is interpreted as the fine-grained sandstone based on the geophysical log. The content of the dolomite cement increases with the grain size, in other words, medium-, and coarse-grained sandstone has more dolomitic cement than the finer-grained sandstone. The medium- and coarse-grained sandstone also contain carbonate lithoclasts (peloids, ooids, and micrites) (Fig. 10a). These intraclasts were derived from local carbonate sediment and have been subsequently dolomitized.

**Contact between Kerbel Formation and Knox Dolomite**

The Kerbel Formation is overlain by the Knox Dolomite. The contact is sharp rather than gradational. The contact was placed based on the change of composition, where siliciclastic composition of Kerbel Formation is passing upward to the carbonates of the Knox Dolomite. The identification of the contact was facilitated by the thin-section study. Towards the contact, sandstone in the Kerbel Formation contain more dolomitic cement, and
Figure 10. (a) Photomicrograph of Kerbel Sandstone and shows medium-grained quartz grains are cemented by calcite cements. (b) Photomicrograph of Knox Dolomite close to the contact with the Kerbel Formation and shows the lamina of quartz grains in the carbonates. Key: Q= Quartz, C= Cement, O= Oolite, In= Intraclasts, Mi= Microcline, D= Dolomite and Pl= Plagioclase.
carbonates in the Knox Dolomite become more arenaceous (with abundant quartz grains) (Fig. 10b). The change of lithology from siliciclastic to carbonate shows the change of depositional environment, which can be associated with shifting environments due to the transgression. In Ohio, a regional transgression is interpreted for late Cambrian time, which created an overall transgressive depositional sequence with the progressively younger rocks deposited over older rocks in a northwesterly direction (Thomas, 1991).

**Knox Dolomite**

In Ohio, the Knox Dolomite consists of light- to medium- gray and very light- to medium- brown dolostone. The dolostone is mostly microcrystalline, with some portions being very fine- to medium- crystalline and rarely portions are coarsely crystalline (Janssens, 1973). In Well- 2580, the Knox Dolomite is recognized from the Kerbel Formation with the help of lithology. The Knox Dolomite is composed of light- gray dolostone that replaced intraclastic limestone and oolitic limestone, while the upper part of the Kerbel Formation consists of light- gray, coarse- grained dolomitic quartz arenite and quartz wacke. The dolomite towards the contact is sandy and coarse- grained, and grade upwards into microcrystalline dolostone. In thin-section, samples of the Knox Dolomite adjacent to the Kerbel Formation contain interbedded quartz sandstone laminae (Fig. 10b).

**Lithology**

**Sandstone**

Sandstones in the Consauga Formation and Kerbel Formation range from very fine- to coarse- grained, with a variety of sedimentary structures including planar- lamination, cross-bedding, hummocky- stratification, massive bedding, and different tidalite bedding such as
ripple lamination alternating with silty mud. Specifically in the Conasauga Formation, sandstones contain planar-lamination, cross-bedding, hummocky stratification, and massive bedding. The rhythmic facies associated with the sandstone include flaser-, wavy-, lenticular-, and rhythmic planar-beddings (Figs. 11). The texture range from very fine-grained to medium-grained, well-sorted, sub-rounded to rounded. Compositonally, the sandstone is light gray, calcareous quartz arenites with lithoclasts, including bioclasts (brachiopods and echinoderm), ooids, peloids, and glauconite (Fig. 12). The trace fossils include Ophiomorpha, Planolites, Arenicolites, and Skolithos (Fig. 13). The Conasauga Formation is rich in burrows compared to the Kerbel Formation.

Sandstones of the Kerbel Formation are of fine- to coarse-grained, poorly to well sorted, subrounded to well rounded, calcareous or dolomitic quartz arenite or quartz wacke. Primary sedimentary structures includes planar-lamination, cross-bedding, hummocky-stratification, and massive bedding. Secondary features include voids. Sandstones of the upper part of the Kerbel Formation are more dolomitic than the sandstones of the lower part of the Kerbel Formation. Some sandstones in Kerbel Formation are rich in dolomite cements (Fig. 12b), which indicates higher porosity because carbonates are precipitated in pore spaces between grains. Lithoclasts in the sandstone include oolites, peloids, grapestone, bioclasts, and micrites. In addition to quartz, minor amounts of microcline, plagioclase, and perthite can be observed (Fig. 14).

Siltstone

Siltstone is mostly found as rhythmic planar laminated siltstone-mudstone couplets with massive bedded and planar-laminated siltstones in the middle part of the Conasauga Formation. The massive and planar-laminated siltstones are well-sorted, sub-angular to angular, coarse-grained, calcareous quartz siltstones with minor feldspar (<10% plagioclase
Figure 11. Photomicrograph of heterolithic sandstone and silty mudstone from Conasauga Formation. (a) Lenticular- bedded sandstone and silty mudstone. (b) Wavy- bedded siltstone and silty mudstone. (c) Planar- bedded siltstone and silty mudstone. Key: In= Intraclast, Q= Quartz.
Figure 12. (a) Photomicrograph of sandstone rich in brachiopod intraclast from Conasauga Formation. (b) Photomicrograph of sandstone rich in calcareous cement and clasts with grapestone from Kerbel Formation. Key: Q= Quartz, Oo= Oolites, Pe= Peloid, Gl= Glauconite, D= Dolomite, and C= Cement.
Figure 13. Core photos of burrows present in the core of the Well-2580 drilled in the Seneca County. (a) *Skolithos* in sandstone and dolostone from Conasauga Formation. (b) *Planolites* in sandstone from Kerbel Formation, (c) *Arenicolites* in sandstone from Conasauga Formation, (d) *Ophiomorpha* in sandstone from Conasauga Formation.
Figure 14. Photomicrograph of sandstone from Kerbel Formation. (a) Massive, coarse-grained Quartz arenite, (b) Massive, fine-grained Quartz arenite. Key: Q= Quartz, C= Cements, M= Microcline, In= Intraclast, Qr= Quartz replaced by dolomite, Oo= Oolite.
and microcline). Lithoclasts of siltstone are also present in minor amounts in the carbonate rocks of the Conasauga Formation. These carbonates also include individual angular clasts of quartz silt that have the same characteristics as the siltstones described above. These individual silt grains in the carbonates are interpreted as eolian.

**Dolostone**

Dolostones are found in the Rome Formation, Conasauga Formation, and Knox Dolomite. The dolostone present in this study are interpreted as replaced limestone. In thin-section, the limestones have been totally replaced by dolomite with subhedral to anhedral crystals. Within the dolostones, replaced original clasts retain their original outlines, preserving ‘ghost’ textures. The presence of ghosts of bioclasts, dolomitized ooids, dolomitized peloids, and clotted fabrics (consisting of clusters of peloids or micrite clasts) are evidence that the dolomite replaced the original limestone. The boundaries of replaced bioclasts and micrite clasts can be identified by rotating the microscope stage.

The formation of dolostones or dolomite is considered to be mostly from replacing the CaCO₃. Epstein et al. (1964) indicated the formation of most of the present dolomite involved rapid alteration of an initial precipitate of CaCO₃.

The Rome Formation consists of the dolomitized massive, intraclastic limestone (intramicrite or intraclast floatstone) with burrows (*Planolites*) (Fig.15). Subrounded coarse-grained quartz are found mostly in the burrow, though the quartz grains are distributed throughout the micrite. Micrite clasts are found with dolomite composition, indicating the dolomitization of earlier limestone clasts. Peloids, broken oolites, and minor plagioclase are other features found in thin- sections of the dolostones in the Rome Formation.
Figure 15. Photomicrographs of Dolostone from Rome Formation. (a) Dolostone with broken oolites and distributed quartz. (b) Dolostone with Planolite burrows. (c) Enlarged Planolite. Key: In= intraclast, Q= quartz, P= Planolite, D= dolomitized micrites, O= ooid.
Dolostone in the Conasauga Formation is found in the middle part and composed of micrite with glauconites, ghosts of bioclasts, micrite clasts, peloids, and burrows (*Skolithos*), Fig. 14 and 17). The dolostones are interpreted to originally be of carbonate mudstone (or micrite) or fossiliferous floatstone (biomicrite). Fossiliferous floatstones have ghosts of echinoderms and brachiopods in a micrite matrix with minor glauconite, peloids, and lithoclasts (Fig. 16). Dolomitized carbonate mudstone originally consists of anhedral micrite. Some micrites are interbedded with siliciclastic rocks such as siltstone. The carbonate mudstone also contains silt-sized angular quartz, plagioclase and muscovite. The presence of silt-sized siliclastic grains in carbonate is interpreted as an eolian input into a carbonate depositional environment (e.g., Pye, 1987).

The measured section in the Knox Dolomite consists of the interbedded dolomitized intraclastic limestone and oolitic limestone. The intraclastic limestone consists of clasts of micrites, peloids, and ooids cemented together by anhedral micrite and also contains irregularly distributed, sub-rounded to angular, fine- to coarse-grained quartz. The oolitic limestone consists of clusters of ooids forming grapestone. The replaced limestone clasts, and presence of dolomitized oolites and pellets are the evidence of the dolomitization of earlier deposited limestone.
Figure 16. Photomicrograph of fossiliferous floatstone rich in glauconites and echinoderms from the Conasauga Formation. Key: Gl= Glauconite, In= Intraclast of micrite, and E= Echinoderm bioclast.
Point Count Analysis

The data obtained from grain counts of 11 sandstones (8 samples from Kerbel Formation and 3 from Conasauga Formation) is in Appendix B. The data is plotted on ternary diagrams (Fig. 17), and shows that most points plot in the craton interior and recycled orogen petrofacies fields of the QFL diagram, and in the craton interior, quartzose recycled, and transitional recycled petrofacies fields of the QmFLt diagram. The cratonic interior petrofacies includes sandstone which contains mostly monocrystalline quartz.

The cratonic interior field indicates compositional maturity by the paucity of lithic fragments and indicates source area from crystalline Precambrian shield complexes and overlying platform sediments (Miall, 1985). The recycled orogen petrofacies reflect the relative abundance of quartz and sedimentary- metasedimentary lithic fragments. The diagram shows no change in the source rock for the Kerbel Formation and Conasauga Formation. Plotting of samples in the craton interior and recycled orogen indicate the source rock was quartz- rich sedimentary rock (Bogg, 2001).

Lithofacies Analysis

Eighteen lithofacies are found in the well- 2580. One lithofacies is found in the Rome Formation, sixteen lithofacies are found in the Conasauga Formation and Kerbel Formation, and two lithofacies are found in the Knox Dolomite. A code was created for each lithofacies that contains both an upper case letter and a lower case letter. The upper case letter determines the lithology (e.g., S represents sandstone, SM represents heterolithic sandstone and silty mudstone), and the lower case letter determines the sedimentary structure (e.g. k for lenticular bedding). The key for lithofacies codes is given in Table 4, and the legends used in
Figure 17. Upper diagram showing the plot of QmFLt plot and lower diagram showing QtFLt (Dickinson and Suczek, 1979). (A) Mean value for both Kerbel and Conasauga Formation plot in the Craton interior petrofacies of the QmFLt diagram. (B) Mean value for both Kerbel and Conasauga Formation plot in the Recycled orogen petrofacies of the QtFLt diagram.
<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Lithology</th>
<th>Sedimentary Str.</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm</td>
<td>Sandstone</td>
<td>Massive</td>
<td>Rapid deposition or destratified (bioturbated)</td>
</tr>
<tr>
<td>Sl</td>
<td>Sandstone</td>
<td>Planar lamination</td>
<td>Upper plane bed</td>
</tr>
<tr>
<td>Sng</td>
<td>Sandstone</td>
<td>Normal graded bedding</td>
<td>Fallout from suspension</td>
</tr>
<tr>
<td>Sh</td>
<td>Sandstone</td>
<td>Hummocky Stratification</td>
<td>Storm deposit</td>
</tr>
<tr>
<td>Sc</td>
<td>Sandstone</td>
<td>Cross-bedded</td>
<td>Migration of dunes</td>
</tr>
<tr>
<td>Sx</td>
<td>Sandstone</td>
<td>Herringbone cross- bedded</td>
<td>Alternating direction of tidal current flow</td>
</tr>
<tr>
<td>SMf</td>
<td>Heterolithic sand ripple with mud-drapes</td>
<td>Flaser-bedded</td>
<td>Tidal rhythmite with rippletmarks</td>
</tr>
<tr>
<td>SMw</td>
<td>Hetolothic sand ripple and mud- drapes</td>
<td>Wavy-bedded</td>
<td>Tidal rhythmite with rippletmarks</td>
</tr>
<tr>
<td>SMk</td>
<td>Hetorolithic mud-drape with sand-starved ripple</td>
<td>Lenticular-bedded</td>
<td>Tidal rhythmite with rippletmarks</td>
</tr>
<tr>
<td>SMI</td>
<td>Heterolithic sand and sily mud interbedded</td>
<td>Planar laminated</td>
<td>Tidal rhythmite</td>
</tr>
<tr>
<td>SSm</td>
<td>Siltstone</td>
<td>Massive</td>
<td>Rapid deposition or destratified (bioturbated)</td>
</tr>
<tr>
<td>SSI</td>
<td>Siltstone</td>
<td>Planar- lamination</td>
<td>Upper plane bed</td>
</tr>
<tr>
<td>SSML</td>
<td>Heterolithic silstone and sily mudstone interbedded</td>
<td>Planar lamination</td>
<td>Tidal rhythmite</td>
</tr>
<tr>
<td>Mm</td>
<td>Mudstone</td>
<td>Massive</td>
<td>Low current condition</td>
</tr>
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</table>
Table 4 (Cont.). Summary of lithofacies and their interpretation

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Lithology</th>
<th>Textures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lm</td>
<td>Limestone</td>
<td>Micrite</td>
<td>Deposition of micrites</td>
</tr>
<tr>
<td>Lo</td>
<td>Limestone</td>
<td>Ooids</td>
<td>Shallow marine sea water saturated with calcium carbonate</td>
</tr>
<tr>
<td>Li</td>
<td>Limestone</td>
<td>Intraclasts</td>
<td>Erosion of carbonate mud within the basin</td>
</tr>
<tr>
<td>Lf</td>
<td>Limestone</td>
<td>Bioclasts</td>
<td>Presence of organisms</td>
</tr>
</tbody>
</table>
making the stratigraphic sections are given in Fig. 18. The lithofacies are grouped into the two assemblages: the siliciclastic lithofacies assemblage and the carbonate lithofacies assemblage.

