SUBSURFACE FACIES ANALYSIS OF THE ROSE RUN SANDSTONE FORMATION IN SOUTH EASTERN OHIO.

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A Thesis

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ABSTRACT

The Upper Cambrian to Ordovician Rose Run Sandstone and its equivalents (Upper Sandstone Member of the Knox Formation) were deposited in the Appalachian Basin in Ohio, Kentucky, West Virginia, and Pennsylvania. The Rose Run Sandstone, which is entirely subsurface in Ohio, is a complex hydrocarbon play because of periodic changes in sea level, the Knox unconformity, and structural complexities (Riley et al., 1993). Therefore, interpreting the depositional environment would aid in exploration for hydrocarbons within the formation.

The purpose of this study is 1) to use subsurface facies analysis to help interpret the depositional environment of the Rose Run Sandstone and create a facies model, 2) to apply the facies model to gain further insight on how these depositional environments contributed to the complexity of this active petroleum exploration play, and 3) to evaluate the facies model so as to improve interpretations from wells where only geophysical data are available.

This research involved detailed analysis of diamond drill core and interpretation of geophysical logs (gamma-ray, density, and neutron-porosity logs) from four wells in SE Ohio. The wells included: 1) Stone Resources and Engineering Company well number 2989 from Coshocton County, 2) Columbia Gas Transmission Corporation well number 2923 from Morgan County, 3) NU Energy Corporation well number 2898 from Jackson County, and 4) Aristech Chemical Company well number 3409 from Scioto County.

Based on the analysis of the four cores, sedimentary structures such ooids and intraclasts, mottling, algal lamination, flaser bedding, wavy bedding, lenticular bedding, heterolithic sandstone and mudstone, current ripple lamination and low-to medium-angle tabular cross bedding, tidal rhythmites, double mud drapes and herringbone cross stratification were used to interpret the paleoenvironment of the Rose Run Sandstone as a tidally-influenced, subtidal
environments with associated tidal flat deposits and related subtidal channels with migrating sandbars. Other workers have varying interpretations of the Rose Run Sandstone depending in part on the previous definition of the upper and lower contacts for the unit, and the location of their wells.

These subsurface facies were correlated to their given gamma-ray, density, and neutron-porosity log signature slice by attributing a lithofacies from the core to a given geophysical log slice through a process called supervised classification. Well 3409, which served as the control well, was used in assigning core attributes to the geophysical logs, while well 2923 was used as the experimental well, for carrying out the sequence stratigraphic model using geophysical logs alone based on the control well. Excellent correlation of core data with gamma-ray, density, and neutron porosity log coverage enabled a facies interpretation and correlation from well 3409 to well 2923.
ACKNOWLEDGEMENT

I wish to express my profound gratitude to the following persons for their immense contribution towards the completion of my thesis.

My parents Mr and Dr. (Mrs) Cletus Nkem Nwaodua, my brothers, Justine and Hillary, and my dear baby sister, Ify for their morale support.

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INTRODUCTION

Facies are signatures of the sedimentary environment that produces them; therefore, identifying facies in core allows one to work backwards from the products of deposition to the processes that acted in the depositional environment. Subsurface facies analysis is a technique that employs geophysical logs and the sedimentary properties of well cores to interpret a depositional environment. In addition, well log correlation is a technique that utilizes the characteristics of gamma-ray, density, and neutron-porosity logs to mark formation boundaries. According to Wylie and Wood (2004), the full potential of well logs as an interpretation tool has not been achieved because the high degree of resolution is generally ignored or averaged in standard practice. Well log analysis offers the potential of using patterns to interpret geological properties (i.e., lithology and facies) in two or three dimensions. For example, subsurface facies analysis was used in interpreting the Mt. Simon Sandstone as deposits of a tidally-influenced, shallow-marine environment (Saeed, 2002). This study demonstrated the ability of using well logs to determine sedimentary patterns and trends and to accomplish subsurface correlation, which would not have been possible through traditional methods (Wylie and Wood, 2004).

The Rose Run Sandstone and its equivalents [upper sandstone member of Gatesburg Formation] were deposited in parts of the Appalachian basin in Ohio, Kentucky, West Virginia, and Pennsylvania (Figure 1). The Rose Run Sandstone is entirely subsurface in Ohio. About 2000 wells have penetrated the Rose Run Sandstone since 1987 (Figure 2). The Rose Run Sandstone in Eastern Ohio has recently become a major hydrocarbon target due to proven oil and gas potential (Roth, 2001). Roth (2001) further stated that different types of stratigraphic, structural, and paleogeomorphic traps are found within this formation. The unit is a complex
hydrocarbon play because of periodic changes in sea level, the Knox unconformity and structural complexities (Riley et al., 1993). The formation comprises interbedded sandstone, shale, and dolostone. Sandstones are commonly crossbedded or flaser bedded quartz arenites or subarkoses. Dolostone typically contain ooids, cryptalgal laminae, and rip-up clasts (Riley et al., 1993).

This study utilizes four wells penetrating the Rose Run Sandstone within the study area (Figure 3). Data used in this research were from wells drilled by mostly oil companies or government agencies. Specifically, wells penetrating the Rose Run Sandstone that are strategically located around southeastern Ohio were used in this research. Most of these wells have geophysical logs from previous studies carried out in the Rose Run Sandstone in order to correlate the unit and describe its reservoir characteristics and structural features. The research was restricted to four wells because other cores within the area of study were either not logged or did not penetrate the Rose Run Sandstone, which is the unit of interest. In other cases, there were multiple wells located close together, such that it would make no difference picking those cores. The availability of core, gamma-ray log, density log, and neutron porosity log coverage data made the unit an excellent choice for this study. The purpose of this study is: 1) to use subsurface facies analysis to help interpret the depositional environment of the Rose Run Sandstone, 2) to use the facies model to gain further insight on how these depositional environments contributed to the complexity of this active exploratory play, and 3) to develop a facies model that can also be used to improve interpretations from wells where only geophysical data are available. Furthermore, interpreting the depositional environment would aid in unraveling the intricacies associated with this unit. This in turn will enhance exploration for hydrocarbon within the formation and the region. Facies are signatures of the sedimentary environment that produces
them; therefore identifying facies in core allows one to work backwards from the products of deposition to the processes that acted in the depositional environment.
Figure 1. Generalized geologic column for early Paleozoic rocks in Ohio, Pennsylvania, and adjacent states (Riley et al. 1993). (*) indicates the Rose Run Sandstone and equivalents.
Figure 2. Showing the location of Knox Group deep wells (with permission from the Ohio Geological Survey).
Figure 3. Showing study wells and location. A: Stone Resources and Engineering Company well 2989; B: Columbia Gas Transmission Corporation well 2923; C: NU Energy Corporation well 2898; D: Aristech Chemical Company well 3409. Line BD indicates the distance of the wells used for facies modeling.
SUBSURFACE FACIES ANALYSIS

Facies can be delineated based on their physical, lithological and biological structures in comparison to adjacent rocks. Subsurface facies recognition of paleo-sedimentary environments has been done using a combination of wireline log responses (gamma-ray logs, neutron-porosity logs), and sedimentary structures, texture and mineralogy from well cores and cuttings. Well cores provide small-scale samples of physical, chemical, and biological attributes of rocks in the subsurface. But there are problems associated with well cores, for example that they are usually incomplete or they could be crushed, during extraction. These shortcomings are responsible for the limited amount of information such as sedimentary structures, body and trace fossils, and succession thickness that could be accessed from these cores. Moreover cores are usually expensive, especially when they are being extracted at greater depths (Nichole, 1999; Saeed, 2002). Well cuttings are smaller than cores. Their sizes limit their usefulness when it comes to determining the thickness of unit in the subsurface or the sedimentary structures, but the biological contents in them can be essential to carrying out a biostratigraphic analysis of the succession (Nichole, 1999).

Geophysical response of logs can be used in delineating lithofacies. For instance gamma-ray logs could be used in differentiating mudstones from carbonates and sandstones, except in situations where those sandstones and carbonates are rich in glauconites and radioactive elements such as potassium and thorium. The shapes of the logs (for instance, the gamma-ray logs in Figure 4) could give an idea of the depositional environment. The problem associated with using logs is that they can not be used to differentiating between different environments having the same log shape and signature. For example, submarine fans and shoreline environments may not be distinguished based solely on geophysical log trend or pattern. In addition, Nichole (1999)
stated that problems associated with using bore hole data are that structures that depict directions (i.e. paleocurrents) are rarely available from borehole, and that information from bore holes is one dimensional, no matter how closely spaced these boreholes are. This limits the process of creating a three-dimensional facies model through a detailed correlation of wells. These problems would also limit paleogeographic interpretations from subsurface data. Furthermore, facies such as bioherms could be too large to be identified from cores.

Using all the tools of subsurface analyses (i.e., both well logs and cores) would give a better interpretation of the subsurface environment, because most of the inadequacies in the tools are compensated for by their mutual advantages. For instance, the thickness of the subsurface units can be confirmed from the well logs, while the signatures of well logs could be confirmed by looking at the cores. In other words, for effective subsurface interpretation, excellent core data and log coverage need to be compared.