**Siliciclastic Lithofacies Assemblage**

**Massive Sandstone (Lithofacies Sm).** This is one of the most common lithofacies found as interbedded in several sections of the Conasauga Formation and Kerbel Formation. In the Conasauga Formation, very fine- to medium -grained massive beds alternate with the parallel- laminated, cross- bedded, and hummocky-cross stratified sandstone. The beds can contain lithoclasts (micrite, peloids, or ooids), glauconite, or burrows (*Ophiomorpha, Planolites, and Arenicolites*). These massive sandstone beds are dolomitic quartz arenites and quartz wackes. The bed thickness ranges between 16-cm to 70-cm. Lithofacies Sm is common in the lower and middle part and rare in the upper part of the Conasauga Formation.

In the Kerbel Formation, lithofacies Sm consists of fine- to coarse- grained, calcareous quartz arenite and quartz wacke, that are of 10- to 60-cm thick. The massive beds are interbedded with parallel- laminated, cross- bedded, and minor hummocky- stratified quartz arenite (Fig. 19). In the upper part of Kerbel Formation, massive sandstone contains more dolomitic cement, also has stylolites, lithoclasts of dolomitized limestone with pellets and ooids, occasional voids, and can be interbedded with dolostones (Fig. 20).

There might be several explanations for the development of massive beds. The most common one is the rapid deposition of homogeneous sediments, resulting in the development of faint structures only recognizable under X-radiography (Hamblin, 1965). Examples include mud flows, grain flows, and the lower part of turbidites (Boggs, 2001). In addition, sometimes primary sedimentary structures can be completely destroyed by the intensive
Figure 18. Symbols used in stratigraphic sections.
Figure 19. Stratigraphic section of a part of Kerbel Formation showing interbedded massive, parallel-laminated and cross-bedded sandstone. A: Lithofacies Sm also contains stylolites resulting from higher dolomite cement content. B: Lithofacies Sl interbedded with the cross-laminated sandstone (lithofacies Sc).
Figure 20. Cores of lithofacies Sm showing massive dolomitic quartz arenite with vugs and interlaminated dolomite.
bioturbation or by fluid escape (Shelley and Bossiere, 2000). Finally, massive beds can also
develop where grain size is homogeneous.

**Planar laminated sandstone (Lithofacies Sl).** Lithofacies Sl is the most common
lithofacies found throughout the core section in the two units. In the lower part of the
Conasauga Formation, beds of lithofacies Sl range between 16- to 60- cm thick. The planar-
laminated sandstone is often interbedded with heterogeneous sandstone and silty mudstone
with flaser- or wavy- bedding, and massive bedded sandstone. Towards the middle part of the
Conasauga Formation, planar-laminated sandstones are interbedded with massive bedded,
cross- bedded, and hummocky stratified sandstone. Some beds are rich in glauconite and
limestone clasts, and also contain burrows of *Skolithos* and *Planolites* (Fig 21).

Lithofacies Sl is the dominant lithology in the upper part of the Conasauga Formation,
with bed thickness up to 74-cm. In the Kerbel Formation, lithofacies Sl is interbedded with
massive bedded and cross- bedded sandstone (Fig 19), and the bed thickness is up to 55-cm.
In the upper part of the Kerbel Formation, lithofacies Sl contains lithoclasts (peloids, ooids
and micrite). Because of the small core widths, the planar lamination found in this study
could be the part of different types of stratification, such as low angle cross- stratification or
hummocky- stratification. In the middle and lower part of the Kerbel Formation, lithofacies
Sl contains burrows of *Planolites, Ophiomorpha, Arenicolites*, and minor *Skolithos*
ichnofacies.

Planar- laminated sandstone can be produced by many mechanisms. According to
McBride et al. (1975), planar lamination can be produced in shallow flow of a small flume by
the downstream movement of very low, depth- limited, current ripples and slow aggradation
of the sediment bed. Planar lamination can also be formed by the fallout of suspended
sediment on a planar surface in the presence of weak current that is unable to transport the
Figure 21. Core photos of: (a) lithofacies Sl with *Planolites* and glauconite, (b) light gray planar laminated sandstone with brown coloration in lamina due to dolomitization, (c) Planar laminated sandstone with section rich in glauconite, which is giving a darker coloration to the sandstone.
deposited sediment. Smith (1971) reported the development of planar lamination created by downstream movement of low-amplitude bed forms in a field study of sand-bedded rivers. Planar-laminated sandstones can also be part of tempestite sequence deposited by oscillatory currents or from waning storm (Walker and Plint, 1992). The full sequence of a tempestite includes scoured surfaces, followed to top by hummocky stratified sandstone (Sh), planar-laminated sandstone (Sl), ripple-laminated sandstone (Sr) and capped by mudstone (Mm). Planar-laminated sandstone (Sl) can also be a part of tidalite sequences as an example of fallout from suspension or low-amplitude ripples. Parallel lamination can be produced by steady flow of currents in three different types of conditions: (1) the plane-bed phase of upper-flow regime transport (Harms and Fahnestock, 1965; Allen, 1984); (2) the shallow-flow phase of the lower-flow regime transport where migration of low-relief ripples lack avalanche faces that prevents the development of the cross-laminae (McBride et al., 1975); and (3) at lower velocity which can’t make ripples but can form parallel-laminae for at least up to 0.7-mm thick (Guy et al., 1966). The headward portion of the macrotidal estuaries also contains parallel lamination in the sand flats (Dalrymple et al., 1990). Horizontal lamination is also produced by swash spillover on the top of berms in beach environment (Friedman et al., 1992) as upper plane bed deposition.

Cross-bedded sandstone (Lithofacies Sc). Lithofacies Sc is found in both the Conasauga Formation and Kerbel Formation. In the Conasauga Formation, it is mainly distributed in the lower part, within the depth between 738-m and 730-m alternating with the planar-laminated and massive bedded sandstone. Lithofacies Sc is commonly interbedded with lithofacies Sm. Lithofacies Sc can also form the transition from flaser-bedded heterolithic sandstone and silty mudstone to planar-laminated sandstone (Fig. 22). The individual sets of lithofacies Sc are up to 31-cm thick. In the Kerbel Formation, lithofacies
Figure 22. Columnar section representing lower part of the Conasauga Formation showing a coarsening- and thickening- upward sequence with tidalite and graded bedding. (A) planar laminated sandstone (lithofacies Sl), (B) lenticular- bedded heterolithic sandstone and silty mudstone (lithofacies SMk), (C) flaser- bedded heterolithic sandstone and silty mudstone (lithofacies SMf), (D) massive sandstone interlaminated with planar- laminated sandstone, and (e) herringbone cross- bedded sandstone (lithofacies Sx).
Sc is present throughout the whole section and is interbedded with planar and massive-bedded sandstones (Fig 19). Individual sets of lithofacies Sc are up to 27-cm thick.

Cross-bedding is produced by the migration of dunes. Planar-tabular cross-beds are common in shoreface deposits in the zone of the longshore current. Clifton et al. (1971) and Greenwood and Mittler (1985) interpreted the presence of planar-tabular cross-beds in shoreface to indicate the migration of two- and three-dimensional dunes. But in the storm-dominated shoreface, cross-beds can be disturbed by storm waves and can be displaced by planar-laminated sandstone and hummocky-stratified sandstone (Walker and Plint, 1992). Cross-stratified sandstone is a common lithofacies in beach environments and related with the unidirectional migration of small dunes and ripples (Friedman et al., 1992). With the change in flow direction across the beach, the orientation of cross-strata will vary. Cross-stratified sandstone can also be a part of tempestites.

**Herringbone cross bedded sandstone (Sx).** Lithofacies Sx consists of subrounded to rounded, well-sorted, calcareous quartz arenite and is found in the lower part of the Conasauga Formation and interbedded with lithofacies Sm (Fig. 22). Individual sets in lithofacies Sx are up to 8-cm thick.

Cross-bedded sandstone form as a result of the migration of dunes or ripples from wind or water currents. Herringbone cross-bedding consists of alternating sets of cross beds dipping in opposite directions. The feature is produced from the periodically alternating direction of tidal current flow in a tidal flat or tidal channel environment. Dalrymple (1992) stated that herringbone cross bedding is an indicator of tidal deposition.
Lenticular bedded heterolithic sandstone and silty mudstone deposit (Lithofacies SMk). Lithofacies SMk is mainly found in the lower and middle part of the Conasauga Formation alternated with wavy-bedded and planar laminated heterolithic sandstone and silty mudstone, and hummocky-stratified sandstone. Lithofacies SMk consists of lenses of sandstone dispersed in the silty mudstone (Fig. 22). The individual lithofacies range between 3- cm to 10-cm thick. Numerous sequences of SMk are found in the Conasauga Formation, with the change of lenticular bedding to planar rhythmites, and from planar rhythmite to lenticular-bedding, which can be interpreted either as the non-continuous availability of sand or as lack of bedload transport conditions needed to produce ripples.

Lithofacies SMk typically forms from the fluctuating tidal currents in a mud-dominated depositional environment (Reineck and Wunderlich, 1968), in other words this lithofacies can be considered as sand-starved ripple marks. Prothero and Schwab (1996) interpreted that the lenticular bedding is formed from trapping sand or silt in the muddy troughs when the sand waves migrate across a muddy substrate. Boggs (2001) interpreted the deposition of the flaser- and lenticular-bedding to take place on tidal flats and related subtidal environments because in these locations strong current flow or wave action depositing sand alternate with slack-water conditions favoring the deposition of mud. When lithofacies SSMk is interbedded with the current ripple-laminated sandstone and heterolithic flaser-bedded to rhythmic planar-bedded sandstone and mudstone, then the sequence is interpreted as an environment characterized by both traction transport and fallout from suspension. Marine delta-front environments, having fluctuating sediment supply and current velocity, lake environment in front of small delta, and shallow-marine shelves having storm-related transport of sand into the deeper water are also considered the possible site of deposition of both as the flaser- and lenticular-bedding.
Planar laminated heterolithic sandstone and mudstone (Lithofacies SMI). Lithofacies SMI is mostly found in the middle- upper part of the Conasauga Formation, and interbedded with flaser-, wavy-, and lenticular- bedded heterolithic sandstone and silty mudstone, or with planar laminated sandstone (Fig. 23). The thickness of the individual lithofacies ranges from 6-cm to 65-cm. Monotonous beds of SMI form the topmost part of the tidalite sequences present in the middle part of the Conasauga Formation. These beds show alternating sandstones and silty mudstones suggesting the alternating current speed and direction which can be from tides. Mudstone thickness is around 1-mm and sandstone thickness is from 1-mm to 11.5-cm. Thin sandstone lamina between the mudstone causes the mudstone to come into contact with each other forming the double mud drapes.

Planar tidal rhythmites are formed by the tidal currents too weak to form ripples and deposit thin sand layers and alternating mud laminae from suspension (Boggs, 2001). The two tidal currents, flood and ebb tides, are associated with the rise (flood) and fall (ebb) of water levels due to the gravitational attraction of moon on Earth and the centripetal force caused by the revolution of the Earth-Moon system. This causes the water in oceans to piles up into two bulges, one underneath the Moon, and another on the opposite side of the Earth (Dalrymple, 1992). Each tide, flood and ebb, have a period of three hours alternating with slack water period of same duration. Each rising or falling tide deposits sand, which is followed by the deposition of mud from the following slack water period, and one flood tide followed by one ebb tide forms one complete tidal cycle; so in one day, there will be two tidal cycles and therefore 14 tidal cycles (or 28 pairs of rhythmites) in a week. The thickness of the daily tides depends on the strength of daily flood or ebb tides.

The patterns of rhythmites can also be interpreted into neap and spring cyclicity. The neap tidal cycle is recognized by a pattern of thinner sand layers between thicker mud layers,
Figure 23. Columnar section through the middle part of the Conasauga Formation showing different tidal deposition. (a) Rhythmic planar- bedded heterolithic sandstone and silty mudstone (SMl) with cyclic changes of sand and mud layer thicknesses showing both the spring and neap tides (b) flaser- bedded heterolithic sandstone with silty mudstone (SMf) overtopping the planar- laminated sandstone (Sl), (c) wavy- laminated sandstone alternating with silty mudstone (SMw).
and the spring tidal cycle is recognized by a pattern of thicker sand layers between thinner mud layers (Dalrymple, 1992). Spring tides are produced when the Sun and Moon lie in a straight line relative to the Earth, and their effects add to produce stronger tidal range; likewise neap tides are produced when the sun and moon are at right angles and their effects counteract each other to produce smaller than average tidal range (Dalrymple, 1992). Tidal range is the difference of water level between successive high-tide and low-tide levels.