The Mt. Simon Sandstone could be used as a case study of this approach. Based on a study of sedimentary structures such as lenticular bedding, flaser bedding, crossbedding, mud-drapes, intraclasts, and significant bioturbation structures, the Mt. Simon Sandstone was interpreted as deposited in a tidally-influenced shallow-marine environment (Saeed, 2002). Using grain size and lithology, the author further went on to interpret the unit as a transgressive barrier sequence. According to Saeed (2002), this implied a migration of the Mt. Simon Sandstone over a lagoonal/estuarine succession. These subsurface facies from the Ohio Department of Natural Resources (ODNR) Warren County well (DGS-2627) were then correlated to a given gamma-ray and neutron-porosity log signature slice, such that a sequence stratigraphic model was created. The model was tested in the British Petroleum Company (BP) Allen County well (BP-4) by correlating the gamma-ray and neutron-porosity log in the control
well (DGS-2627) with the log from the experimental well (BP-4) using only gamma-ray and neutron-porosity log. The results from the correlation were then confirmed by examining the cores from the experimental well to see if the lithofacies match (Saeed, 2002). This is an excellent case study because it is similar to this research (Figure 5a-d and Table 1).
Figure 4. Diagrams showing gamma-ray log patterns for different depositional environments, A. Cylindrical, clean, no trend (eolian, braided fluvial, carbonate shelf, reef, submarine canyon fill), B. Funnel shaped, abrupt top coarsening upward, (crevasse splay, distributary mouth bar, clastic strand plain, barrier island, shallow marine sheet sandstone, carbonate shoaling upward sequence, submarine fan), C. Bell shaped, abrupt base, fining upward, (fluvial point bar, tidal point bar, deep sea channel, some transgressive shelf sands), D. Symmetrical, rounded base and top, (sandy offshore bar, some transgressive shelf sands, amalgamated coarsening and fining upward units), E. Irregular shape, mixed clean and shaly, no trend (fluvial floodplain, carbonate slope, clastic slope, canyon fill), (modified from Walker et al., 1992).
Figure. 5A. Location map of Ohio showing the five wells discussed in the study of the Mt. Simon sandstone by Saeed (2002). (1) Well DGS-2627, in Warren County. It was continuously cored from surface to the total depth at 1640m by the Ohio department of Natural resources (ODNR). (2) Well BP-4, in Allen County. It was drilled by British Petroleum Company to total depth of 1039m. (3) Wells Long-1 (permit 2), in Pickaway County. It was drilled by Kewanee Operator to total depth of 922m. (4) Hockman-1, in Hocking County. It was drilled by Dunigan Operator to total depth of 1979.5m. (5) Ulman-1, in Noble County. It was drilled by Amerada Petroleum Corporation to total depth of 3487m.
Table 1. Lithofacies summary of the Mt. Simon Sandstone from Saeed (2002).

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<th>Interpretation</th>
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<td>T1</td>
<td>Siltstone and mudstone.</td>
<td>Planar lamination, small scale ripple lamination, flaser bedding, and lenticular bedding. This facies is locally bioturbated in the form of small individual burrows (<em>Diplocraterion</em>).</td>
<td>Lagoon, estuary, bay, or abandoned channel.</td>
</tr>
<tr>
<td>T2</td>
<td>Claystone, siltstone, and very fine-grained sandstone.</td>
<td>Planar lamination, multidirectional (herringbone) cross lamination, ripple features, tidal bundles, and burrowings (<em>Skolithos</em> and <em>Diplocraterion</em>).</td>
<td>Tidal rhythmites.</td>
</tr>
<tr>
<td>B1</td>
<td>Fine- to very coarse-grained, well sorted, well-rounded quartz arenite</td>
<td>Planar lamination, multidirectional (herringbone) cross-bedding, ripple-lamination, wavy bedding, or wavy cross bedding, and clay intraclasts, clay drapes.</td>
<td>Tidal inlet channel sedimentation.</td>
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<tr>
<td>B2</td>
<td>Medium- to very coarse-grained sandstone with local fine-grained sandstone.</td>
<td>Herringbone cross-bedding, with local planar bedding and lamination, tidal bundles, clay intraclasts, and bioturbation including <em>Skolithos</em>, <em>Arenicolites</em>.</td>
<td>Tidal inlet channels.</td>
</tr>
<tr>
<td>B3</td>
<td>coarse- to very coarse-grained quartz arenite.</td>
<td>B3 is a planar-tabular cross-bedded increasing in its angle upward. Several reactivation surfaces,</td>
<td>Tidal inlet facies</td>
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<tr>
<td>B4</td>
<td>Fine- to medium-grained sandstone.</td>
<td>Bioturbated to highly bioturbated, which includes <em>Skolithos</em>, <em>Arenicolites</em>, <em>Diplocraterion</em>, and <em>Monocraterion</em>.</td>
<td>Subtidal sheltered area (such as a small bay or lagoon).</td>
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<td>C1</td>
<td>Granule conglomerate</td>
<td>Generally no internal sedimentary structures.</td>
<td>Beach or swash zone.</td>
</tr>
<tr>
<td>C2</td>
<td>coarse- to very coarse-grained sandstone.</td>
<td>Planar-tabular and trough cross-bedded, and multidirectional (herringbone) cross bedding.</td>
<td>Beach (swash zone), or small channels within the upper shoreface.</td>
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Figure. 5c. Regional correlation between wells, Warren County DGS-2627 and Allen County, BP-4. The Precambrian boundary is set horizontal to show the lateral variation. This correlation diagram shows a general thinning trend from well DGS-2627 to well BP-4 for both the Mt. Simon Sandstone and the Eau Claire Formation (from Saeed, 2002).
Figure 5d. Diagram showing proposed depositional model for the Cambrian Mt. Simon Sandstone. Saeed (2002) interpreted the unit as a tidally-influenced barrier-island and lagoon environment.
GEOLOGIC BACKGROUND

Tectonic setting and history

Both Ohio and Pennsylvania were part of Laurentia during the late Precambrian to early Cambrian. According to Riley et al. (1993), the crust of Laurentia was made up of the Canadian Shield and overlying platform, which are locally upwarped making a structure called the transcontinental arch. Physiographically, Laurentia was composed of a continental slope, continental rise, and continental shelf in the vicinity of Ohio and Pennsylvania. During this period, the Iapetus Ocean was formed from the rifting of Rodina from the southern Baltic plate and eastern Laurentia plate. Riley et al. (1993) stated that either eustatic rise in sea level or the subsidence of the southern margin of Laurentia in response to sediment loading gave rise to the deposition of basal orogenic sands on the previously weathered and highly eroded southern continental margin of Laurentia. In Ohio, the Precambrian unconformity is recognized by Paleozoic sedimentary rocks overlying Grenville Province metamorphic and igneous rocks in the east, and either the East Continent Rift basin sedimentary and volcanic rocks or the Granite-Rhyolite Province igneous rocks in the west (Baranoski, 2002).

Riley et al. (1993) further stated that Cambrian sandstones were deposited around the margin of the Transcontinental arch while the carbonates were deposited in the adjacent shallow marine environments. Cyclic fluctuations in sea level during the Cambrian resulted in the interfingering of the sandstone and carbonate deposits. From thin-section point-count analysis, the Rose Run Sandstone mainly consists of quartz-rich sandstone indicating a continental province, although locally, the presence of feldspathic-rich sandstones may also show basement uplifts as another sediment source.
The Rome trough was formed during the early to middle Cambrian along the southern margin of Laurentia. Riley et al. (1993) speculated that its formation is related to the opening of the Iapetus Ocean. One interpretation of this feature is that it formed as a result of incomplete rifting, in other words it was an aulacogen (failed arm of a triple junction) that extended from the Mississippi embayment through Kentucky and Pennsylvania, and into New York.

During the early to middle Ordovician, the Iapetus Ocean continued to expand until a transform boundary became a subduction zone. The subduction resulted in southern Laurentia Plate margin being overridden by the northeastern margin of a small continent called Avalonia (part of the Gondwana plate). The collision resulted in the narrowing of the Iapetus Ocean, formation of the island arcs, and a fold-and-thrust belt resulting in the continental shelf of Laurentia being uplifted, folded, and block faulted. Subsequent weathering and erosion created the overlying Knox unconformity. Mussman and Read (1986) stated that in the middle Ordovician, post-Knox deposition of both basal carbonates and clastics (including the Rose Run Sandstone) in the margin of the foreland basin (Appalachian basin) towards the continental interior occurred as a result of the covering of the Knox unconformity during sea-level highstands.

By middle to late Ordovician, the Laurentia plate had become stable, and accumulated thick carbonate sequences. These carbonates are interbedded with clastic muds and infrequently with bentonites. These lithologies were the result of recurring tectonic activities that were associated with the collision of the Laurentia plate and the island arcs in the early-late Ordovician. During the Ordovician Taconic orogeny, the collision of Laurentia with an island arc marked the climax that result in the formation of the first manifestation of the Appalachian Mountains (Riley et al., 1993).
Structural Styles

According to Riley et al. (1993), the Rose Run Sandstone is affected by both the basement involved (thick-skinned) and detached (thin-skinned) structural styles. These structures, especially the thick-skinned structures, are interpreted to have occurred along Grenville weakness zones reactivated by the thrust sheet. Examples of the basement- associated structures include compressional block faults, extensional block faults, and wrench faults (such as the Tyrone - Mt. Union Lineament and the Highlandtown fault-Pittsburgh-Washington Lineament) (Figure 6). The thin-skinned structures include growth faults, salt and shale diapirs, and wrench faults. Most of these thin-skinned structures mimic the basement structures. According to Riley et al. (1993), for example, growth faults occur over normal faults in the Rome trough, which probably explains why they are restricted to the extreme end of eastern Ohio. The most important of these is the set of faults that define the Rome trough. The Rome trough is deepest in Pennsylvania, and extends across states like Kentucky and West Virginia. The Rome trough is said to have controlled sediment thickness in the region. For instance, the thickness of the equivalent unit to the Rose Run Sandstone (upper sandy member of the Gatesburg Formation) increases from 130 m in eastern part of Ohio to 210 m in the western part of Pennsylvanian, as a consequence of the Rome trough (Figure 7).

Another example of structural control on deposition is the geometry of the sandstone unit in the Copper Ridge-Ore Hill Formation, which is attributed to the influence of the Cambridge cross-strike structural discontinuity (CCSD). Harper (1989) stated that periodic movement along the CCSD affected sedimentary facies allocation. The tectonic setting of features (Figure 6) also influenced diagenesis, for instance, dolomitized and brecciated carbonate rocks may be due to hydrothermal processes in fault zones (Smith, 2004).
Figure 6: Location map showing the location of study wells to major tectonic features that affected Late Cambrian deposition and structural development in Ohio and Pennsylvania (Riley et al. 1993). AF: Akron fault; BSF: Burning Spring fault; CCSD: Cambridge cross-strike structural discontinuity; HF/P-W CSD: Highlandtown fault/Pittsburgh-Washington/cross strike structural discontinuity; MF: Middleburg fault; SF: Suffield fault; SM: Serpent Mound disturbance; STF: Smith Township fault; TML: Tyrone-Mt. Union lineament.
Figure 7. Isopach map of the Rose Run Sandstone in Ohio and western Pennsylvania (Riley et al. 1993).
Regional Stratigraphy

The distribution, stratigraphy and thicknesses of the different groups and formations in Ohio, especially the Knox Dolomite and its correlative equivalent, are given in Figure 1. This research will concentrate mostly on the Rose Run Sandstone.

According to Ryder et al. (1997), the Knox Group is the unit of deposition between the Conasauga Group and the Knox unconformity. The Knox Group is made up mostly of dolostone with minor sandstone and chert. The unit is subdivided into the Copper Ridge Dolomite, the Rose Run Sandstone (a thin unit of sandstone), and the Beekmantown Dolomite. The Rose Run Sandstone represents the stratigraphic interval between the Copper Ridge Dolomite and the Beekmantown Dolomite. The Copper Ridge Dolomite is the equivalent of the Ore Hill Member of the Gatesburg Formation of Pennsylvanian, while the Beekmantown Dolomite is the correlative equivalent of the lower part of the Beekmantown Group of Pennsylvania (Riley et al., 1993).

The Rose Run Sandstone comprises interbedded sandstone, shale, and dolostone. The sandstones are commonly crossbedded or flaser bedded, quartz or feldspathic arenites. The dolostones typically contain ooids, thrombolitic algal mounds, cryptalgal laminae, and rip-up clasts (Riley et al., 1993).

From the isopach map (Figure 7) constructed by Riley and Baranoski (1991) and Harper (1991), Paleozoic sediments show a strong degree of variation in thickness, increasing from the western part of Ohio to western Pennsylvania. Hansen (1997) stated that these sediment thicknesses vary from 751 m in western Ohio to more than 3904 m in eastern Ohio. These ranges in thickness can be attributed to basinward thickening and locally to erosional processes and structural factors. Riley et al. (1993) further stated that the carbonate- to- sand ratio increases
from the northwest to the southeast across the Waverly arch, with carbonate deposition also increasing along the trend. This implies a likely northwestern source for these clastic rocks (Riley et al., 1993).

**PREVIOUS WORK ON THE ROSE RUN SANDSTONE**

**Nomenclature**

The Knox Group got its name from Knox County in Tennessee (Riley et al., 1993). The Rose Run Sandstone, which is a member of the Knox Group, was first named in Kentucky (Freeman, 1949, 1953). Because the unit transverses through different states, for instance Ohio and Pennsylvania, it is bound to have stratigraphic names across state boundaries, which do not match. In Pennsylvania, it is called the Upper Sandy Member of the Gatesburg Formation, while in Ohio, it is known as the Rose Run Sandstone. Because of this problem with nomenclature, Riley et al. (1993) defined the unit as equivalent to the middle arenaceous dolostones of the Knox Group and the Upper Sandy Member of the Gatesburg Formation. In some cases, the names for formations having different nomenclature within their area of study are indicated with a slash separating them. Because this research is limited to Ohio, nomenclature will not be much of an issue.
Age, Stratigraphy and Thickness

The Rose Run Sandstone is upper Cambrian to early Ordovician in age. The age of the unit is based on lithocorrelation to dated units (Figure 1). It can be found in Ohio, West Virginia and Kentucky. According to Atha (1981), the Rose Run Sandstone comprises interbedded sandstone and dolomite in the northeastern part of Kentucky. McGuire and Howell (1963) and Patton and Dawson (1969) found that the unit pinches out into dolomite in the southern and western part of Kentucky, while in the northwestern part of the state, it is truncated by the Knox unconformity. In Ohio, the Rose Run Sandstone is restricted to the eastern part of Ohio as seen in Figure 2. This unit forms in the western part of the Appalachian basin, and is erosively truncated by the Knox unconformity of middle Ordovician age in the west. This unconformity inclines gently about 9.5 m/km to the southeast from Ohio into the southwest Virginia and Pennsylvania. To the east, the Rose Run Sandstone pinches out into a dolomitic unit (Atha, 1981). Riley et al. (1993) stated that the Rose Run Sandstone grades in thickness from 0 to 62 m from the western limit of the unit in Ohio to the northwestern boundary in Pennsylvanian (Figure 7). Elsewhere, the Rose Run Sandstone is approximately equivalent to other clastic intervals. In the Michigan basin, the Jordan Sandstone was correlated by Janssens (1973) and McGuire and Howell (1963) to the Rose Run Sandstone. The Jordan Sandstone is 182 m thick in Michigan, and thins to the SE into Ohio, where it is truncated by the Knox unconformity, and eroded over the Findlay- Algonquin arch. In Indiana, the Knox Sandstone was correlated by Patton and Dawson (1969) to the Rose Run Sandstone based on similar lithology and texture (Atha, 1981). Atha, (1981) further stated that the Knox Sandstone consists of sandstone to the eastern part of Indiana; while lenses of interbedded sandstone and dolomites are found in the western part of the
state. Patton and Dawson (1969) stated that the Knox Sandstone was truncated by the Knox unconformity over the Cincinnati arch in the east, and over the Kankakee arch in the northern part of the state. They also stated that the unit is approximately 121 m thick westward.

In Pennsylvania, although the Upper Sandy Member of the Gatesburg formation (150 feet (45.72 m) thick) may not be exactly time equivalent to the Rose Run Sandstone, but both units have been correlated by Wagner (1966, 1976) based on lithology. Correlation of the Rose Run Sandstone in Ohio and the Upper Sandy Member of the Gatesburg Formation in Pennsylvania was also carried out using petrographic characteristics, geophysical logs, and shale marker beds (Enterline, 1991). The Upper Sandstone Member of the Gatesburg Formation comprises interbedded sandstone and dolomite which pinches out into limestone from a northwest to southeast trend (Wilson, 1952; Wegner, 1976).

The source of sediments for all of these early Cambrian – late Ordovician units is assumed to be in the northwest (Swartz, 1948; McGuire and Howell, 1963; and Wagner 1966) based on the trend in thickness. The thickest part of these units is in Michigan and Indiana, and they all thin to the south-southeast. A specific estimation of the general thickness of the unit cannot be determined, because the Rose Run Sandstone and its equivalents have been affected by erosion over a tectonically active region (Atha, 1981).

**Lithology and Paleontology**

The Rose Run Sandstone consists of quartz arenite, sub-feldspathic arenite and feldspathic arenite (Enterline, 1991; Atha, 1981; and Riley et al. 2003). The sandstones are fine-to medium-grained, subrounded to rounded, and poorly to moderately sorted (Riley et al., 2003),
although well sorted beds have been reported (Baker, 1974). According to Enterline (1991), and Riley et al. (2003), the dominant minerals observed in the unit were quartz, potassium feldspar, and dolomite with minor glauconite, illite, chert, and pyrite, and rare anhydrite and plagioclase. Atha (1981) noted that reworked sediments make up the unit. He made this assertion due to the presence of quartz and feldspar with abraded overgrowths. The types and abundance of cements vary, from about 11% dolomite cement, 1-4% clay cement, 4-5% quartz overgrowths, and 1% feldspar overgrowths. The preexisting sediment source is possibly basement rocks of the Canadian Shield area or older (Early Cambrian) feldspathic sandstone (such as the Mt. Simon Sandstone) (Atha 1981).

Fossils are relatively rare in the Rose run sandstone, which is probably because preservation is typically poor in coarse-grained clastics. The fossil content of the Rose Run Sandstone as stated by Riley et al. (1993), Babcock (1994) and Hagadorn et al., 2002 is shown in Table 2.
Table 2. List of the fossils in the Knox Group within the late Cambrian

<table>
<thead>
<tr>
<th>Major Groups</th>
<th>Taxa</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trilobites</td>
<td><em>Saukia</em> sp</td>
<td>Riley et al., 1993</td>
</tr>
<tr>
<td></td>
<td><em>Ptychaspis-prosaukia</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Conaspis</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Elivinia</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Dunderbergia</em> sp</td>
<td>Babcock, 1994</td>
</tr>
<tr>
<td></td>
<td><em>Aphelaspis</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Crepicephalus</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Cedaria</em> sp</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Undetermined polymeroids</td>
<td></td>
</tr>
<tr>
<td>Echinoderms</td>
<td>Undetermined ossicles</td>
<td></td>
</tr>
<tr>
<td>Graptolite</td>
<td>Undetermined dendroid</td>
<td></td>
</tr>
<tr>
<td>Scyphozoan</td>
<td>Medusa or jelly fish</td>
<td>Hagadorn et al., 2002</td>
</tr>
</tbody>
</table>
Depositional Environment

From subsurface mapping, petrophysical, and core data analysis, Riley et al. (1993) stated that the Rose Run Sandstone is made up of three principal facies namely 1) sandstone facies, 2) mixed sandstone and dolostone facies, and 3) dolostone facies. An interpretation of the Rose Run Sandstone as deposited in peritidal to shallow marine environments was given based on the sedimentary structures (Table 3) from the three principal facies.