Flaser bedded heterolithic sandstone and mudstone (Lithofacies SMf). Lithofacies SMf is present in the lower and middle part of the Conasauga Formation (Fig. 22 and 23). These beds contain thin mud laminae present in the trough of the sand ripples (Fig. 24). Beds of lithofacies SMf alternate with massive, cross-bedded, planar-laminated sandstone, and wavy-bedded heterolithic sandstone and silty mudstone. In the lower part of the Conasauga Formation, the lithofacies is mostly present in between planar-laminated and massive bedded sandstone while in the middle part of the Conasauga Formation, the lithofacies is forming the transition from the planar laminated sandstone to rhythmic-planar laminated heterogeneous sandstone and silty mudstone. The beds in the lower part range between 10- to 35-cm thick and in the middle part range between 10- to 20-cm thick.

Lithofacies SMf commonly forms in a fluctuating tidal environment favoring traction transport and deposition of sand and silts relative to mud. Flaser-bedding is common on intertidal flats. It is created when sandy ripples alternate with the mud-laminae that form in the ripple trough during slack water intervals (Reineck and Wunderlich, 1968). The muds deposited by the slack-water over the ripples can be partially eroded in the next tidal cycle, leaving a thin layer of mud in the troughs. With an increase in the abundance of mud, flaser beds change gradually to wavy beds and then to lenticular beds (Prothero and Schwab, 1996). Reineck and Wunderlich (1968) interpreted flaser-beds as an indicator of tidal current
Figure 24. Core photographs of flaser-bedded heterolithic sandstone and silty mudstone (lithofacies SMf).
deposits. Flaser bedding passing landward into lenticular bedding can represent the transition from sand flats to mixed flats to mud flats.

**Wavy bedded heterolithic sand and mud deposit (Lithofacies SMw).** The middle part of the Conasauga Formation consists of a few beds of lithofacies SMw alternating with lithofacies SMI and lithofacies Sl (Fig. 23). In the lower part of the Conasauga Formation, lithofacies SMw forms the transition from lithofacies SMk to lithofacies SMf. In the middle part of Conasauga Formation, lithofacies SMf is interbedded with lithofacies SMI.

These heterolithic wavy beds are formed in the fluctuating high-energy and low-energy tidal conditions which neither favors sand nor mud deposition. Reineck and Wunderlich (1968) interpreted these beds as tidal current deposits. The presence of wavy-beds in between planar rhythmites can be interpreted as the temporary increase of tidal currents, an increase of mud drapes accompanied by wave activity. The change from wavy-bedding to flaser-bedding can be interpreted as the product of an increase in sand amount and of current erosion (Reineck and Wunderlich, 1968). Tidal flats on open coasts contain more wavy-rhythmites than those in protected areas (Thompson, 1968; Larsonneur, 1975).

**Hummocky stratified Sandstone (Lithofacies Sh).** Lithofacies Sh is found in the middle part of the Conasauga Formation. Minor beds of lithofacies Sh are also present in the lower part of the Conasauga Formation and in the Kerbel Formation. The lithofacies consists of the sets of undulating laminae organized into both concave-up swales and convex-up hummocks (Fig. 25). Lithofacies (Sh) alternates with lithofacies Sm, Sl, or SMf. The color of the lithofacies Sh is of light-gray and the thickness of hummocky stratified intervals ranges from 2-10 cm.

Lithofacies Sh is interpreted as the product of ancient shallow-marine storm deposits, due to the effect of combined (oscillatory and unidirectional) flows. Open coast settings are
Figure 25. Core photographs of hummocky- stratified sandstone (lithofacies Sh).
one of the areas where wave-generated structures including hummocky stratification are commonly found. Hummocky stratification has been interpreted as storm deposits in fine- and very fine-grained sandstone (Harms et al., 1975). Lithofacies Sh tends to form in very fine- to fine-grained sandstone containing abundant mica and fine carbonaceous plant debris (Dott and Bourgeois, 1982). There are two mechanisms for the formation of hummocky stratification. One relies upon combined flows, and the other relies on strong, purely oscillatory flows (Southard et al., 1990). Hummocky stratification has been observed in the shoreface (Greenwood and Sherman, 1986), and also from offshore areas. Weak tidal activity below fair-weather wave base is considered important for the preservation of HS (Markello and Read, 1981). Generally, lithofacies Sh forms in all water depths down to storm-weather wave base, but it is not typically preserved above fair-weather wave base due to subsequent wave reworking.

**Normally graded Sandstone (Lithofacies Sng).** Lithofacies Sng is present in the lower and middle part of the Conasauga Formation, grading upward from medium- to fine-grained sandstone with mud-drapes (Fig. 26). The change of grain size is subtle. Normal grading is associated with planar-laminated sandstone and in some places it is associated with the hummocky-stratified sandstone. For example, hummocky stratified sandstone can grade upward into planar-laminated sandstone, and then planar laminated sandstone can grade upward into heterolithic tidalite laminae, or massive, medium-grained sandstone can grade upward into siltstone. In thin-section, normally-graded sandstone can contain dolomitized bioclasts, peloids, or carbonate mudstone clasts (Fig. 12a). The thickness of the lithofacies Sng ranges between 30- to 60-cm.

Normally graded sandstones can be considered as the result of fallout from suspension, most likely the product of waning flow. Normally graded sandstones can be
Figure 26. Core from Conasauga Formation showing normally graded sandstone (lithofacies Sng).
deposited from episodic, high energy events such as turbidity currents, storm events, or flood events (river discharge into offshore areas). For example, normally graded sandstones can be formed from erosion and then redeposition of sediments during and following storms (Markello and Read, 1981). In this case, the coarser materials are deposited over the basal erosion surface which forms from the scour of the high-energy storm waves (Brenner & Davis, 1973; Bowen et al., 1974). The overlying normally graded finer-grained materials can be massive or planar laminated, and represent suspended material deposition under waning storm-energy conditions (Reineck & Singh, 1972; Hamblin & Walker, 1979).

**Massive mudstone (Lithofacies Mm).** Massive mudstone up to 2- to 3-cm thick can be found in the upper part of the Conasauga Formation interbedded with lithofacies Sl. Three intervals of massive mudstone are found in the upper part of the Conasauga Formation. Based on previous discussion the mudstones are interpreted as representing deposition during the slack water period of the tides.

The massiveness nature of lithofacies Mm may indicate the deposition of homogeneous mud in low-energy regime. The presence of mudstone beds between sandstone beds indicates alternating events of transport and deposition of sand and mud. The stratigraphic position of lithofacies Mm above lithofacies Sl may represent tidal current, river flood, or storm events (Walker, 1992).

**Massive bedded siltstone (Lithofacies SSm).** Thin layers of massive, light gray siltstone are found in the middle part of the Conasauga Formation interbedded with lithofacies SSL, lithofacies SMw, and lithofacies SMk (Fig. 27). Lithofacies SSm ranges between 2-cm to 10-cm thick.
Figure 27. Core stratigraphy and representative lithofacies from the middle part of the Conasauga Formation. (A) Core photograph shows the grading of lithofacies SSMI up to lithofacies SSI, SMw, and SMk. (B) Core photograph shows the transition from lithofacies SSm to SSI. (C) Lithofacies SSm followed by lithofacies SMw. (D) Lithofacies SMw grades upward to lithofacies SSMI.
Siltstones are considered as deposited in the transitional environment in between the environments favoring shale and sandstone. Glaciated and desert areas are considered as the major source of silt (Pye, 1987). Silts can be transported both by wind and water. Massive beds can be formed by the lack of traction transport with deposition from suspension or through sediment dispersion from very highly concentrated sediment gravity flows (Boggs, 2001). Here, the sediments are deposited in a more or less homogeneous mass without subsequent reworking. There is also a large amount of angular to subangular quartz silt in the carbonate, so it is possible the silts are eolian. This would imply the source of the siltstone beds represented eolian events, such as dust storms.

Planar laminated siltstone (Lithofacies SSI). Planar laminated, light gray siltstone (Lithofacies SSI) is present in the middle part of the Conasauga Formation and is interbedded with massive siltstone, and with lithofacies SMk and lithofacies SMI (Fig. 27). Lithofacies SSI is also distributed throughout the upper Conasauga Formation interbedded with lithofacies Sm and lithofacies SI. Lithofacies SSI is up to 45-cm thick. In the interpreted tidal sequences, the individual beds of lithofacies SSI are of 2- cm to 4-cm thick. Planar laminated siltstone also overlies hummocky stratified sandstone forming part of tempestite sequences.

Siliciclastic silts can be windblown as dust onto the tidal flats where they will be reworked by tidal action (“eolian-marine” deposition of Fischer & Sarnthein, 1988) and redeposited as planar laminae and low- angle cross- laminae (Osleger and Montanez, 1996).

Rhythmic planar laminated heterolithic siltstone and silty mudstone (Lithofacies SSMI). Rhythmic, planar- laminated, heterolithic light gray to brownish gray siltstone and silty mudstone (Lithofacies SSMI) form the transition from lithofacies SSm, SSI, or SMw, and also present interbedded with lithofacies SSI (Fig. 27). The presence of lithofacies SMk above SSMI (Fig. 28) can be interpreted as due to decreasing energy conditions. Lithofacies
Figure 28. Core from Conasauga Formation showing grading upward from lithofacies SSMI to lithofacies SMk.
SSMI ranges from 2-cm to 15-cm thick, with 1-mm to 2-mm silty mudstone laminae alternating with 2-mm to 3-cm thick siltstone. The most common rhythmite sequence consists of 1-mm to 2-mm silty mud laminae alternating with 1-mm to 3.5-cm siltstone laminae. The silty mud-siltstone alternation makes two packages, with one thick sandstone layer in between silty mud layers and another with a thin siltstone layer between silty mud layers.

The deposition of lithofacies SSMI over lithofacies SSm and SSI can be interpreted as the increase of the deposition of fine-grained materials or mud, or reduction in the current strength of the depositing media. The change of thickness of the interlaminated mudstone and siltstone can be interpreted as the periodic changes in current speed from tides. In the tidal environment, ripples are formed in the strong current of the dominant tide, and followed by deposition of a mud layer during the following slack-water period (Dalrymple, 1992).

Depositional environment of SSMI is similar to the deposition of SMI, so earlier comments about SMI can be used for SSMI.

**Carbonate Lithofacies**

Carbonate lithofacies found in this study includes dolomitized carbonate mudstones, intraclastic limestones, oolitic limestones, and fossiliferous limestones. The limestones were almost completely dolomitized and there was partial-to-complete diagenetic loss of primary features. For example, fossils are present as ghost with loss of original features. Intraclasts can be recognized in hand sample but oolites, peloids, and bioclasts can only be identified at microscopic scale. The recognition of carbonate lithofacies is based on the thin-section study (e.g., microfacies). The Rome Formation consists of intraclastic limestone, the Conasauga Formation contains fossiliferous limestone and carbonate mudstone, and the Knox Dolomite contains intraclastic limestone and oolitic limestone.
Carbonate mudstone or micrite (Lithofacies Lm). The lithofacies Lm consists of the dolomitized carbonate mudstone and is found in the middle part of the Conasauga Formation. Lithofacies Lm originally consisted of mircrocrystalline calcium carbonate matrix with scattered allochems less than 10%. The intraclasts derived from lithofacies Lm are distributed in sandstones throughout sections of the Conasauga Formation and Kerbel Formation. The carbonate lithofacies in the middle part of the Conasauga Formation start with fossiliferous limestones that are overlain by carbonate mudstones (Fig. 29). Thin-sections of the carbonate mudstone show few scattered silt-sized quartz grains. These scattered quartz grains have angular- to subangular shape, and are interpreted as eolian silts.

Prothero and Schwab (1996) considered micrite to be polygenetic in genesis. It is commonly formed by the physical disintegration of calcareous green algae masses. It can also form from the physical disaggregation of larger allochems (e.g., fossils, peloids and limeclasts), or by small chips derived by mechanical abrasion or bioerosion (e.g. burrowing and ingestion or grazing and gnawing by organisms).

Oolitic limestone (ooomicrite or ooid packstone) (Lithofacies Lo). Lithofacies Lo is found in the Knox Dolomite overlying intraclastic limestones. These are light-gray, massive, oolitic dolostones. Where, individual ooids have subspherical to spherical shapes, with a nucleus of shell fragments, peloids, or quartz grains. The surrounding cortex was probably originally aragonite, but they have been replaced by dolomite. Clasts consisting of groups of cemented ooids are also present as intraclasts in the sandstones of the upper part of the Kerbel Formation (Fig. 12b). Some of these ooids are interpreted to be grapestone. Grapestone is also noted from the Knox Dolomite. The lithofacies also contains few scattered quartz grains. Diagenetic stylolites and vugs are also observed (Fig. 30).
Figure 29. Stratigraphic section through the middle part of the Conasauga Formation consisting of both the siliciclastic and carbonate sequence with representative cores showing lithofacies SMk, SMw, Lm, and Lf.
Figure 30. Core from Knox Dolomite showing lithofacies Lo, with stylolites and voids.
In present time, ooids are formed in warm, supersaturated, shallow, highly agitated marine water and associated with the zones of high tidal activity in a subtidal or lower intertidal environment. Prothero and Schwab (1996) interpreted the formation of ooids and peloids as simple accretion of cortex crystals from the sweeping of ooid nucleus back and forth from wave, tidal, and storm currents in shallow-marine seawater that is supersaturated with dissolved calcium carbonate. This process can be compared with the growth of snowballs formed by rolling on the slope covered with freshly deposited snow. This process may also be biologically mediated.