Enterline (1991) used three cores (the Beckwith well, Ashtabula County in Ohio, the Parabek well from Ashtabula County in Ohio, and the Hammermil well from Erie County in Pennsylvania) to interpret the Rose Run Sandstone as a tidal flat environment with migrating tidal channels. During the course of the study four facies types were delineated (Table 4). These facies tend to succeed each other sequentially, with the sandstone facies overlain by oncolite facies, bioturbated facies, and algal laminated /stromatolite facies at the top (Enterline, 1991).

Atha (1981) used 6 cores up to 10.3m long from two wells located in Ohio (Bart #1 from Coshocton County and US Steel #1 from Scioto County) to examine the Rose Run Sandstone. Atha (1981) interpreted the unit as a peritidal environment based on sedimentary structures such as stacked hemispheroid stromatolites, lenticular bedding, herringbone cross stratification, reactivation surfaces, flat-pebble conglomerate, and large rounded limestone intraclasts.
Table 3. Interpreted depositional environments of the Rose Run Sandstone based on sedimentary structures (Riley et al., 1993).

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Lithology</th>
<th>Sedimentary structure</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heterolithic</td>
<td>Wavy bedded, flaser bedded and cross laminated</td>
<td>Shallow subtidal</td>
</tr>
<tr>
<td>2</td>
<td>Limestone</td>
<td>Massive (oooids, peloids)</td>
<td>Carbonate sand shoals</td>
</tr>
<tr>
<td>3</td>
<td>Dolostone</td>
<td>Massive, bioturbated</td>
<td>Carbonate tidal flats</td>
</tr>
<tr>
<td>4</td>
<td>Dolostone</td>
<td>Scours, intraclasts</td>
<td>Carbonate tidal flats</td>
</tr>
<tr>
<td>5</td>
<td>Limestone</td>
<td>Algal lamination, stromatolites</td>
<td>Carbonate tidal flats</td>
</tr>
<tr>
<td>6</td>
<td>Sandstone</td>
<td>Herringbone cross bedding</td>
<td>Shallow subtidal</td>
</tr>
<tr>
<td>Lithofacies</td>
<td>Lithology</td>
<td>Sedimentary-Structure</td>
<td>Interpretation</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>-----------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>1</td>
<td>Very fine to coarse grained, rounded to well rounded sandstone</td>
<td>Low-to-high angle cross bedding, rip-up clast, current ripples, herringbone cross bedding</td>
<td>Tidal channel (clastics)</td>
</tr>
<tr>
<td>2</td>
<td>Dolomite</td>
<td>Oncolites, Rip-up clasts</td>
<td>Tidal channel (carbonate)</td>
</tr>
<tr>
<td>3</td>
<td>Dolomite</td>
<td>Massive, with bioturbation</td>
<td>Intertidal environment</td>
</tr>
<tr>
<td>4</td>
<td>Dolomite</td>
<td>Algal laminated/stromatolites, mud cracks</td>
<td>Lower supratidal to upper intertidal</td>
</tr>
</tbody>
</table>
Diagenesis and Burial History

Atha (1981) was able to deduce a diagenetic and burial history of the Rose Run Sandstone. After the initial deposition of the unit, the primary cement was sucrosic dolomite with possible intercrystalline porosity. The evidence for this is suspended detrital grains found in the dolomite cement and the absence of quartz overgrowths.

The formation of the Knox unconformity and uplift of the unit gave rise to a secondary porosity. This occurred by the dissolution of the matrix, cement, and grains by meteoric water that penetrated the unit at the time the Knox unconformity was formed. The evidence for this are cement remnants, corroded grains, cements, or ooids, and oversized pores. The re-burial of the unit resulted in a decrease in porosity. This stage of burial and diagenesis is evident by the abundance of quartz overgrowths, absence of dolomite cement and presence of poikilotopic dolomite (Atha, 1981). These three phases of burial and diagenesis in the order described above are called the eodiagenetic phase, telodiagenetic phase, and mesodiagenetic phase, respectively.

According to Riley et al. (2003), during the burial of the Rose Run Sandstone cementing materials originated from fluids super-saturated in silica that were a response to pressure-solution. Quartz overgrowths and feldspar overgrowths were the resulting cements. Some of the primary or early diagenetic calcite was dissolved, transported from the Rose Run Sandstone due to pressure solution and compaction, and precipitated in the Beekmantown Dolomite. At greater depths, warm basinal brines gave rise to dolomitization and the presently observed oversized and hybrid pores within the unit. Uplift associated with the formation of the Knox unconformity probably gave rise to the extensive dissolution of the dolomite and feldspars. This dissolution may have led to the formation waters rich in magnesium and potassium, which subsequently led to the precipitation of mixed layer illite-smectite, and, at greater depths, illite (Riley et al. 2003).
A late diagenetic event caused a second dolomitization event and finally partial replacement of dolomite by pyrite. The various stages of diagenesis according to Riley et al. (1993) within the Rose Run Sandstone are shown in Figure 8.
Economic Geology

From the isopach map in Figure 7, it can be seen that the Rose Run Sandstone is completely eroded (or was probably not deposited) from central Ohio, and also thins towards the western part of Ohio with a reduction in the sandstone-to-carbonate ratio. This pattern or trend in thickness is observed from the close packing of the contour lines. The maps also show various embayments and promontories and isolated outliers. These promontories could act as traps for hydrocarbon. The up-dip truncation of the unit by the Knox unconformity towards the central part of Ohio could also be another trapping mechanism within the unit (Atha, 1981). Riley et al. (1993) listed the trapping mechanism within the Rose Run Sandstone as fault-related traps, erosional remnants, combination of both fault-related traps and erosional remnants, erosional truncation at the angular unconformity, anticlines and the nose plunging folds, and up-dip and lateral pinch-out of facies. Hensen (1998) stated that most of the exploration for hydrocarbon within the Rose Run Sandstone is along a linear belt that runs from Ross County to Ashtabula County. The linear belt that is likely the Rose Run Sandstone subcrop is shown in Figure 6. Hensen (1998) further stated that gas was first produced from the well since 1965 in Holmes County. About 2000 (or 85%) of the Rose Run Sandstone wells have been drilled since 1988.

Exploration of hydrocarbon is greatest along the subcrop linear belt due to an increase in porosity of the sandstone reservoir. However, the potential for hydrocarbon exploration tends to be more difficult towards the eastern part of the subcrop linear belt as a result of a decrease in porosity of the reservoir; and an increase in depth to traps (Atha, 1981). Furthermore, porosity distribution has been studied within this unit, utilizing and cross-plotting neutron-density logs with petrographic study. This trend in porosity has been attributed to secondary dissolution of
cement and matrix, and compaction of sediments. During the formation of the Knox unconformity, the Rose Run Sandstone was exposed to meteoric water, which aided the dissolution of the unit matrix and cement. Away from the subcrop linear belt towards the east, there seems to be a reduction in porosity, probably due to decreased dissolution of cement and matrix. This explanation has been supported by the paleo-drainage map of Coshocton County, which was found to coincide with the porosity distribution map of the unit within the county (Atha, 1981). In the east, where the units are thickest, there is also a reduction in porosity, which has been attributed to a greater depth of burial, a process that has lead to a greater compaction of the unit by the thick overburden overlying it. Riley et al. (2003) used geophysical logs to show that porosity increases at deeper depths, which they attribute to dissolution by basinal brines undersaturated in carbonates.

Intergranular porosity is the most common type of porosity within the Rose Run Sandstone although intragranular, intercrystalline, and fracture porosity also exist (Atha, 1981). Dolomite cementation is a major porosity-reducing factor, in addition, chert and authigenic clays also contribute to porosity reduction (Atha, 1981). Finely crystalline sucrosic dolomite is the most common cement, with intercrystalline porosity. Enterline (1991) stated that diagenetic features such as quartz and feldspars overgrowths reduce porosity within the unit. Alteration and dissolution of orthoclase also creates secondary moldic porosity. Vuggy porosity is reduced through the infilling by glauconite. Concentration of glauconite and illite within stylolites also tend to reduce porosity. Pyrite infilling of voids and fractures is another porosity reducing agent, although it is relatively rare. The presence of authigenic minerals such as K-feldspars (probably orthoclase replacing plagioclase) and pyrite signals a reduction in porosity. Porosity is also reduced by the infilling of pore space with dolomite having planar- euhedral textures (Enterline,
1991). He further stated that these diagenetic features occurred after the hydrocarbons have migrated through the Rose Run Sandstone.

**METHODOLOGY**

This research involved analysis of diamond drill core sections by visual inspection, core photomosaics, and thin-section analysis. In addition, this study involved the interpretation of geophysical logs (gamma-ray logs, density log and neutron-porosity logs).

**Diamond Drill Core**

The cores are held at the Horace R. Collins Laboratory of the Ohio Geological Survey facility at Alum Creek, Ohio. The cores were used for hand sample and thin-section description and analysis to identify facies and microfacies. Descriptions of the four cores are given in Table 5.

The cores are stored in boxes 2 feet (0.610m) long. Core 3409 is stored in boxes with 5 compartments, giving the total core length per box of 10 feet (3.048m), while cores 2989, 2898 and 2923 are stored in boxes with sections of 3 compartments, giving the total length per box as 6 feet (1.829m). Each of these cores was examined, starting from the Copper Ridge Dolomite beneath the Rose Run Sandstone up to the Beekmantown Dolomite, above the unit of interest.

At the Horace R. Collins Laboratory, description of the cores included sedimentary structures, grain size, composition, and lithology. Descriptions were completed by visual inspection, use of hand lens, and use of the binocular microscope. Overlapping photographs were taken along the whole length of the cores at a uniform scale to create a photomosaic of each core.
The photomosaics were used for a pictorial examination of the trends in any of the cores. Cores were logged using the following methods (Figures 9 and 10).

The cores were then sampled for unique properties at different depths to avoid a situation of sampling the same property more than once. A total of 67 samples were taken from the four cores (Table 6).