The intraclasts composed of ooids or oolitic grapestone can be interpreted as erosion of the early lithified ooids, or grapestone, and subsequent re-sedimentation. The erosional episodes were probably storm events (Sim and Lee, 2006). The micrite matrix surrounding individual ooids was probably subsequent cement, because the high-energy condition necessary to transport the sand-sized ooids would have suspended any carbonate mud component.

Intraclastic limestone (intramicrite or intraclast floatstone) (Lithofacies Li). Lithofacies Li is found in the Rome Formation, and the Knox Dolomite. The measured section of the Rome Formation contains monotonous sequences of massive, intraclastic limestone that also include micrite clasts and burrows (Planolites). Quartz grains are mainly present as infill in the burrows, and peloids and broken ooids are distributed throughout the thin-section of the lithofacies Li in the Rome Formation. This lithofacies is overlapped by planar-laminated, very fine-grained sandstone of the Conasauga Formation. In the Knox Dolomite, lithofacies Li is present below the oolitic limestone. This lithofacies is rich in quartz grains above the contact with the underlying Kerbel Formation.
Boggs (2001) interpreted carbonate intraclasts to form from erosion of semiconsolidated carbonate sediments from the seafloor, adjacent tidal flats, or a carbonate beach within the basin where the host rock is formed. For example, carbonate mud chips are commonly formed from mudcracks in an intertidal setting. Due to early cementation, the carbonate mudchips have greater persistence than soft siliciclastic mudchip counterparts.

**Fossiliferous limestone (biomicrite or fossiliferous packstone) (Lithofacies Lf).**

Lithofacies Lf is found in the middle part of the Conasauga Formation, and present in the depth between 720-m to 718.5-m (Fig. 29). In the thin-section, lithofacies Lf consists of echinoderm and brachiopod fossils cemented together by micrites. The rocks also contain abundant glauconite, and peloids. Clasts consisting of fossiliferous limestones are also found as intraclasts within siliciclastic sequences in the Conasauga Formation.

Skeletal limestone can be found in the different environments of a carbonate platform. Fossils represent the places organisms used to live, which are typically higher energy (reefs, mounds, inlet channels, tidal flats, etc.).

**Geophysical Log Analysis**

**Well Core- Geophysical Log Correlation for Well- 2580**

Each lithology has unique physical property that affects response of the geophysical log which has made the logs as a useful tool for lithology study and correlation. In this study, because of the lack of cores other than the one from Well- 2580, geophysical methods were used for studying lithologic pattern changes in the study area. First, the gamma-ray and neutron- porosity logs were matched with cores of the same well, Well- 2580, to identify the log signature patterns for different lithologies that could be useful for correlation between
wells. Then, based on gamma-ray, Well-2580 correlated with the three wells from Erie, Huron, and Marion.

In the process of matching the logs with the cores, some problems were found because they were not exactly matched on a depth basis which can be from the effect of stretching the logging cable. Also, there may be missing section in the drill core. Some of the variation was random, but also there was a systematic 2- to 3-m discrepancy was found in the matching process. Shrake et al. (1990) also found the depth indicated by drilling records was 3-m deeper than the depth measured by the logging tool, in a continuously cored hole in Warren County, Ohio. Matching with logs from other wells, in this study, is done on the basis of log patterns, rather than trying for exact depth matching. The problem of matching can also be created by the procedure of documenting or scanning the original paper format of the geophysical logs into a digital format. Saeed (2002) pointed out that in contrast to the sharp lithostatic boundaries found in the cores, the boundaries in the logs are gradational because they average (or blur) lithological responses over an interval of measurement. Thus, the logs in this study are only used to find the extension of major changes in lithology patterns. In order to detect changes of every lithofacies, it would be necessary for logs to be correlated with the cores.

**Log pattern analysis:** Gamma-ray (GR) logging is used to measure the naturally occurring gamma radiation in rocks or sediments. The GR log is mainly used to differentiate between the shales and sandstones. Shales have a higher GR response than sandstone, dolomite, or limestone because shales are rich in clay content which contains radioactive potassium, and also the cation exchange capacity of clay causes adsorption of uranium or thorium. But sometimes, non-shales can also give high GR response, for example, if sandstone contains potassium feldspar, glauconite, clay coatings, or rock fragments rich in
radioactive minerals. Uncommonly, dolomite or limestone may be rich in absorbed uranium, in which case spectral gamma ray logging can be helpful. A potential source of error in GR log for this study is the presence of glauconites, which is rich in clay minerals, in sandstone. In this study, larger values of the GR log are considered the result of the higher clay content.

The neutron- porosity (NP) log measures the total amount of pore spaces in the rock by measuring the hydrogen content, which is correlated with formation water. In general, shales have higher porosity than sandstones so will obtain a lower amount of backscattered neutrons (higher neutron- porosity response). Sandstone in general will present both lower GR- readings and lower NP- log response because of the lower porosity. However, one of the problems for the NP- log is cementation. The rocks of the Well- 2580 are highly cemented thereby reducing porosity and affecting the NP- log response. In summary, the GR- log and NP- log are correlated with each other in Well- 2580 (Fig. 31).

This study uses the GR- log as the basis for interpreting the log patterns in Well-2580, and its correlation with the other wells. In Well- 2580, the GR- log presents the combination of coarsening- upward funnel shapes with an abrupt top, and irregular patterns with no trend (Fig. 31). The log pattern is divided into five sections from bottom of the Conasauga Formation to top of the Kerbel Formation. The section between 739-m to 730-m presents an irregular shaped GR- log pattern. The GR- log response varies between 40 to 150 API units, shows no uniform response. The section between 730-m to 719-m shows a funnel shaped GR- log pattern indicating a coarsening- upward trend (the GR- log response changes from 146 in API units at the base to 84 in API units at the top). In the section between 719-m to 707-m, the GR- log pattern is irregular. Overall the GR response at bottom is 125 API units and at the top it is 108 in API units and it varies between 164 and 96 in API units. Between 707-m to 701-m, the GR log shows another funnel- shaped pattern where the value
Figure 31. Calibration of geophysical logs (GR-log and NP-log) for Well-2580.
of GR-log response changes from 124 in API units at the bottom to 100 in API units at the top. Between 701-m to 679-m, the GR-log shows a funnel-shaped pattern with gamma-ray values in between 162 in API units and 0 in API units, and the gamma-ray response pattern decreases towards the top. Between 701-m to 690-m, the gamma-ray log, of funnel shaped pattern, shows a gradual decrease with a slight increase at the top at about 681-m in log.

The section of the geophysical log between 739-m to 730-m in the log is correlated with the core length between 741.20-m to 732-m. The core consists of tidalites (lithofacies SMf, SMw, and SMk) and massive bedded, planar-laminated, and cross-bedded sandstone (lithofacies Sm, Sl, and Sc). The tidalites are heterogeneous sandstone with silty mudstones, which have a strong radioactive response either because of the mud content or possibly because the gamma-ray log is affected by K-feldspar (microcline) present in the sandstone, though this is a small amount (less than 8%). This section is interpreted as deposited in bay head delta depositional environment.

The geophysical log between 730- to 719-m is correlated with 732- m to 721- m section of the core and contains tidalites and tempestite sequences. The tidalites include lithofacies SMf, SMw, and SMI, where the clay mineral content of the silty mud may be responsible for high gamma-ray response. The tempestites consist of lithofacies Sm, Sl, Sh, and Sc. In this section, the sandstones are rich in glauconite, which may be influential in the gamma-ray response (Asquith and Gibson and, 1982). This section, between 739-m to 719-m in log (i.e., 741-m to 721-m in core), is interpreted as a subtidal or lower intertidal flat overtopping the bayhead delta deposit discussed above.

The geophysical log between 719-m to 707-m corresponds to the core section between 721-m to 709-m. This section includes carbonates (lithofacies Lm and Lf) and a tidalite (lithofacies SMk, SMf, SMw, and SSML) sequence in the core. Tidalites affect the
response of gamma-ray log because of the clay mineral content of the shales. The presence of clasts of glauconite might also be considered important for the GR-log response for this section. The section, between 719-m to 707-m is considered the mixed tidal flat overtopping the subtidal or lower intertidal flat discussed above.

The geophysical log response between 707-m to 701-m in log corresponds to the core section from 709-m to 703-m. The lithology of this section includes lithofacies Sl with interbedded minor beds of lithofacies SMf and Sc. The grain size of sandstone is very fine-grained at base and fine-grained towards top, which is also the boundary between the Conasauga Formation and Kerbel Formation. These sandstones contain some K-feldspar (less than 10%) and some clay-rich mud drapes which may be factors affecting the log response. This section can be interpreted as either the portion of the washover fans reaching the estuary or lagoon, or as sand bars present in the tidal flats, or as the deposits of tidal inlet channels.

The geophysical log between 701-m to 679-m is matched with the 703-m to 681-m in core which is the full section of the Kerbel Formation. The funnel-shaped GR-log pattern is supported by the presence of coarsening-upward sandstone in the core, changing from fine-grained at the base to coarse-grained at the top. This interval is interpreted as a migrating beach/barrier island or strandplain above the underlying tidal flat sequence. As described in the next section, overall this environmental succession can be interpreted as a retrograding barrier type migrating towards land, as part of a transgressive sequence (Kraft and John, 1979).

**Subsurface Correlation between Wells.** The GR log signature for the five major sections of the two stratigraphic units taken for study in the Well-2580, are matched with the geophysical logs from the three adjacent wells (Figs. 32). In GR-logs, the contact between
Figure 32. Subsurface correlation of the stratigraphic-section of the Well-2580, including Kerbel Formation and the Conasauga Formation, drilled in Seneca County, to the wells from adjacent counties based on the GR-log pattern analysis. Well-20233 is 18- km east, Well-20154 is 15- km northeast, and Well-20148 is 19 km south from the Well-2580 (refer to Fig. 1). Key to symbols: I= Irregular, F = Funnel.
the Kerbel Formation and Knox Dolomite found in 679-m in Seneca County, 1184-m in Huron County, 901-m in Erie County, and 896-m in Marion County. Likewise, the contact between the Conasauga Formation and Kerbel Formation found in the depth of 701-m in Seneca County, 1202-m in Huron County, 915-m in Erie County, 921-m in Marion County.

Although the general pattern of the GR- logs and the NP- logs (Figs. 32 and 33) found in the Well-2580 match with logs from other three wells, there is discrepancy in the thickness of the Conasauga Formation and Kerbel Formation from well to well. The Conasauga Formation is thickest in the Marion County well (with 49-m thick) and thinnest in the Huron County well (28-m). In the Conasauga Formation, the interpreted bay-head delta sequence is thicker in the well of the Seneca County and thinner in the well of Erie County, while the interpreted tidalite sequence is thickest in the Marion County well (30-m thick) and thinner in the Huron County well (8-m thick). Thickness of the Kerbel Formation is highest in the Well-2580, where the thickness is of 23-m, and lowest in the well of the Huron County with thickness of 10-m.
Figure 33. Neutron-porosity logs from wells of Seneca, Huron, Erie, and Marion Counties.
DISCUSSION

Provenance Analysis

The composition of minerals and rock fragments in the siliciclastic sedimentary rocks gives an important clue of the provenance, or lithology of the source rocks (Boggs, 2001). In general, source areas that are mature and contain monocrystalline quartz are expected to plot very close to the Q or Qm mode in the craton interior petrofacies (Prothero and Schwab, 1996) where the sources are either part of the stable shield and platform or are part of uplifts marking plate boundaries and trends of intraplate deformation transecting the continental block (Dickinson et al., 1983). In contrast, rocks rich in sedimentary and metamorphic rock fragments are expected to plot in the recycled orogen petrofacies, which represents uplifted source areas formed during the collision of major plates and are formed along the collision suture belt (Boggs, 2001). The different tectonic settings associated with the recycled orogen petrofacies include the subduction complexes of arc orogens, highlands along the suture belts of collision orogens, and thin-skinned foreland fold-thrust belts along the flanks of arc or collision orogens (Dickinson and Suczek, 1979).

In a study of the provenance of North American Phanerozoic sandstones, Dickinson et al. (1983) indicated that subsidence of the margins of the North American continent during the late Precambrian to mid-Ordovician accommodated accumulation of mature sediments derived from the craton. Thus, based on an analysis of tectonic setting during the time, Dickinson et al. (1983) indicated that the compositions of sandstones from nearly all regions should reflect provenances with the continental block. During this interval, rocks which fall in the recycled orogen petrofacies suggest that the source was the platform cover overlying the basement, or local volcanic fields related to rifting events, or from belts of metamorphic rock associated with basement terranes (Dickinson, 1982).
The study area is associated with the North American craton and a major source area of sediment would have been the transcontinental arch, which had topographic relief and affected sedimentation patterns in this part of North America (Riley et al., 1993). The transcontinental arch formed by the Canadian Shield and overlying platform, and was present as a trend in northeast-southwest across the western midcontinent of North America from southeastern New Mexico to Minnesota and beyond into Canada (Levorsen, 1931). The Grenville province can be the source of sediment for the recycled orogen petrofacies, and transcontinental arch may be influential for cratonic interior. The plotting of mean value for both Kerbel Formation and Conasauga Formation in the ternary diagram also shows there is no major change of source area. During the continuous transgression in Cambrian time of Ohio, only the depositional environment was changing but the basin was receiving sediment from the same source.