The sampled rocks were then brought to the Geology Department at Bowling Green State University for more detailed study using a binocular microscope. In addition, 17 samples were also used for thin-section preparation.

The thin sections were used for micro-facies analysis and mineral composition estimation using a petrographic microscope and cathodoluminescence (see below). Microstructures were also observed in some of the sections. A total of 26 photomicrographs of microstructures were also taken. Composition was determined by point counts (see later section).

**Cathodoluminescence methods**

Cathodoluminescence was effectively used in differentiating quartz, reworked quartz, feldspars and authigenic feldspar, and cement types based on their colours. Although the quartz is only weakly luminescent, it was differentiated by its blue to violet or purple luminescence and sometimes red coloration depending on the activator (i.e., Fe$^{3+}$ or Ti$^{4+}$) (Boggs and Krinsley, 2006). They further state that feldspars are recognized by their bright blue colours. Feldspars could also be green or yellow depending on the activator. Dolomite and calcite cements are viewed as red to orange, but are differentiated based on their shapes. Dolomite has an euhedral outline while calcite cements are usually anhedral.
Table 5. Summary of cores

<table>
<thead>
<tr>
<th>NO</th>
<th>OWNERS</th>
<th>COUNTY</th>
<th>WELL</th>
<th>TOTAL CORE THICKNESS (FT)</th>
<th>ESTIMATED THICKNESS OF THE ROSE RUN SANDSTONE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Aristech Chemical Company</td>
<td>SCIOTO</td>
<td>3409 (D)</td>
<td>56.5</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>NU Energy Corporation</td>
<td>JACKSON</td>
<td>2898 ( C )</td>
<td>31</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>Stone Resources and Engineering Company</td>
<td>COSHOCTON</td>
<td>2989 (A)</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Columbia Gas Transmission Corporation</td>
<td>MORGAN</td>
<td>2923 (B)</td>
<td>61</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 6. Number of samples taken from each core.

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>CORE NUMBERS</th>
<th>NUMBER OF SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2923</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>2989</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>2898</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>3409</td>
<td>19</td>
</tr>
</tbody>
</table>
Point count method

Mineral composition was determined by placing 17 thin sections in a counter under cross-polarized light. Grains found underneath the cross hairs were identified and recorded using a cell counter. A total of 300 grains per thin section were counted. The percentage composition of the various components making up the thin section was then calculated.

Cathodoluminescence images were imported into Adobe Illustrator and then the images were gridded at regular intervals forming cross hairs. Grains and cements that fall underneath the cross hairs were counted and recorded using a cell counter (an average of 270 grains per image were counted), and then the percentage composition was estimated as done above.

Geophysical Log Data

Gamma-ray log

Gamma-ray logs measure natural radioactive properties in lithologies such as shale. Readings (1986) listed potassium, uranium, and thorium as common sources of gamma-ray radiation. In addition, Readings (1986) attributed the radioactive (shaly) response of sandstone to K-bearing minerals like clays, micas, K-feldspars, and glauconite. Miall (1984) stated that the gamma-ray log acts as an indicator of the clay mineral content of a unit, which correlates to grain size. In contrast, texturally and mineralogically matured quartz arenite and clean carbonate give a low gamma-ray log reading. Thus, the log is an excellent tool for differentiating shale/mud from rocks like clean sandstone and dolostone in the subsurface. The pattern of the log trace is a sensitive lithostratigraphic tool as shown in Figure 4. The log is also commonly used in facies studies and correlation (Miall 1984). In this research, maximum and minimum readings of the gamma-ray log are 373 and -31.78, respectively, with units in API.
Density Log

Density Logs are measurements of back scatterings of gamma-rays from a formation of interest. This process works on a principle known as Compton scattering. The backscattering depends on the electron density of the formation which is roughly proportional to the bulk density of the formation.

Density logs have been established as a tool for differentiating rocks on the basis of their bulk densities (grain and fluid density). Readings stated that they are commonly used in combination with neutron logs. The log is used to differentiate between dolostone and sandstone based on the fact that dolostone possesses a greater density than sandstone. In this research, the maximum and minimum readings of the density log are 3.11 and 1.89 respectively, with units in g/cm$^3$.

Neutron porosity log

Neutron porosity log are measurements of the back scatterings of neutrons from a formation. Since hydrogen captures or slows down neutrons, the amount of neutrons measured gives an indication of hydrogen within pore spaces. Therefore, neutron porosity log indirectly measures the hydrogen concentration in fluids (water, hydrocarbon, and gas) within the pore spaces of rocks. Readings (1986) stated that porous limestone, dolostone, and sandstone have moderate porosity, while shale has a high porosity. In this research, the maximum and minimum readings of this log are 70.60 and -7.02. The unit of neutron porosity log is in percent porosity.

During a depositional environmental investigation, information of the lithology is required to enable a proper assessment of the unit. Sometimes these units are buried in the
subsurface, and the only means of acquiring data of the *in situ* condition of such unit is through
the application of bore-hole geophysics. According to Butler (2005), a geophysical log represents
the data that result from recording the geophysical response as a function of depth, as the logging
probe is moved along the well bore. According to Readings (1986), because logs are run
continuously in such a way that they provide a continuous depth profile of the physical
properties of the formation, they are good indicators of unit sequences on scales ranging from a
meter to hundreds of meters. He further stated that based on their ability to measure
sedimentological criteria, they are excellent tools for carrying out sequential environmental
studies. In addition, Butler (2005) stated that these profile measurements with depths are used to
discern stratigraphy and structures of formation where cores are not available.

Geophysical logs are sensitive to certain rock properties, such as radioactivity and
density. These properties depict grain size, lithology, density, porosity, and pore-fluid (Readings
1986). The gamma-ray log, density, and neutron-porosity log were used in this study to correlate,
model, and define limits of the unit along side with the cores.

**Petrel® software**

To combine cores and geophysical logs seamlessly, Petrel® served as efficient and
flexible software, combining data from geology, geophysics, and reservoir engineering; it
provides a better description and understanding of a reservoir. This software aids in improved
reservoir production and performance by creating a better understanding and clearer view of
reservoirs in 2- or 3-dimensions.

Gamma-ray, density, and neutron-porosity logs which were in ASCII format were
converted to graphical logs utilizing Petrel® software. The logs were imported into Petrel at a
scale of 1:10000; this scale would have made it difficult to work with the log signatures of the Rose Run Sandstone, because the unit is thin within the study area. In order to efficiently work with the unit, the logs were enlarged by reducing the scale to 1:1000. These logs were used in conducting a trend analysis of the entire area, so as to visualize the variations in thickness of the Rose Run Sandstone from the southeastern to the northeastern part of the area of interest. In this research, the modules of Petrel® pertaining to lithocorrelation and facies modeling were used. This involved identifying lithofacies based on their unique log profile. Relationships between facies were then modeled, using the Train Estimation Model. The Train Estimation Model is a neural network method that uses a deterministic approach in modeling facies, specifically, it identifies a trend based on the pattern of distribution of facies from the data input (Schlumberger, 1997). The resulting facies model was calibrated by projecting (comparing and assigning similar log signatures lithofacies values in the modeled well to those in the experimental well) the interpretation to a new region based solely on geophysical logs, and then evaluating (matching the log signatures in the modeled well to the experimental well core to see how well they correlate) data to confirm the predictions.
Figure 9. Symbols used in the stratigraphic sections
Figure 10. Example of a logged well core interval (core 2923).
RESULTS

The four core sections are shown in Figures 11, 12, 13, and 14. Based on geophysical log signatures three formations were identified from the cores, the Cooper Ridge Dolomite, the Rose Run Sandstone, and the Beekmantown Dolomite. The coarsening and fining-upward sequence within the Rose Run Sandstone is cyclic as seen in Figure 13. The siliciclastic rocks vary in color from white to creamy tan and medium to dark brown with alternations of greenish to brownish lamination. The sandstones within the unit contain flaser bedding and cross bedding, bioturbation, current ripple lamination, and carbonate and shale intraclasts. The dolostone within the unit are generally light to medium brown (depending on the quartz content) and are massive or laminated. Typically, the dolostones are rhythmically bedded, consisting of alternating siliciclastics and arenaceous carbonates. The dolostones contain clasts of carbonate intraclasts, and they are mottled probably due to bioturbation.

Facies and Micro-facies Analysis

Ten lithofacies were defined from core data analysis and micro-facies analysis. Sedimentary structures such as mottling, tidal rhythmites, rip-up clast, ooids, flaser bedding, and bioturbation were identified in the core interval representing the Rose Run Sandstone (Table 7). Each lithofacies is discussed below.
Facies D1

This facies is a mottled packstone, distinguished by patches of light brown colorations in dark brown colors of dolostone as shown in Figures 15 and 16. A specific cause of the mottling could not be determined.

Shinn (1983) and Wilson (1983) stated that mottling is indicative of deposition in an intertidal environment. This facies was interpreted as deposited in a lower intertidal environment based on the studies carried out by workers listed in this paragraph.

Facies D2

This facies is heterolithic sandstone and mudstone interpreted as tidal rhythmite. The sandstones are arenaceous packstones. The mudstones are thin clay-rich laminae < 1mm thick. The sandstone and mudstone are arranged as couplets that show double mud drapes (daily asymmetry of two high tides and two low tides). The daily tidal cycle consist of a dominant tide which tends to deposit more than the subordinate tide. Because of the very thin deposits of the subordinate tide, the separation between the mud drapes of both the dominant and subordinate tide is so small that the two drapes are referred to as double mud drapes (like nothing was deposited between them).

This facies also comprises combinations of double mud drapes that form thickening and thinning sets of tidal rhythmites. These are interpreted as spring-neap tide cycles (Figure 17). According to Walker and James (1992), spring and neap tides occur due to the orientation of the moon and the sun relative to the earth. The spring-neap cycle is actually a monthly tidal cycle. Spring tides occurs when the moon and the sun are positioned in the same axis to the earth such that both the gravitational effect of both the moon and the sun result in a greater tidal range;
while the neap tides occur when the moon is oriented perpendicular to the sun such that they both offset their gravitational effect. This causes a lower tidal range relative to those of the spring tide. Spring – neap cycles are 14 days package of tidal rhythmites. The dominant tide results in a greater thickness of deposits, while the slack water phase of the dominant tide results in the deposition of mud drapes. The subordinate tide gives rise to very thin deposits, while the slack water phase also results in the deposition of mud drapes.

Walker and James (1992) also attributed the variation in lamina thickness to variation in current speed of the tides. Alvaro et al. (2006) stated that sorting, roundness, grading and alternating laminae (rhythmites) all indicate reworking in medium to high-energy subtidal environment. Therefore, tidal rhythmites are interpreted as deposition in a subtidal environment.

**Facies D3**

This facies is an arenaceous packstone with rip-up clasts. The clasts within this facies occur in very fine-to coarse-crystalline dolostone matrix. The clasts in the carbonates include quartz, chert, and feldspar (Figures 16 and 18). The clasts are typically subrounded to angular in shape. The color of the clasts varies, depending on the quartz content. In rare cases, the clasts in the dolostone include 0.1-3.0cm dolostone. The sandy dolostone clasts indicate transport. The angular to subangular shape of the quartz and feldspar in the clasts indicate a local source- short distance of travel from the source. The mud chip intraclasts are derived from tidal reworking of mudcracks. The intraclasts were derived from intertidal environment when mudcracks formed. When the intertidal environment was flooded at high tide, the mud chips were eroded to make intraclasts.
Facies D4

This facies consist of fine-to medium-grained quartz arenite containing mudstone or shale intraclasts. The intraclasts in the sandstones are cream colored and small in size, composed of muddy material (Figure 19). Riley et al. (1993) stated that shale clasts are observed within their study well. The intraclasts observed within this unit are about <1cm and are also subrounded to subangular.

These muddy intraclasts indicate reworking of mudcracks (see earlier discussion). Intraclasts have been described as deposits of channel in any environment. The intraclasts were interpreted as having been deposited in a subtidal to lower intertidal environment where frequent fluctuations in tidal current results in previous deposited sediments (i.e. mudstone or shale intraclasts), being ripped up by the forces of incoming tidal current.

Facies D5

This lithofacies consists of flaser bedded, wavy bedded or lenticular bedded, fine-to coarse-grained, rounded to subrounded, calcareous quartz wacke. Flaser bedding, wavy bedding and lenticular bedding are caused by mud drapes in the troughs of ripple laminated sandstones (Figures 19, 20 and 21). The color of the mud drapes varies in the different study wells from green to brown. Also within the sandstone unit are wavy bedding and very low-angle cross bedding caused by the interposition of single mud flasers in the ripple lamination as shown in Figures 19 and 20.

Klein (1977) interpreted wavy, flaser, and lenticular bedding as the alternation of bedload and suspension deposits during changes in states of subaqueous tidal current flow from high to low energy. Reineck and Wunderlich (1968) interpreted flaser bedding as common in intertidal
environments resulting from ripple troughs containing trapped and incomplete mud laminae during cessation of strong flow of current or still water. This facies is interpreted as being deposited in a sand flat environment because of its similarity to those mentioned by workers in this paragraph.

**Facies D6**

This facies consists of a planar-tabular cross bedded, medium- to coarse-grained rounded to subrounded, moderately sorted, hematitic quartz arenite. The planar-tabular cross bedding consists of low-to medium-angle sets (Figure 21). The sandstones are dark to medium brown, depending on the hematite staining.

Although planar-tabular cross bedding could be unidirectional or bidirectional, the form observed from the study well is unidirectional. Reversing sets of unidirectional cross-beddings probably occur in these cores, but they seem to have occurred in separated/broken cores. Mellere and Steel (1995) listed high- angle cross bedding and herringbone cross stratification as characteristics peculiar to tidal-influenced depositional environments. The strong currents could also be responsible for the removal of portions of herringbone cross stratification. But then, herringbone cross stratification are rare structures, formed only when flood tides energy equals ebb tide energy. In this study, the planar-tabular cross bedded facies is interpreted as sand bars/dunes. This facies is interpreted as being deposited in a sand flat environment because of its similarity to those mentioned by workers in this paragraph; secondly, this facies is indicative of sandbars/ dunes which are known to form under high current velocity as the dunes/ bars migrate (Walker and James, 1992).
Facies D7

This facies consists of oolitic grainstone. At the micro-facies scale, the ooids are concentric, and the nucleus has been micritized. The ooids are siliceously cemented and partially tainted by coarse-grained cherts as shown in Figures 22 and 23. The micritization process replaces the ooids, leaving different versions of ghost ooids. The dolostone containing the ooids are fine-to medium-crystalline. The ooids are sometimes associated with carbonate intraclasts as shown in Figure 18.

Ooids form in shallow marine or lacustrine environments (Reineck and Wunderlich 1968). Specifically, ooids are found in high-energy settings such as carbonate shoals or tidal deltas associated with tidal inlet channels (Ball, 1967; Hine, 1977). Riley et al. (1993), interpreted the ooids in the Knox Dolomite as shallow marine and subtidal because of their areal extent and thickness, and also because they show evidence of submarine carbonate cementation. In this study, facies D7 is interpreted as being deposited in a subtidal marine environment because of their peculiarity to this environment, as determined by previous workers and because the ooids were siliceously cemented and dolomitized.
<table>
<thead>
<tr>
<th>FACIES</th>
<th>LITHOLOGY</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>INTERPRETATION</th>
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<td>Bioturbated carbonate</td>
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<td>D2</td>
<td>Heterolithic sandstone and mudstone</td>
<td>laminated</td>
<td>Tidal rhythmite</td>
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<td>D3</td>
<td>Arenaceous Packstones</td>
<td>Intraclasts</td>
<td>Reworked arenaceous dolostone (desiccation cracks)</td>
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<td>Fine- to medium-grained sandstone</td>
<td>Intraclasts</td>
<td>Reworked mud chips (desiccation cracks)</td>
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<td>Flaser bedding, wavy bedding and lenticular bedding</td>
<td>Ripple marks with mud drapes (tidal)</td>
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<td>Low to medium angle planar-tabular cross bedding</td>
<td>Sand bars/dunes</td>
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<td>Oolitic grainstone</td>
<td>Ooids</td>
<td>High energy beach and shoal</td>
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<td>Carbonate mudstone</td>
<td>Algal lamination</td>
<td>Stromatolites</td>
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<td>D10</td>
<td>Fine- to medium-grained sandstone</td>
<td>Massive, burrows</td>
<td>Bioturbated sandstone</td>
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Figure 11. Well core section from core 2989
Figure 12. Well core section from core 2923
Figure 13. Well core section from core 2898
Figure 14. Well core section from core 3409
Figure 15. Examples of sedimentary structures from well cores in carbonates of the Knox Group. (1) and (2) Both showing probably biogenic mottling in dolostone (facies D1).
Figure 16. Examples of sedimentary structures from well cores in carbonates of the Knox Group. Showing biogenic mottling (Facies D1) and clast (Facies D3), and algae lamination (Facies D9) in dolostone.
Figure 17. Heterolithic sandstone and shale, interpreted as tidal rhythmites. Note the double mud drapes (daily) tidal cycle and spring-neap (monthly) tidal cycle. (Facies D2).
Figure 18. Examples of sedimentary structures from well cores in carbonates of the Knox Group showing ooids (facies D7), clast (facies D3), and glauconite filling intercrystalline porosity and fractures.
Figure 19. Wavy bedded and lenticular bedded (facies D5) hematitic sandstone with carbonate intraclast (facies D4) from the Rose Run Sandstone.
Figure 20. Wavy bedded sandstone (facies D5) with vug and stylolite from cores within the Rose Run Sandstone.
Figure 21. Flaser and wavy bedded sandstone (facies D5), grading up into tabular cross bedded sandstone (D6). The flaser bedded sandstone also probably contains burrows (Facies D10).
**Facies D8**

This facies consists of current ripple laminated, fine-to coarse-grained, rounded to subrounded, calcareous quartz wacke. Current ripple laminations are brown to greenish in color; the structure is well portrayed by the continuous greenish shale laminae. The current ripple laminations are asymmetrical.

This facies is interpreted as being deposited in an intertidal to shallow subtidal environment where wane in current energy results in the formation of current ripple lamination as stable bedform sometimes with associated mud/shale drapes due to slack water stage.

**Facies D9**

This facies consists of thinly laminated carbonate mudstone, interpreted as lithified algal mats. The unit was subsequently dolomitized. The dolostones are characterized by thin, wavy, and brownish laminations (Figure 16). Algal mats are filamentous algae originating both in marine and fresh water settings. They are found dominantly in moist setting, particularly in relatively quiet shallow water environment (Horodyski, 1982).

Walker and James (1992) stated that the facies are usually associated with intraclasts, pores, digitate stromatolites and they are usually brecciated. Based on the above description by Walker and James (1992), the facies is interpreted as being deposited in a peritidal environment.
Figure 22. Photomicrographs of the Rose Run Sandstone. Interbedded sandstone (SST) and mudstone (M). (facies D2). Concentric ooids in fine to coarse chert cement, glauconite (G), and dolomite (D). (facies D7)
Figure 23. Photomicrographs of the Rose Run Sandstone. Calcareous quartz wacke showing carbonate cement (CC), quartz (Q), microcline (MC), and glauconite coatings (G). Micritized concentric ooids (O) in fine to coarse chert cements (CH).
Figure 24. Herringbone crossstratification (facies D6) and bioturbated (facies D10) sandstone from cores within the Rose Run Sandstone. The bioturbated unit grades into the crossbedded sandstone.
Facies D10

The facies consists of massive, fine-to medium-grained quartz arenite with abundant burrows. The structure can be observed as mottled light to medium brown. This mottling discoloration may be biogenically caused. The possible cause of this structure could not be determined due to its present preservation state.