**Lithofacies Assemblages**

Lithofacies assemblages are the key for the analysis of the depositional environment, because individual lithofacies can be produced by different environments. By grouping lithofacies into different assemblages (or associations), the assemblage serves to uniquely identify the environment that produced the facies. In other words, lithofacies assemblages are groups of genetically related facies (Reading 1986). In addition, for interpreting the depositional environment, Walker (1979) suggested the importance of analyzing available facies together to find the sequence in which the facies occur that will be useful like the facies themselves. To narrow the amount of data obtained from this study, facies are grouped into four assemblages, which are given below.
Tidalites

Tidalite sequences in Well-2580 include rhythmic beds of siliciclastic lithofacies (Figs. A1, A2, and A3). Tidalites are mainly found in the middle part of the Conasauga Formation and consist of heterolithic, flaser-bedded sandstone and silty mudstone (lithofacies SMf), heterolithic, lenticular-bedded sandstone and silty mudstone (lithofacies SMk), heterolithic, wavy-bedded sandstone and silty mudstone (lithofacies SMw), heterolithic, planar-laminated sandstone and silty mudstone (lithofacies SMI), and heterolithic planar-laminated siltstone and silty mudstone (lithofacies SSMI).

Tidalite lithofacies in the Conasauga Formation start from the section between 741-m to 734-m, where minor tidalite beds of lithofacies SMf, SMw, and SMk are present along with coarsening- and thickening-upward beds of lithofacies SI, SC, SX, SH, or Sm. In this section, lithofacies SMf is the dominant types of tidalite. The thickness of tidalite sequences is about 115-cm.

Between 734-m to 718-m, thin tidalite sequence (consisting lithofacies SMf, SMk, SMw, and SMI) are present, along with lithofacies Sh, SI, SC, SX, and Sng. Planar laminated sandstone (lithofacies SI) is the dominant lithofacies in this section and this section is rich in glauconite.

The section between the depth of 718-m to 709-m is rich in tidalites. This section contains sequences of heterolithic siltstone and silty mudstone, and heterolithic sandstone and silty mudstone composition (lithofacies SSMI, SMk, SMI, SMw, and SMf) interbedded with lithofacies SSm, SSI, Sh, SI, and Sm. The different tidalites facies alternate without any trend. In the tidalite sequence, flaser-bedding passes upward into lenticular-bedding, and into rhythmic planar-laminated beds, which is interpreted as the transition from sand flats to mixed flats to mud flats (Dalrymple, 1992). In this sequences, the thickness of the sandstone
portion of each rhythmite ranges from 1-mm to 11.5-cm and the thickness of the mudstone laminae varies from 1-mm to 3-mm.

Tidal bedding is produced from daily cycles of reversing flow direction, partial to complete exposure at low tide, and partial to complete preservation. The fluctuation in currents and slack water intervals produces a regular cycle of sand and mud (Prothero and Schwab, 1996). Both low and high slack water periods favor the settlement of the muds. Sands deposit in the form of planar lamination, ripple lamination, or cross bedding during flood or ebb tides. When the tidal currents are too weak to form ripples, then thin sand layers will be deposited between the mud laminae and form double mud-drapes (Dalrymple, 1992). Herringbone cross-bedding is an example of the reversing current directions, where flood tide and ebb tide are evenly matched. In most cases, tidal bundles are produced showing asymmetric tidal current strength. In addition to daily tides, monthly tidal patterns can be deduced from systematic variation in sand bed thickness representing spring-neap cycles, which has a period of 14.77 days and produce 28 semidiurnal tidal cycles. The neap cycle contains thinner sand laminae between muds than the spring cycle.

**Tempestites**

Tempestites are storm deposits that are produced from periodic storms operating on shallow marine environment (Ager, 1974). Tempestites show fining-upward sequences with both complete and incomplete cycles. A tempestite sequence includes: (1) scoured base overlain by (2) hummocky-stratified sandstone (lithofacies Sh) overlain by (3) planar-laminated sandstone (lithofacies Sl) overlaid by (4) ripple-laminated sandstone (lithofacies Sr) and topped by (5) pelagic mudstone (lithofacies Mm or Ml) (Dott and Bourgeois, 1982). Myrow (1992) identified tempestite sequences from sandstone-dominated facies consisting of thin hummocky stratified, normally graded, fine-to medium-grained sandstones. In this
study lithofacies assigned to tempestites, include lithofacies Sh, Sl, and Sm compared with MI or Mm (Fig. 35). These lithofacies are formed to make partial to complete tempestite sequences in the middle and lower part of the Conasauga Formation and in the Kerbel Formation.

Hummocky stratification is the most obvious part of the tempestite sequence (Hamblin and Walker 1979; Kreisa 1981; Dott and Bourgeois 1982; Leckie and Walker 1982; Craft and Bridge 1987). In this study, hummocky stratification generally consisted of graded upward, undulose bedding that change upward into the planar laminated sandstone (Fig. 34). Because the drill core has a small width, identification of hummocky stratification was based on observation of curved surfaces (swales) and thickening or thinning of overlying beds (infilling of swale); observation of normal grading of infilled layer (fallout from suspension, not traction transport); trend upward from undulose sandstone beds to planar-laminated sandstones; escape burrows; and capping fine-grained layer (fair weather deposits).

Tempestite sequences are mainly observed in the lower-middle part of the Conasauga Formation from the depth of 730.8-m to 720-m. In the section between 730.8-m to 729-m, tempestites consist of lithofacies Sh grading upward to lithofacies Sl or lithofacies Sc. Several tempestite beds can be identified in between 725.5-m to 724.5-m (Fig. 34) consisting of lithofacies Sh overlain by lithofacies Sl, and also the lithofacies Sh overlain by lithofacies Sm (Fig. 35). The planar laminated sandstone (Sl) sandstone overlying the lithofacies Sh is interpreted as the product of the waning storm deposit and wave deposit, which are found in more than 50% of the sequences. The presence of low angle cross-bedded sandstone (lithofacies Sc) above amalgamated hummocky-stratified sandstone (lithofacies Sh) is
Figure 34. Stratigraphic section of a portion of the Conasauga Formation, showing tempestite sequences.
Figure 35. Core from Conasauga Formation showing a tempestite sequence with lithofacies Sh overlain by lithofacies Sl.
considered as the shoreface deposits, and the cross-beds are considered to be formed from the dune migration (Johnson and Baldwin, 1986).

**Graded Rhythmite**

Graded rhythms are river flood deposits in marine environments that have a tidal influence. Graded rhythms are interpreted as deposition from suspension of flood-related sediment plumes that show the effects of alternating flood/ebb tidal currents and slackwater intervals (Gadow and Reineck 1969; Reineck and Singh 1972; Dott and Bourgeois 1982). In the present study two graded rhythms are found, both in the Conasauga Formation, one at a core depth between 738.4-m to 737.5-m, and another at core depth between 729.2-m to 729.6-m (Fig. 36). These intervals show fining- and thinning upward sandstones, and each sandstone is interbedded with mudstones (or rhythmite). The first interval, between 738.4-m to 737.5-m, consists of two amalgamated graded rhythmite beds. Each graded rhythmite starts from lithofacies Sl or Sm followed by lithofacies SMf, or overtopped by lithofacies Sc (Fig. 36a). The combination of cross beds (which indicate the shallow water conditions), rhythms (which indicate the tidal settings), and graded beds (lithofacies Sng) (which are the product of fallout through suspension from plume of sediment from flood events) indicate the presence of both the tidal currents and slackwater water condition. The graded rhythmite in between the depth of 729.2-m to 729.6-m (Fig. 36b), consists of the lithofacies Sl followed by lithofacies SMw, SMf or Sl. The overall decrease in grain size can be interpreted as the product of deposition under decelerating flow.
Figure 36. Graded rhythmite sequence observed in the lower part of the upper Conasauga Group. Full description of (a) and (b) are in text [(a) have two graded rhythmite, and (b) have one graded rhythmite].
Carbonate deposits

Carbonate deposits are found in the Rome Formation, the middle part of the Conasauga Formation, and the Knox Dolomite. The measured section of the Rome Formation consists of monotonous sequence of intraclastic limestone (lithofacies Li), with some peloids and quartz grains. Quartz sand is especially present as infill in the burrows, and burrows are of planolites types.

In the Conasauga Formation, the carbonate sequence starts with fossiliferous limestone (Lithofacies Lf) containing echinoderms and brachiopods, succeeding upward into carbonate mudstone. In these deposits echinoderms and brachiopods are only present as bioclast ghosts after the limestone was dolomitized. The sequence also consists of interbedded beds of heterolithic planar-laminated siltstone and silty mudstone (lithofacies SMI). The two lithofacies, Lf and Lm, are rich in glauconites (Fig. 29), and also contains carbonate clasts, and sand and silt sized quartz. These sequences are interpreted to be part of sandflat or shallow subtidal environments.

In the Knox Dolomite, the carbonate sequence consists of the interbedded intraclastic limestone and oolitic limestone. This limestone also consists of scattered quartz grains from very fine-grained sand to coarse grained sand. The amount of quartz grains increases toward the contact with the Kerbel Formation. The oolitic limestone also consists of the oolitic intraclasts forming grapestone.

The carbonate of this study doesn’t show any evidence of the presence of reefs or other bioherms, which are important factor for the formation of carbonates. The carbonate deposits are present just above the siliciclastic sequence of subtidal and sand flat deposits, which suggest the peritidal carbonate depositional environment. Presence of both carbonate clasts and quartz indicates the nearby source of siliciclastic composition and carbonates.
Coastal areas or beaches can be the source of both siliciclasts and carbonates. Silt sized quartz are angular in shape and can be interpreted eolian in origin.

**Lithofacies Sequences**

Based on the vertical relationship of the lithofacies assemblages, and based on the concept of the different depositional environments, five lithofacies sequences can be recognized in the studied well core: (1) shoaling- upward, siliciclastic shoreline sequences, (2) clastic tidal flat- lagoonal sequences, (3) offshore transition zone, (4) carbonate tidal flat-lagoonal sequences, and (4) bay- head delta siliciclastic sequence. These sequences are mixed with each other because, according to Walther’s Law, vertical sequences of lithofacies represent the vertical stacking of adjacent environments from the progressive migration of an ancient shoreline (Howard and Reineck, 1979).

The lithofacies of the Well-2580 are divided into four sections. First, the lower one (between 741.2-m to 729.6-m) consists of coarsening- and thickening- upward sandstone beds with interbedded tidalites and graded rhythmites. This package consists of lithofacies Sl, Sm, Sr, SMf, SMk, SMw, Sng, and Sh. The sandstones are grading upward from very fine-grained to medium-grained sandstone. This package is interpreted as a part of bay- head delta siliciclastic sequence. The detail explanation of the sedimentary characteristics of the bay- head delta is given in the depositional environment sub- chapter.

The second section is formed by the tempestite and tidalites beds of the Conasauga Formation from the depth of 729.6 -m to 709-m. In this package, the lower part is composed of the tempestite sequences of sandstone beds overlain by carbonates and tidalites of siliciclastic composition. The lower part with tempestites includes lithofacies Sm, Sx, Sl, Sc, Sh, SMf, SMw, SMI, Lf, and Lm. The upper tidalites includes the lithofacies SSMk, SSMw, SSMI, SSMf, SSm, SSI, SSH, SMI, SMw, SMf, Sl, and SMk. This section is interpreted as
offshore transition zone, clastic tidal flat-lagoonal sequences, and carbonate tidal flat-lagoonal sequences. The detail descriptions of the sedimentary characteristics of these sequences are given in the depositional environment sub-chapter.

The third section, which starts from 709-m to 703.8-m, and composed of the coarsening-upward, siltstone to very fine-grained sandstone. The package starts from SS1, grading upward into Sl, Mm, SMI, Sr, Sm, and SMf. Lithofacies Sl is the dominant lithofacies. This package is interpreted as a part of the shoaling-upward, siliciclastic shoreline sequences because of its presence above the offshore transition zone and siliciclastic-carbonate tidal flat-lagoonal sequences and the detail description of the sedimentary characteristics is given in the depositional environment sub-chapter.

The fourth section, which starts from 703.8-m to 680.2-m, consists of coarsening-upward, fine-grained sandstone to coarse-grained sandstone of the Kerbel Formation. This package includes lithofacies Sl, Sm, Sr, and Sh. The grain size change is smooth with fine-grained sandstone at bottom grading upward into medium-grained to coarser-grained sandstone. Both the third and fourth sections represent shoaling-upward siliciclastic shoreline sequences.