Shin (1983) and Wilson (1983) stated that mottled-burrows (bioturbation) are indicative of an intertidal environment. This facies is thus interpreted as deposited in an intertidal environment based on observation by workers listed in this paragraph, and probably because this is where sediments are least disturbed by current energy.

Lithofacies association and succession

Siliciclastic environment facies association

In this study, facies D8 is commonly associated with facies D5 (Figures 19 and 20). This is common because, according to Reineck and Wunderlich (1968), both are formed during the cessation of strong current flow. Ripples that are formed may or may not contain mud drapes, giving rise to this facies association. Facies D4, D5 and D8 occur as an association in the sandstone (Figure 19). Facies D4 occurring with facies D5 and D8 may be attributed to intraclasts being deposited by currents with great tidal range. This assertion is supported by the presence of facies D5 and D8 which denotes a low-energy environment. Finally, facies D8, D10 and facies D5 occur together in sandstone (Figure 21). This facies association is found where low current-energy resulted in low sediment movement.
Siliciclastic environment facies succession

The general sequence of facies successions is the shallowing-upward sequence. This sequence can be initiated by either facies D6 transitioning to facies D5 or facies D8 transitioning to facies D2, then a change to facies D3 with or without facies D10 further landward. The most predictable of the facies succession is that of facies D6 being preceded and succeeded by facies D5, indicating a sort of cyclic sequence of both fining and coarsening upwards. This is shown in Figures 11, 12, 13, 14 and 21.

Carbonate environment facies association

Ball (1967) and Hine (1977) stated that both facies D7 and D3 are found in high-energy settings such as carbonate shoals or tidal deltas associated with tidal inlet channels. Ooid grainstone (facies D7) are formed in association with carbonate intraclasts (facies D3), as shown in Figure 18. Facies D9 is associated with facies D1 as shown in Figure 16. This association could be interpreted as a period of stability with little or no movement in deposits. These conditions, according to Walker and James, 1992 are required for the formation of algal mats and bioturbation (biogenic mottling). Figure 16 also shows mottling associated with intraclasts. This probably denotes a transitioning from a quiet to a disturbed environment or that the tidal range was high that it probably carried intraclasts into the bioturbation zone.

Carbonate environment facies succession

The succession trend here is generally a carbonate shallowing-upward sequence. This trend is denoted by the transitioning of facies D7 to D3 and then finally to D9 with or without D1
further landward. These facies succession based on previous discussion of individual facies
denotes a transitioning from an active high energy environment to a relatively quiet environment.

Core Descriptions

Core 2989

Core 2989 (Figure 11) comprises mostly dolostone, with thin beddings of sandstone. At
the bottom of the well, dolostone containing ooids and intraclasts grade into bioturbated
dolostone. These then grades back into a rhythmic dolostone with intraclasts and ooids and
interbedded cherts. This represents transitioning from the shallow subtidal to the intertidal and
migrating dune/bar and then back to the shallow subtidal. The sandstones within the unit of
interest are generally fining upwards.

Core 2923

At the bottom of core 2923 (Figure 12), there is a repetition of these facies successions:
ooids, intraclasts and mottling. Within these repeating facies association, algae lamination and
bioturbation also occurs. Towards the middle of the core, flaser bedding grades into cross
bedding, and current ripple lamination grades into tidal rhythmites and intraclasts. This then
grades into the same facies seen at the base of the well.

Core 2898

The study interval of core 2898 (Figure 13) contains only sandstone. Within the flaser
bedded sandstone units, there are repetition and alternation of tabular cross bedding. The well
also contains pockets of intraclast. The sand within this well show an alternation of both fining- and coarsening-upwards sequences.

Core 3409

At the bottom of core 3409 (Figure 14), there is a repetition of facies succession (i.e. intraclasts, mottling, and ooids). Towards the top of the study interval, intraclasts, flaser bedding, current ripple lamination, and cross bedding occur. These then grade into some of the carbonate facies (i.e. intraclasts and ooids) seen at the base of the well. Intraclasts, mottling, and ooids were found in fine to very coarse crystalline grained dolostone, while flaser bedding was found in fine-to coarse-grained sandstone. The sandstone units show both fining- and coarsening-upwards sequences.

Petrology

The Rose Run Sandstone varies from calcareous to non-calcareous, fine-to coarse-grained, rounded to subrounded, moderately sorted, glauconitic, quartz or feldspathic arenite or wacke. The unit also consists of interbedded dolostone and shale. The point count data are given in Table 8, and compositions are plotted in Figure 25.

Most of the quartz is monocrystalline (99%) with very small amount polycrystalline quartz (1%). The dominant feldspars are the orthoclase, then the microcline (Figure 26), and then the plagioclase making up <1%.

The authigenic feldspars show a highly luminescent color (white) surrounded by orange coloration (Figures 27, 28, 29). The cores of the authigenic feldspars are detrital grains that have been transported some distance from their source before being cemented by feldspar (usually
albite). The detrital grains can be recognized by their almost well rounded shape (Figures 27, 28, 29). The probable feldspar cement is albite, which is recognized by its euhedral outline.

The cements vary laterally from well to well; for instance well 2898 contains dolomite cement, quartz overgrowths, and feldspar overgrowths cement; whereas well 3409 consists of quartz overgrowths, clay cement, feldspar overgrowths. In general, from the thin sections within the study wells, the dolomite cement dominates, followed by the quartz overgrowths, then clay cement, with very small amount of feldspar overgrowths (Table 8). The dolomite cement is euhedral in shape (Figure 29), supporting the notion of dolomite being the initial cement. In Figure 29, cathodoluminescence shows multiple generation of carbonate cement based on the colour types, and shape of carbonate cement. In the same figure, dolomite cement is viewed as red with planar-euhedral texture, while calcite cements comprise planar-anhedral texture.

The dolostone comprise dominantly fine-to coarse-crystalline sparry calcite. Within the dolostone, allochems such as ooids were micritized or replaced by silica, or left as ooids ghost (Figures 22 and 23). The dolostone usually include quartz and feldspar (arenaceous dolostones). Calcite occurs as both cement and matrix within the dolostones; however dolomite cements which were derived from the calcite cements, are also found occurring dominantly as cements (Figure 30).
Table 8. Point count analysis from both cross polarized and cathodoluminescence method

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<th>Quartz cement</th>
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Figure 25. QFL plot of samples A-E from the Rose Run Sandstone. Petrographic fields are: 1= Quartzose, 2= Sub-arkose (sub feldspathic), 3= sub-lithic, 4= arkose (feldspathic), 5= litho-arkose (litho-feldspathic), 6= Feldspatho-lithic, 7= Lithic.
Figure 26. Photomicrographs of the Rose Run Sandstone. (A) Quartz sandstone (SST), interbedded mudstone (M) and glauconite (G). (B) Subfeldspathic arenite, showing quartz (Q), orthoclase (OT), microcline (MC), and glauconite (G).
Figure 27. Cathodoluminescence photomicrograph showing quartz (Q), feldspars (F), albite cement (AC), Quartz cement (QC), pore spaces (PS) and orthoclase (OT) enclosed in albite cement.
Figure 28. Cathodoluminescence photomicrograph showing quartz (Q), feldspars (F), albite cement (AC), Quartz cement (QC), pore spaces (PS) and detritus grains (orthoclase (OT)) enclosed in albite cement.
Figure 29. Cathodoluminescence photomicrograph showing quartz (Q), altered feldspars (F), Dolomite cement (DC) with planar-euhedral texture, and calcite cement (CA) with planar-anhedral texture.
Figure 30. Photomicrographs of the Rose Run Sandstone. (A) Calcareous quartz arenite showing carbonate cement (CC), quartz (Q), polycrystalline quartz (PQ), microcline (MC), orthoclase (OT), and quartz cement (QC). (B) Calcareous quartz wacke showing rounded to well rounded quartz grains (Q), plagioclase (P), and carbonate cement (CC).
Figure 31. Photomicrographs of Rose Run Sandstone showing quartz (Q), feldspar (F), albite cement (AC), orthoclase (OT) and quartz cement (QC) in A= cathodoluminescence (CL), B= plane polarized light (PPL), and C= Plane light (PL). The quartz cement is delineated by dust rims (DR).
Figure 32: Photomicrographs of Rose Run Sandstone showing feldspar reaction in terms of its alteration and dissolution in A= cathodoluminescence (CL), B= plane polarized light (PPL), and C= plane light (PL). The image shows feldspar cement (probably albite (AC)).
Geophysical log Facies

By comparing the gamma ray log signatures in the different wells (Figures 33, 34, 35 and 36) to those gamma-ray models given in Figure 4, the depositional environment was inferred. Gamma-ray logs in well 3409 and 2923 come close to irregular shape, interpreted as mixed clean and shaly, or showing no trend; while gamma-ray logs in well 2989 and 2898 come close to cylindrical, clean, or no trend. Both of these gamma-ray log models are consistent with the tidally influenced depositional environment (mixed clastic-carbonate shoreline).