**Shoaling-upward Siliciclastic Shoreline Sequence**

In general, this sequence consists of lithologies indicating a shallowing-upward trend, leading to the gradual deposition of coarser-grained over finer-grained sediments. In the marginal marine depositional environment, the depth of the depositional basin can be deduced from the presence of tempestites at the base of the section. These tempestites are deposited in the offshore transition zone between FWWB and SWWB, overlain by shoreline deposits above the FWWB. The offshore transition zone is followed to the land by shoreface (between FWWB and the surf zone), beachface (foreshore), backshore, and dune environments (Boggs, 2001). Dune environment towards land is followed by washover fans.
The shoreface environment is primarily affected by waves, and storms also can strongly modify the features of the environment. Small-scale cross-bedded, planar laminated, amalgamated hummocky stratified, and trough cross-bedded fine- to coarse-grained sandstone to conglomerate are found in the shoreface environment. The beachface consist of fine- to coarse-grained sandstone and conglomerate with heavy mineral laminae, shell debris, and log casts. The backshore is affected by storm-waves and eolian processes, producing planar beded sandstone and small- to medium-scale eolian trough cross-bedded sandstone. In some places, eolian dunes have characteristic with large-scale cross bedding and climbing ripples. Washover fans are formed by two dominant sedimentary structures, sub-horizontal (planar) stratification, and small- to medium-scale foreset strata in fine- to medium-grained sandstone (Reinson, 1992).

Both the Conasauga Formation and Kerbel Formation lack the lithofacies having characteristic similar to those of shoreface, beachface, backshore, and dune environments. The upper part of the Conasauga Formation and Kerbel Formation are composed of very fine-to coarse-grained sandstone with dominant planar lamination, and minor cross beddings or minor hummocky stratification overlying tidalites in the Conasauga Formation. Accordingly, the Kerbel Formation can be interpreted as a transgressive barrier where sand was transported into the lagoon by washover fans and there was reworking of the beach and shoreface sands. A detailed description will be given in the depositional environment sub-chapter.

Siliciclastic Tidal Flat Sequences

Tidal flat sequences form on open coastlines of low relief and low energy, or in the case of high-energy coasts, they are found in protected areas associated with estuaries, lagoons, bays, and other areas lying behind barrier islands (Weimer et al., 1982). Tidal flats are generally found on the mesotidal and macrotidal coasts with minimal strong wave activity (Boggs, 2001).
In the present study, the numerous clastic tidal rhythmites are interpreted to record the tidal sedimentation that occurs in a wide range of water depths from intertidal (Dalrymple et al., 1991) to subtidal environment (Jaeger and Nittouer, 1995). The subtidal zone normally lies below mean low-tide level, and bedload transport and deposition is dominant, with the formation of festoon cross bedding, megaripples, and ripple laminae. Deposition generally takes place by lateral accretion of sandy sediment in the tidal channels and point bars (Weimer et al., 1982). The intertidal zone lies in between the low- and high-tide levels and categorized into the sand flat, mixed flat, and mud flat environments.

The sand flat environment occupies the areas closest to the low tide line, and is affected by both wave and current action. Common sedimentary structures in sand flats include cross bedding, ripple lamination, and parallel lamination and flaser bedding. In contrast, the mixed flat contains small-scale ripple lamination, flaser-, wavy-, and lenticular bedding, and rarely finely laminated bedding (Boggs, 2001). In contrast, the mud flat is rich in laminated mud with little sand (Dalrymple, 1992). The change from sediment dominated by flaser bedding to wavy bedding to lenticular bedding can be considered as the lateral change from sand flat to mixed flat to mud flat. Finally, the supratidal zone lies above high-tidal level and contains marshes, mudcracked mudflats, evaporites, and eolian features.

The tidalite sequences found in this study represent both sub-tidal and intertidal environments. Between core depths of 739.6-m to 717.7-m, of both siliciclastic and a carbonate sequence with tidalite and tempestite assemblages, are are interpreted as a sub-tidal and sand flat, where bedload transport is dominant. Sedimentary structures include flaser bedding, rhythmic wavy bedding, and rhythmic planar lamination. Key features such as mud-draped foresets, reactivation surfaces, and herringbone cross-beddings are indicators of the subtidal and lower intertidal flat environment (Dalrymple, 1992). The cross- beds and ripple
lamination can be the part of the dunes, megaripples, and oscillation ripples which are observed in modern subtidal facies (Reineck, 1967).

The sequence from 717.7-m to 709-m consists of tidalite beds interpreted to represent mixed flat sequences. The lithofacies found in the sequence are SSMl, SSm, SSl, SMk, SMf, SMw, and SMI. Mixed flats commonly contain the flaser bedded, lenticular bedded, and wavy bedded sand, and interbedded mud (Weimer et al., 1982). These tidalite sequences are overlapped by the planar laminae, and flaser-bedded sandstones in the upper part of the Conasauga Formation.

Lithofacies similar to this study is described by Sellwood (1975) in the study of the tidal deposits of the Jurassic Lower Coal Series on the island of Bornholm near the mouth of the Baltic Sea. The lower part of this deposit consists of alternating sequences of large-scale tabular to trough cross-bedded, herringbone cross-bedded, or upper plane bed sandstones. The sequence was interpreted to be deposited in the tidal-dominated, low-tidal-flat (subtidal and lower intertidal zone), under high-energy wave conditions. The overlying sequence contains wave and current rippled, flaser bedded, or lenticular bedded sandstones. This sequence was interpreted to be deposited in the mid-flat region (Fig. 37). At Bornholm, the two sequences are overlain by coal deposits, but in this study above the mixed-flat, there are planar-laminated, very fine-grained sandstones. Thus, Well-2580 is interpreted to show mixed flat overtopping the low tidal flat (which includes subtidal and lower intertidal flat).

**Offshore transition zone**

This zone lies between fair-weather wave base (FWWB) and storm-weather wave base (SWWB). Interbedded sandstone, siltstone, and mudstone are the dominant lithologies of the offshore transition zone. In this study, tempestites are considered as the indicator of the offshore transition zone, and only part of the idealized sequence of the tempestite is observed rather than the full sequence, so they are considered as incomplete tempestite sequences.
Figure 37. Progradational depositional sequence of tidal-flat deposits showing the dominant sediment-transport processes and depositional environments of the Middle Member, Wood Canyon Formation (Late Precambrian), Nevada. (Source: Klein, 1977).
This zone can be significantly affected by bioturbation, which can destroy the primary sedimentary structures.

Strong unidirectional currents are important for the erosion and initial depositional flow conditions of tempestite beds (Walker 1984; Craft and Bridge 1987; Myrow 1992). Tempestites are produced from episodic storm events and each recurrent event is associated with the depositional regime (Einsele et al., 1991). Most tempestite beds are preserved between the storm weather wave base and fair weather wave base. Below wave base there is no wave activity on the shoreface and the depth of wave base is commonly on the order of 10-m, but it can be significantly deeper (up to 100-m) during storms (Boggs, 2001). The inner shelf is the best place for the development of the tempestites, but tempestites can be observed as far as 40-km from the coast (Reineck and Singh, 1980). Tempestite development and morphology can be related to the type of coast, where coasts can be divided into the microtidal, mesotidal, and macrotidal based on the tidal range. On microtidal coasts, waves are the dominant physical process (Hayes, 1975, 1979), in mesotidal coast, effects of waves and tides balance each other, and on macrotidal coast, tidal activity is dominant (Davis and Hayes, 1984).

In this study, most tempestite sequences are found in the depth between 730-m to 720-m. Lithofacies Sh, Sl, Sc, Sm and scoured surfaces are the building units of the tempestites. Tempestite sequences are interbedded with the beds of the interpreted subtidal or lower intertidal deposits. Tempestite morphology is also associated with the paleowater depth. Generally, hummocky stratification wavelength decreases with the increase in paleowater depth (Ito et al., 2001). In the present study, because of the small width of the core, measurement of wavelength is impossible. But in this case, based on the lithofacies features of the tempestites and its relation with the adjacent lithofacies, some idea about the
water depth can be extracted. The presence of the lithofacies Sl or Sm over the lithofacies Sh, represents the waning current condition, and the association of the tempestite sequence with the subtidal/sandflat sequences indicate the presence of shallow water with storm activity, and the sediments of the offshore transition environment are reworked into the subtidal or sandflat sequences.

**Carbonate Lithofacies Sequences**

In this study, carbonate sequences are found in between 719.8-m to 717.2-m in Conasauga Formation. The carbonate sequence contains carbonate mudstone (micrites) and fossiliferous limestone (biomicrite or fossiliferous floatstone). Clasts of intraclastic limestone (intramicrite or intraclast floatstone) and oolitic limestone (oomicrite or ooid packstone) are found in both siliciclastic and carbonate rocks of both the Conasauga Formation and Kerbel Formaiton. All of these limestones were subsequently dolomitized. The carbonate mudstone and fossiliferous limestone are interbedded with the siliciclastic sequences of the sandflat or lower intertidal flat sequences of the Conasauga Formation.

Calcareous mud forming the carbonate mudstone and the micrite matrix in fossiliferous limestone can also be formed by the breakdown of green calcareous algae (e.g., Penincillus, Halimeda), and by the disintegration of large skeletal particles into their smallest crystallographic unit (Jones and Desrochers, 1992). One of the major component of the packstones is the pellets which can be result of burrowing activity (e.g., ghost shrimps) and grazing animals (e.g., sea cucumbers) (Jones and Desrochers, 1992).

Lee and Kim (1992) interpreted coarse- grained bioclastic grainstone to packstone beds as storm lag deposits formed during high energy conditions, and micritic limestone beds as the product of the waning phase of storms. Mount (1984) stressed the importance of storms in the influx of carbonate sediments from nearby carbonate sources into the area of
siliciclastic deposition. The carbonate mudstone can be interpreted as deposited in either low energy deposition of fine-grained sediments suspended during storms (Reineck & Singh, 1972), transported from offshore (Gagan et al., 1988), or background sedimentation between storms (Kreisa, 1981). The bioclastic sheets can be interpreted as storm deposits (Specht & Brenner, 1979; Markello & Read, 1981; Aigner, 1982) and sharp erosional base present below the bioclastic or fossiliferous limestone can be interpreted as formed by scouring during maximum instantaneous bed shear stress (Duke, 1990). In contrast, the intraclasts can be interpreted as the mud chips from the mudcracks.

Glauconites are diagenetic minerals that form at shallow burial depths. According to Boggs (2001) glauconites are considered to be a product of a specific environment and considered as a powerful tool for paleoenvironmental reconstruction. Glauconites are formed in agitated, oxidized, normal shallow marine waters with the depth range of 50-m to 200-m. Large amount of glauconite can be found on shallow shelf environments that are starved of clastic sediment or that have low sedimentation rates. Odin and Matter (1981) concluded that to form modern glauconites, the source material needs to be present in the sediment-water interface for between 1,000 to 10,000 years.

In summary, dolomitized limestones in this study are interbedded with clastic tidal flat sequences, which give the idea that the carbonate is also formed in the tidal flat environment. Carbonate deposition can occur in the intertidal/subtidal environment in the form of fossiliferous, pelletal carbonate mudstone as in the Manlius Formation, New York (Prothero and Schwab, 1996). Calcareous mud accumulated in moderate- to high-energy areas are considered to be bounded by cyanobacterial mats, sea grasses like Thalassia, or trees such as mangroves (Jones and Desrochers, 1992). Many peloids can be the fecal pellets of waste matter produced by organisms like fish and shrimps. Storms are the major factor for
the deposition of intraclasts in supratidal flats, and in subtidal channels as basal channel lag.
The carbonates consisting of the material eroded from the muddy subtidal and intertidal environments, consists of grapestone, pellets, or mud-sized particles and fossils (Scholle et al., 1983).

**Bay- head Delta Siliciclastic Sequence**

This sequence consists of the lithofacies present between the depths of 741.2-m to 729.6-m. Lithofacies Sm and Sl are dominant in this sequence. Other lithofacies representative of this sequence are SMf, SMw, SMk, Sc, Sng, Sx, and Sh. The texture of sandstones shows the coarsening upward sequence from very fine- grained sandstone to medium- grained sandstone. Beds are thicker upward. This sequence lies below the siliciclastic- carbonate tidal flat sequences and can be considered as the deposits of a small river entering the tidal flats. Lithofacies Sm, Sl, Sc, and Sng represent the river process, lithofacies Sh represent the storm environment, and lithofacies SMf, SMw, Smk, and Sx represent the tidal environment. The river built a small delta called bay- head delta in its mouth in the estuary, and during transgression the deposits of bay- head delta can be covered by deposits of estuary or tidal flat.

**Depositional Environments**

Based on lithofacies associations, the following four depositional environments are interpreted for the Conasauga Formation and Kerbel Formation: (1) clastic strandplain or barrier depositional environments, (2) clastic tidal flat, lagoon, or estuary depositional environments, (3) bay- head delta, and (4) peritidal carbonate depositional environments. The Conasauga Formation contains the lagoon or estuary depositional environment, bay- head
delta, and the peritidal carbonate depositional environments, while the Kerbel Formation contains the clastic strandplain or barrier depositional environments.

**Clastic Strandplain or Barrier Depositional Environments**

Barrier islands and strandplains are the common features along the coast lines adjacent to low-gradient continental shelves and low relief coastal plains, with abundant sediment supply, and moderate (mesotidal) to low (microtidal) tidal ranges (Glaeser, 1978). Microtidal coasts have long, narrow barrier islands, and mesotidal coasts have short barrier islands broken by abundant tidal channels. Sediment derived from the shelf, rivers, and coastal erosion provides sediment for wave processes to construct the barrier island. The difference between the strandplain and barrier islands is that the strandplain lacks extensive lagoonal environments and tidal channels. The barrier island is separated from the mainland by a lagoon, estuary, or marsh. Barrier islands also move either landward or seaward according to the sea level change and rate of sediment supply from both the river and ocean, and include a large portion of the transgressive or regressive shoreline sedimentary deposits.

Barrier islands consist of three sand-accumulating environments (Fig. 38): (1) the beach and shoreface environments on the seaward side of barriers and strand plains; (2) the inlet channels and tidal deltas, separating barriers laterally; and (3) the washover fans on the landward or lagoonward side of barriers (McCubbin, 1982). Beach sands have planar, nearly horizontal stratification on the berm, and planar, seaward-dipping stratification on the beachface. The angle of inclination of lamina is $2^\circ \text{ to } 10^\circ$ in fine- to medium-grained sand. Upper shoreface deposits show high angle, tangential cross stratification in trough-shaped sets that represent longshore troughs and rip-current channels (Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979); planar, and nearly horizontal stratification produced by shore-normal oscillatory motion on the crests and seaward slopes of longshore bars in some areas (Davidson-Arnott and Greenwood, 1976; Hill and Hunter, 1976).
Figure 38. (a) Map showing the major environments and facies of the barrier island-lagoonal system. (b) Cross-section through the barrier island showing the position of lagoon, washover fan and beach facies [BD= Beach dune, US= Upper shoreface, LS= Lower shoreface] (modified from Mc Cubbin, 1982).
Tidal channels are passageways between barrier islands connecting the ocean and the lagoon, estuary, and tidal marshes behind the islands (Fig. 39). Flood tide deltas are produced where landward transport through the tidal inlet is stronger, Ebb tide deltas are produced when the opposite is true (McCubin, 1982). The deep channel contains ebb- oriented, tabular, planar cross-strata, with reactivation surfaces formed by flood-oriented tidal currents.

Another important feature of the beach/barrier island are washover fans, which are the subaerial, fan-shaped landforms present on the landward or lagoonward side of the barrier island and formed by planar, horizontal, small- to medium-scale forest strata into the lagoon (Schwartz, 1982) (Fig. 40). Lithologies range from fine-grained sandstone to conglomerate, but fine- to medium-grained sandstone is dominant. Washover fans are created from the storm tides which overtop and erode channels cutting through beach-dune ridges bordering the open sea and deposit sands in the landward portion (McCubbin, 1982). Washover is the dominant process of the landward migration of the barrier island and also in the formation of new tidal channels.

In the Well-2580, between a depth of 709-m to 680.5-m, sedimentary structures include planar, horizontal lamination with small scale cross-stratification and some hummocky-stratification. This section includes the upper part of the Conasauga Formation and Kerbel Formation. The grain size of the lithology varies from very fine-grained sandstone to coarse-grained sandstone. The sedimentary composition and structure of the Kerbel Formation and upper Conasauga Formation closely match with the characteristics of washover fans. Very fine-grained sandstone with planar, small-scale cross-stratification and flaser bedding are present in the upper part of the Conasauga Formation.

Lithofacies Sl, Sm, Sc, and Sh represents the Kerbel Formation. Planar lamination is the dominant sedimentary structure (or massive bedding that may also have faint lamination
Figure 39. Diagram showing examples of the relative position of the barrier islands, flood- and ebb- tidal deltas, and different sized main channel (tidal inlet), along with the general direction of the current (arrow). (a) Example from the Texas coast, (b) Example from the New England coast (McCubbin, 1982).
Figure 40. Diagram showing the relation between the washover fan, barrier island and adjoining areas. (a) Small washover fans passing from the barrier island into adjacent ponds through the washover channels (lagoons to the right). (b) Cross-sections of the washover-fan showing the stratification produced by single storms (McCubin, 1982).
which is invisible because of the uniformity of the grain size). Cross-bedding seems to be the part of low-angle, large-scale cross-bed sets. The lithofacies of the Kerbel Formation can be interpreted as a continuum of washover fan-beach-shoreface sequences (e.g. Boggs, 2001). The section between 709-m to 680.9-m overlies the tidalite sequences of the middle part of the Conasauga Formation, and can be interpreted as part of the landward migration of an evolving washover fan or part of the growth of a flood tidal delta into the lagoon or estuary (Fig. 38).

**Clastic Tidal Flat, Lagoon and Estuary Depositional Environments**

Estuaries form from drowned river valleys having an open connection to the sea receiving sediment from both marine and fluvial sources, and have tidal, wave, and fluvial processes in effect (Zaitlin & Shultz, 1990; Dalrymple et al., 1992, and Pritchard, 1967) (Fig. 41). Estuarine sediments are dominated by the well-sorted fine-grained sand and mud, where the abundance of sand is mostly controlled by longshore drift and the mud is mostly contributed by river discharge. These two lithologies types are combined in different layers and give different bedding structures. According to Frey and Howard (1986), estuarine sediments include complex facies relationships including both intertidal and shallow subtidal environments. Thus the sediment composition, texture, physical and biological sedimentary structures are varied in an estuarine environment.

Estuaries vary from enclosed lagoonal types to open-ended embayments, which may or may not have a barrier separating them from the open ocean. Lagoonal sequences include interbedded sandstone, siltstone, shale, carbonate, and coal deposits representing different overlapping environments (Reinson, 1992). These environments include tidal environments (sandflat, mixed flat, mudflat), barrier island environments (sheetlike washover deposits), and channel-fill deposits of flood-tidal deltas or fluvial environments (Fig. 42).
Figure 41. Diagram of the generalized energy condition in an idealized estuary. Marine environment dominates toward ocean, while fluvial process dominates toward the land. The central basin represents the mixture of both processes (after Dalrymple et al., 1992, Pritchard, 1967).
Figure 42. Diagram showing the distribution of sedimentary environments in lagoonal estuary. Towrd the ocean, marine process dominate and the depositional units include barrier islands, washover fans, and flood-tidal delta. In the central basin, mixed-energy from both river- and marine-process work. The landward part of the estuary is a bay-head delta (after Dalrymple, et al., 1992).
The interpreted depositional environment of the section of the Well-2580 is similar to a lagoonal estuary depositional environment (Fig. 42). These are small, shallow bodies of brackish water that are almost completely separated by a barrier from the marine source. This type of estuary typically has a small tidal prism, low freshwater input, and is found in microtidal coast (Reinson, 1992).

In well-2580, subtidal and sandflat depositional environments can be observed from 729.6-m to 720-m, where lithofacies Sm, Sl, Sr, Sng, SMf, SMw, and Sh occur. These lithofacies also contain some tempestites and graded rhythmites. The dominant sedimentary structures include tidal bedding, planar lamination, hummocky stratification, and cross bedding. The tidalite sequences of the section from 718.5-m to 709-m consists of a combination of different interbedded tidalite lithofacies. This section is interpreted as a transition from mixed flat to mud flat environments (Klein, 1977). The upper part of the Conasauga Formation, between 709-m and 703-m, includes planar bedded and cross bedded sandstones, and minor flaser bedded sandstones which could be interpreted as sand flat or deposits of a flood tidal delta. In summary, Well-2580 includes about 26-m of estuary or lagoonal deposits in the Conasauga Formation.

In a landward direction, these interpreted estuary/lagoonal facies are interbedded with an interpreted bay-head delta facies. This transition is represented in Well-2580 by the facies present in the lower part of the Conasauga Formation. Bay-head deltas are the landward part of a lagoonal estuary environment (Fig. 42), representing the joining of river with the lagoons or estuary. Towards the ocean, the lagoonal estuary is connected with the sandflats located in the headward portions of the estuary (Dalrymple et al., 1990). In estuaries with a moderate tidal influence, headward prograding, flood-tidal deltas are a major component of sandbodies (Hayes 1980; Honing and Boyd 1992).
Today, the geographic and stratigraphic distribution of the different estuarine subenvironments (tidal flats, marsh, washover fans, etc.) and the facies distribution of the barrier island system itself are determined by the degree of tide or wave dominance or type of coast. For example, mesotidal coasts present more developed tidal flat, tidal channel, and delta deposits than microtidal coasts. The present study finds tidal flat facies but does not find distinctive tidal channel or tidal delta deposits, thus it is interpreted that the Conasauga Formation and Kerbel Formation must have been deposited in either a microtidal or mesotidal coast.

**Bay-head delta Environments**

Bay-head delta deposits form at the mouth of rivers entering the estuary or lagoonal system, and are distinguished from the true fluvial sediments by the presence of tidal structures and/or a brackish-water fauna (Dalrymple, 1992). Bay-head delta sediments are commonly found at the base of the transgressive successions in the head of the progradational estuary and exhibit a coarsening-upward succession (Reinson et al., 1988). With the continuous infilling of the estuary, the bay-head delta will eventually merge with the flood-tidal delta (Smith 1987; Nichol; 1991) and form meandering tidal channels containing inclined heterolithic strata (Thomas et al., 1987).

In Well-2580, the lower part of the Conasauga Formation, include bay-head delta deposits, consists of the coarsening- and thickening-upward sequence of the sandstone facies with some interbedded tidalite beds. Some of these deposits include graded rhythmites, which indicate the nearby presence of a river system. The total thickness of the beds assigned to the deltaic deposits is about 12-m (741.2-m to 729.6-m). The sequence starts with lithofacies Sl, followed by lithofacies SMf, and minor lithofacies SMw and SMk. The planar-laminated sandstone may represent low-angle foreset bedding in the bay-head delta front. This
sequence grades upward to lithofacies Sl, Sc, Sm, or SMf with thin beds of normally graded sandstones (lithofacies Sng) interpreted as graded rhythmtes. In general, this whole section represents a coarsening-upward sequence and interpreted as a prograding delta. However, this bay-head deltaic sequence is abruptly terminated and overlain by estuarine or lagoonal sediments, indicating delta front abandonment and reworking.

**Peritidal Carbonate Environment**

According to Prothero and Schwab (1996) most carbonates formed in clear, warm, shallow, tropical to subtropical seas in what is called the carbonate factory. Subtidal zones and offshore reefs are the most productive parts of the carbonate factory, and supply the carbonate sediments to the tidal flat by physical processes, where the carbonate deposited as allochthonous sediment and form gently wedges sloping along the shoreline (Pratt et al., 1992). Carbonate production is primarily restricted to the very shallow-water areas of the ocean and the supersaturated surface waters of the deeper ocean because of decreasing calcium carbonate saturation of seawater with depth (Boggs, 2001). Water depth, sea water chemistry, and biological evolution are considered to have most influential controls on carbonate-secreting organisms. For example, the increase of the skeleton-secreting and sediment-ingesting invertebrates after the Cambrian is considered as one of the major factors for the increase of the carbonate production.

Carbonates which formed in the shallow subtidal zone are transported short distances down the slope (onto the shelf) or up-slope shoreward (into the peritidal regions) (Fig. 43). Shorelines having carbonate peritidal regions are typically partially to completely sheltered from strong wave action but affected by daily tidal fluctuations and by occasional storms. Due to protection from strong wave action in the intertidal environment, occasional storms will have a disproportionately great effect with carrying significant amounts of suspended
Figure 43. Regions of sediments accumulation on a carbonate shelf (after James, 1984).
sediment, and may form storm lags of carbonate debris and carbonate mud. Each storm lag may be eroded or partially reworked during normal wave conditions.

Peritidal carbonate environments include areas having tidal influence during the deposition of carbonate sediments. Peritidal carbonate facies typically form a shallowing-upward sequence (James, 1984). As with the siliciclastic tidal environments, peritidal carbonate environments are divided into subtidal, intertidal, and supratidal zones. One difference between the carbonate and the siliciclastic tidal facies is that the carbonate facies include abundant intraclast horizons. This is due to rapid cementation of mud chips derived from mud cracks in the carbonate supratidal zone. In addition, the subtidal zone of carbonate tidal flats can include higher energy shoals which contain distinctive deposits, such as ooids and grapestones. Peloids are commonly produced in the subtidal zone from fecal pellets of organisms or micritized bioclasts. The peloids can subsequently be redistributed by waves and tides.

From the carbonate lithofacies found in this study, the fossiliferous limestone and carbonate mudstone found in the Conasauga Formation, from core depth of 720-m to 717.2-m, are assigned to the subtidal or sandflat environment due to their relation with the clastic tidalite lithofacies. The subtidal or intertidal deposits grade upward into the intertidal rhymites of the mixed tidal flat. So, the carbonate peritidal environments found in this study is a part of an overall shallowing-upward succession (James, 1984; Tucker and Wright, 1990). In addition, weakly lithified carbonate clasts were eroded, transported, and redeposited in both carbonate and siliciclastic deposits of the Conasauga Formation and Kerbel Formation. These clasts include oolitic limestone, carbonate mudstone, bioclasts, and peloids.
Depositional Architecture (based on subsurface correlation between wells)

A modern example of a similar environmental interpretation to this study includes the landward retreat of the Holocene transgressive barriers in the U.S. middle Atlantic coast (Kraft, 1971), due to shoreface erosion and retreat. This process has been generalized into a theory used by coastal geomorphologists (Brunn, 1962; Schwartz, 1967; Swift, 1975). The theory states that during the rise of sea level, a proportionally steep concave-upward shoreface profile is maintained and translated landward through erosion of the upper shoreface and beach zones. Thus, the continuous transgression would make the preservation of beach and upper shoreface deposits impossible, and these environments would be formed in the stratigraphic record as a transgressive disconformity or “ravinement” surface (Swift, 1968) in the shoreface or shelf environments. The sediment for the movement of the barrier or strandplain would be abundantly supplied through wave-generated longshore currents from nearby rivers or distributaries. Thus the sands deposited in Holocene lagoonal and marsh sediments are interpreted as the product of the shoreface erosional retreat (Swift, 1975; Field and Duane, 1976).

In this study, the presence of the beach/barrier sequence stratigraphically above the tidalite facies can be interpreted as the migration of the barrier towards land, into a lagoon or estuary. Such a transgression could be due to eustatic sea level rise, tectonic subsidence, or a reduction in sediment supply (retrogradation) (Reinson, 1992). Barriers can migrate landward during a transgression, thus the depth of the water decreases and there is diminished exchange of the tidal flow around the island margins. This diminishes the tidal influence, while the wave influence is relatively increased. With a transgression, sediments are deposited in spits, flood-tidal deltas, washover fans, dunes, and tidal inlets along the barrier islands (Penland et al., 1988).
Two models for the presence of the barrier island sediments above the estuarine or lagoonal sediments due to transgression would be either retrogradation of barrier, or else along-shore migration of inlet channels (which erode and rework barrier sediments). However, the migration of inlet channels will create notable channel-fill successions. These can be recognized by the presence of an erosional surface with a coarse lag deposit, deep channel facies with bidirectional large-scale planar and/or medium-scale trough cross beds, a shallow spit platform facies with bidirectional medium-scale planar cross-beds and “washed-out” ripple laminae, and an overlying fining-upward trend and a reduction in cross bed set thickness upward (Kumar and Sanders, 1974; Hayes, 1980; Moslow and Tye, 1985). These types of features were not observed in the lithofacies of this study, so the explanation of along-shore migration of inlet channels is rejected.

According to Reinson (1992), retrogradation of barrier island during transgression end in two results- either progressive shoreface retreat, or else in-place drowning of the barrier. Progressive shoreface retreat erodes the sediments of the upper shoreface and transports them into the lower shoreface or offshore as storm beds, or transports them to the lagoonal or estuary as washover fan deposits. Continued erosional shoreface retreat would erode the sediments of barrier, washover, and lagoonal facies and form a planar erosional surface (ravinement surface), over which the eroded and redistributed lower shoreface-inner shelf sands are deposited (Nummedal and Swift, 1987) (Fig. 44a and b). The thickness of the transgressive facies succession depends on the rate of relative rise of sea level. If the rate of sea level rise is slow compared to the landward erosion, then all of the facies of the barrier system will be destroyed leaving only a thin layer of lagoonal, tidal channel, and washover facies resting unconformably on older sediments. In an overall transgressive succession with fining-upward sequence, the thin layer will be truncated by a ravinement surface and covered by offshore storm deposits.
Figure 44. Diagrammatic sections showing effects of the transgression on the barrier island position. (a and b) Progressive barrier retreat by shoreface erosion and offshore deposition under conditions of slow and steady rise of sea level. (c and d) Barrier “drowning” in place, as the surf zone jumps landward across the flat marsh-lagoonal area under conditions of relatively rapid rise of sea level (modified from Sanders and Kumars, 1975).
The in-place drowning model suggests that there will be partial to complete preservation of the barrier facies with a complete preserved transgressive sequence (Fischer, 1961; Swift, 1975). The barrier will be in its original place until the wave zone reaches the top of the barrier and drown the barrier in place (Rampino and Sanders, 1980). Then the wave zone oversteps and forms another new barrier on the landward side of the lagoon/estuary (Fig. 44c and d).

The lithofacies analysis of the Well-2580, and its correlation to the adjacent three wells shows that there are three depositional units, two in the Conasauga Formation and one in the Kerbel Formation. The lower unit consists of the bay-head delta deposits, followed by a mixed siliciclastic-carbonate clastic tidal flat or estuarine or lagoonal sequence, overtopped by barrier island and washover fan deposits. The wells of the Erie and Huron Counties lie shoreward from the wells of the Seneca and Marion Counties. From the correlation of wells, Kerbel and Conasauga Formations are found in lesser depth from ground surface in the wells of the Seneca and Marion Counties than in the Erie and Huron Counties. This information can also strengthen the idea of marine transgression of the shoreline. As the shoreline is migrating towards the land, it will continuously deposits sediment according to land topography. Sediments are found in higher elevation farther from ocean because land topography slopes toward the ocean. Still the problem of interpretation from the well correlation is to determine the size of Estuary, or either there is only one Estuary or there were more than one. This needs more works on the Kerbel Formation and Conasauga Formation in Ohio.

Generally, the transition from the estuary or lagoon to the barrier is punctuated by sands showing the washover from the nearby barrier itself. In other words, the estuarine sandstone resembles sands that are commonly formed by storm washover layers or by delta foresets associated with a flood tidal delta (which is formed by sand brought through tidal
inlet in the area). Modern flood tidal deltas contain well sorted sand with planar lamination and the deposit is laterally discontinuous because of the lobate sheet shape at the mouth of the tidal inlet. Although, certain criteria such as sorting and sedimentary structures match, modern examples, Kerbel Formation is laterally continuous, which appears to discount the possibility of being the flood-tide delta deposits. In summary, all the evidence is consistent that the two stratigraphic units were deposited as a transgressive barrier island/strandplain system that migrated landward through washover fans across a mixed siliciclastic- carbonate tidal flat- estuarine- lagoon system and associated bayhead delta (Fig. 45).

According to Reinson (1992), a transgressive vertical succession of an overwash-dominated coast can be correlated with high-wave energy, microtidal coast with numerous shoreline-parallel estuaries or lagoons, and the scarcity of large active tidal inlets. In contrast, mesotidal coastlines will present facies distributions indicative of numerous tidal channels and spits, which were not observed. In the case of the transgressive estuary, the preserved facies succession will present an overall coarsening-upward facies succession indicating the superposition of distal part of estuary over proximal deposits. The preservation of any of these successions depends upon shoreface erosion, because erosion of the shoreface will preserve only a partial sequence, while a rapid rate of sea level rise might preserve the full succession. The lithofacies of the Well-2580 shows the best explanation of a barrier island and complex with shoreface erosion.
Figure 45. Block diagram showing the various subenvironments in a transgressive barrier island system (Reinson, 1992).
SUMMARY AND CONCLUSION

In Well-2580 (Seneca County, Ohio), the Cambrian Conasauga Formation and Kerbel Formation altogether consist of about 61-m thick mixed siliciclastic rocks and carbonate rocks that lie between the carbonates of the Rome Formation and Knox Formation. Previous interpretations of the Conasauga Formation and Kerbel Formation include deltaic environments (Janssens, 1973) and tidal flat, tidal-channel, or shallow subtidal marine environments (Donaldson et al., 1975, 1985). The re-interpretation in this study of the depositional environments of the Conasauga Formation and Kerbel Formation interpreted the units as deposited in estuary-lagoonal and barrier island environment. In Well-2580, the lower part of the Conasauga Formation represents a bay-head delta, which is overlain by the estuarine or lagoonal sediments of the middle part of the Conasauga Formation. The upper part of the Conasauga Formation represents the foreset strata of the washover fans over estuaries or lagoons. The Kerbel Formation represents a barrier island sequence with washover fans. In general, the presence of Kerbel Formation over the Conasauga Formation is interpreted as the transgression of a barrier island system over the estuarine or lagoonal system.

Sandstone is the dominant lithogy of the two formations with the abundance of lithofacies Sm and Sl. The lower part of the Conasauga Formation consists of the coarsening-and thickening-upward sandstone sequences with lithofacies Sl, Sm, and Sc interbedded with minor beds of lithofacies Sng, SMf, Sx, SMw, and SMk. The grain size of the beds varies from very fine-grained sand to medium grained sand, with carbonate intraclasts, and trace fossils as Planolites. The lithofacies indicate the traction transport of sediments in a shallow body of water with the effect of tides. The lower part of the Conasauga Formation is
interpreted as the bay-head delta, which forms at the mouth of river entering the lagoon or estuary.

The middle part of the Conasauga Formation consists of the tidalites, tempestites, and carbonates with lithofacies Sm, Sl, SMf, SMw, SMk, SMI, SSm, SSI, Sh, SSML, Sc, Sng, Lf, and Lm. This part is rich in glauconite and carbonate clasts. Some ichnofacies, such as *Planolites*, *Skolithos*, *Ophiomorpha*, and *Arenicolites* are also observed. These ichnofacies indicates a high-energy environment. The presence of tidalites and tempestites indicate the presence of the both tides and storm-events. Tidalites show both daily and monthly tide effect indicating the higher levels of stratigraphic complexity. Most of the Tempestites are partial sequences, preserving hummocky-stratification, planar lamination, or massive bedding. The loss of the upper parts of these tempestites can be interpreted as the subsequent reworking from waves and tides after the storm events.

Offshore transition zone is the depositional basin for tempestites which can be reworked in subtidal and lower intertidal environment duing the change of sea level or the change in sediment supply. Presence of carbonates clasts in the siliciclastic sequence indicates the nearby source of carbonates. Carbonate lithofacies Lm and Lf lack any evidence of major carbonate producing environment like reefs or other bioherms, and are considered as a product of the subtidal environment. Both organic activity and the storm activity are important for the formation of carbonate mudstone and fossiliferous limestone of the middle Conasauga Formation. The middle part of the Conasauga Formation is interpreted to be formed in offshore transition zone, and subtidal and intertidal subenvironment of clastic tidal flat-lagoonal, carbonate tidal flat-lagoonal depositional environment.

The upper part of the Conasauga Formation consists of planar laminated, cross-bedded, and massive bedded, very fine-grained sandstone and interbedded thin beds of mudstone. Lithofacies association of the upper Conasauga Formation forms part of the
shoaling upward lithofacies succession, and consists of the coarsening-upward siliciclastic composition. The lithofacies association is interpreted to be deposited as part of the washover fan entering the lagoon or estuary.

Kerbel Formation is formed by coarsening-upward beds of sandstone ranging from fine-grained at base to coarse-grained at top. The Kerbel Formation consists of lithofacies Sm, Sl, Sc, and Sh. The Kerbel Formation is rich in ichnofacies such as *Planolites*, *Arenicolites*, and *Ophiomorpha*. These ichnofacies indicate the nearshore environment. Traction transport in a shallow body of water is the depositional media for the Kerbel Formation. Lithofacies association is interpreted as the product of the washover fan during the migration of beach towards the land. Deposition of washover fan over the tidal flat environment and the offshore environment is considered as the shoaling-upward shoreline sequence.

The provenance of the Conasauga Formation and the Kerbel Formation is interpreted to be from parts of the craton and uplifted areas during the collision of major plates. The transcontinental arch, formed by the Canadian Shield and the overlying platform can be the source of sandstone plotting in the cratonic interior petrofacies and Grenville Province can be the source of sandstone plotting in the recycled orogen petrofacies. Plotting the mean value of both the Conasauga Formation and Kerbel Formation in the same class of the ternary diagrams shows no pattern of change in the source rock composition for the two formations.

Correlation of the Well-2580 with the three wells (Well-20154 in Erie County, Well-20233 in Huron County, and Well-20148 in Marion County) indicate that the lithofacies association and succession in Well-2580 are also present in the well from three counties. This states that the depositional environment interpreted for Well-2580 is regional in character.
In summary, in east-central Ohio, the Conasauga Formation and Kerbel Formation were deposited in a marginal-marine environment and shallow marine environment, specifically in a transgressive barrier island system associated lagoonal estuary system. Both marine process and river process are important for the deposition of the two Cambrian units. Due to increase in relative sea-level, the lagoonal estuary system deposited sediment over bay-head deltaic deposits, and the barrier system migrated across the lagoonal estuary system. Due to sea-level fluctuation, reworked deposits of the offshore transition zone were deposited into the sub-tidal and intertidal environment of the lagoonal estuary system. During the progressive migration of the barrier, shoreface and beach were eroded and re-deposited in the form of washover fans over lagoonal estuary deposits during continuous rise of relative sea level.
REFERENCES


Kumar, N., and Sanders, J. E., 1974, Inlet sequence, a vertical succession of sedimentary structures and textures created by lateral migration of tidal inlets. Sedimentology, v. 21, p. 491-532.


Figure A1. Description of Core-2580 from the depth of 743.7-m to 730-m.
Figure A2. Description of Core- 2580 from the depth of 730-m to 716-m.
Figure A3. Description of Core- 2580 from the depth of 716-m to 702-m.
Figure A4. Description of Core-2580 from the depth of 716-m to 688-m.
Figure A4. Description of Core-2580 from the depth of 716-m to 688-m.
Figure A5. Description of Core-2580 from the depth of 688-m to 676.6-m.
APPENDIX B
Table B1. Summary of point count data with QFL and QmFLt percentage for samples 8, 10, and 13.

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<td>Counts</td>
<td>%</td>
<td>%</td>
</tr>
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<td>Frag.</td>
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</tr>
<tr>
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<tr>
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Table B2: Summary of point count data with QFL and QmFLt percentages, Samples 14, 6, 30.

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</tr>
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<td>14</td>
<td>7</td>
<td>42</td>
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<td>14</td>
<td>7</td>
<td>42</td>
</tr>
<tr>
<td>Potassium</td>
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<td>5</td>
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</tr>
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</tr>
<tr>
<td>Cement</td>
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<td>5</td>
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</tr>
<tr>
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<tr>
<td>Total</td>
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<td>240</td>
</tr>
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<td>Plagioclase</td>
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<tr>
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Quartz compositions include Monocrystalline and Polycrystalline. Feldspar compositions include Potassium and Plagioclase. Rock Frag. includes Sedimentary and Lt. Cement and Unkowns are also included in the total count.
Table B4: Summary of point count data with QFL and QmFLt percentage for sample 12 and 11

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<td>%</td>
<td>%</td>
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