Stratigraphy and Correlation

The three formations within the Knox Group were delineated using geophysical logs. Gamma-ray logs, density logs, and neutron porosity logs were imported into Petrel as las. files. These logs were used to identify the Cooper Ridge Dolomite, Rose Run Sandstone and the Beekmantown Dolomite. The stratigraphic section contains shale, sandstone, and dolostone. A relatively high peak in the gamma-ray slice was used to identify clay minerals in shale, although peaks could also be due to glauconite. Sandstone was identified by a relative reduction in the bulk density log curve accompanied by an increase in the neutron/porosity log. The dolostone was recognized by low gamma-ray reading and an increase in bulk density (greater than sandstone) signature slice. From the log signatures, it could be observed that the dolostone is most abundant of the three lithologies. Thus, dolostone is usually the standard of reference in terms of identifying other lithologies using the bulk density and gamma ray logs. This implies that any deviation from normal of the bulk density and gamma ray logs curve could be due to either sandstone or shale. These actually made it easy differentiating and delineating the top and bottom boundary of the Rose Run Sandstone as shown in Figure 33.
Figure 33. Output of PETREL®, showing the use of gamma-ray log (GR), density log (RHOB) and neutron porosity log (NPHI) to identify the Rose Run Sandstone from core 3409. Unit thickness is 29 feet (8.84m)
Figure 34. Output of PETREL®, showing the use of gamma-ray log (GR), density log (RHOB) and neutron porosity log (NPHI) to identify the Rose Run Sandstone from core 2989. Unit thickness is 10 feet (3.05m).
Figure 35. Output of PETREL®, showing the use of gamma-ray log (GR), density log (RHOB) and neutron porosity log (NPHI) to identify the Rose Run Sandstone from core 2923. Unit thickness is 20 feet (6.10m).
Figure 36. Output of PETREL®, showing the use of gamma-ray log (GR), density log (RHOB) and neutron porosity log (NPHI) to identify the Rose Run Sandstone from core 2898. Unit thickness is 24 feet (7.32m).
**Projection to Unknown Well**

The log signatures at well 3409 were supervised classified by assigning lithologies to the log signatures based on core data. The supervised classification was then modeled using the train estimation model of Petrel, to get an accurate and reasonable assignment of log signatures to lithologies. After the well 3409 has been properly modeled to create a high-resolution depositional model, the model was calibrated by projecting (comparing and assigning similar log signatures lithofacies values in the well 3409 to those in well 2923) an interpretation to well 2923 (which is 70 miles away from the model well 3409). In other words, lithologies were assigned to well 2923 using interpretations from well 3409 as shown in Figure 37. These assigned lithologies in well 2923 were also modeled using the train estimation model as done in the well 3409 (Figure 37). The model from the well 2923 was then confirmed using core data.

**Evaluation of Projected Interpretation**

During correlation, apart from classifying shale as glauconite on few instances, and arenaceous dolostone as either dolostone or sandstone (depending on the amount of quartz content), the modeling in well 2923 was confirmed with core data to a good degree of accuracy. In brief, excellent core data, gamma-ray, density, and neutron porosity log coverage enabled a facies interpretation and correlation from well 3409 to well 2923. The train estimation model actually showed some lithologies that were missed during core inspection for instance based on the gamma ray log; mudstone was identified, interlaminated in sandstone. This was noticed during the confirmation of results of the model at different depths. Because of the small thickness of the Rose Run Sandstone within the study well, lithofacies were to some degree of accuracy correlated from well 3409 to well 2923. The lithofacies were interpreted as subtidal to
lower intertidal environments. The Petrel® software also showed the relative depths and porosity distribution within the study wells. This is shown in Figure 38.
Figure 37. Output of PETREL® model, showing how the log response in well 3409 was projected to well 2923. Subsequent examination showed that both wells represent subtidal to lower intertidal environments.
Figure 38. Output of PETREL® model, showing the trend in thickness and porosity within one of the study wells
DISCUSSION

Depositional environment

Siliciclastic tidal flat environment consist of the intertidal zone, subtidal zone, and the supratidal zone. The intertidal zone is further subdivided into the sand flat, mixed flat, and the mud flat.

Within the sandflat environment in the intertidal zone, flaser bedding, low angle cross bedding, reactivation surfaces, double mud drapes, bioturbation, and herringbone cross stratification usually dominate (Walker and James, 1992). All of these features were observed in the Rose Run Sandstone. However reactivation surfaces were not observed in the study wells.

The subtidal zone comprises siliciclastics which are usually fine-to coarse-grained depending on the energy of the subtidal environment. Within this environment, high- angle cross bedding, tidal rhythmites, herringbone crossstratification, rip-up clasts, and intraclasts dominate (Walker and James, 1992). They further stated that low-energy subtidal environments are usually denoted by the presence of tidal bundles and double mud drapes. Double mud drapes and herringbone cross stratification were observed from the study wells, however tidal bundles were probably not observed. The general trend in grain size from the subtidal to the intertidal environment is fining upwards. Glauconite is believed by Enterline (1991) to represent lots of biological activity. According to Enterline (1991), glauconite forms by alteration of fecal pellets within the marine environment. The association of glauconite and ooids points to shallow marine environment.

The general sequence of events based on the occurrence of the sedimentary structures show shallowing-upward sequence in both the siliciclastic and carbonate rocks. Within the
clastic rocks the sequence is initiated by either facies D6 transitioning to facies D5 or facies D8 transitioning to facies D2, then finally a change to facies D3 with or without facies D10 further landward. The carbonate sequence is also is denoted by the transitioning of facies D7 to D3 and then finally to D9 with or without D1 further landward. These sequences indicate that the Rose Run Sandstone was deposited in an area influenced by tides. During tidal rise, previously deposited sediments are ripped up as intraclasts by the force of the incoming tidal current. Furthermore, as the tidal current moves landward, current ripple laminations develop. Flaser bedding develops where there is high enough energy to moderately sort the sandstones, leaving a few mud or shale intercalations during slack water phase. Tabular cross bedding indicates a probable progradation of bars/dunes within channels, further seaward. The low-angle cross bedding in the sand flats to high-angle cross bedding in the subtidal environment indicates progradation of dunes into deeper marine environments. The occurrence of these structures at different depths (for example in Figure 39) indicates multiple progradation within the unit. Figure 39 also shows repetition in coarsening-upwards sequence. Based on the facies assemblage, these sedimentary structures were used to interpret the Rose Run Sandstone as subtidal, with associated tidal flat deposits and related subtidal channels with migrating sandbars/dunes.

Atha (1981), Enterline (1991), and Riley et al., (1993), working at different locations of the Rose Run Sandstone, observed structures such as reactivation surfaces, herringbone cross stratification, flat pebble conglomerate, and mud cracks, in addition to some of the structures mentioned in this research. Collectively, these structures point to a tidally-influence depositional environment. Mellere and Steel (1995) listed characteristics peculiar to tidal-influenced depositional environment as: high-angle cross bedding, abundant, thick mudstone drapes,
heterolithic facies, herringbone cross bedding, mud clasts, double mud drapes and bioturbation. This research also shows the presence of these structures listed by Mellere and Steel (1995).

The presence of dominantly monocrystalline quartz, weakly luminescence quartz and detrital feldspar indicates an igneous provenance. The presence of quartz with abraded overgrowths indicate reworking of siliciclastic rocks at low temperatures. Sutter and Hearn (1985) attributed the formation of authigenic feldspars to reaction of brine with siliciclastic debris at low temperature.

Saeed (2002) stated that to perform an accurate depositional model analysis, lots of wells cores, logs, outcrops, and most importantly seismic data are required. The seismic data enable a lateral trace of a subsurface stratigraphic section, while well data would enable a vertical examination of a section at a point. Well data are constrained by being one-dimensional, no matter how closely spaced the boreholes are, and this limits the process of creating a three-dimensional facies model through a detailed correlation of wells (Nichole, 1999). Constrained by the sparse data available and, moreover, the small thickness of the unit within the study area, attempting an accurate depositional system analysis would be impossible. However, based on the sedimentary structures, the study area was interpreted as subtidal with associated tidal flat deposits and related subtidal channels with migrating sandbars/dunes. The sedimentary structures were used to propose a depositional environment for the unit as shown in Figure 40.
Figure 39. Showing a cross-section of the different formation within the Knox Group from the stratigraphic profile from cores 3409, 2898, 2989, and 2923.
Figure 40. Model of the depositional environment of the Rose Run Sandstone based on sedimentary structures
Paragenesis

Burial history and diagenesis can be deduced from the physical changes of the original composition of the Rose Run Sandstone at the time of deposition; for instance, were the original minerals mostly quartz, feldspars or lithics, knowing fully well that each of these minerals have different chemical and physical attributes. These attributes controls how these minerals react at different conditions of exposure (Riley et al. 2003).

Bioturbation

Both the sandstone and dolostone were massively bioturbated. Figure 24 shows bioturbation as mottled light to medium brown colors. This bioturbation tends to obscure sedimentary structures such as lamination and bedding. During the processes of bioturbation, sediments are generally mixed such that they are rearranged and compacted. Figures 15 and 16 show bioturbation in dolostone. This bioturbation is distinguished by patches of light brown colorations in dark brown colors of dolostone. This bioturbation also destroys early sedimentary structures such as lamination and bedding in the dolostone.

Authigenesis

The sandstones are very rich in glauconite as it is conspicuous in hand specimens. Glauconites are recognized by their greenish coloration; under the microscope, a speckled greenish birefringence denotes their presence. Although most glauconites originate from fecal pellets, another possible source of glauconite is the alteration of biotite (Scholle, 1978). Glauconite may show very fine granular texture as seen in Figures 22. Most of the glauconite were found filling intergranular porosity. Most of the intercrystalline porosity and fractures in the
carbonates have been in-filled dominantly by clays, glauconite, and pyrite. Figures 22 and 26 show some mudstones stringers occupying pore spaces within the arenaceous dolostone. This gives it a sort of rhythmitic appearance Figures 26. Pyrite constitutes a minor component infilling fractures. The dolostone also experienced minor replacements by chert.

The feldspars are highly eroded in well 3409. Dissolution of the feldspars could aid porosity improvement, however, clay resulting from the alteration can lead to reduction in porosity else where.

**Early Cements**

The study, and that by Riley et al. (1993), show that most of the calcite cements are anhedral. The euhedral dolomite rhombs (Figure 29) may have been derived from the initial calcite/aragonite cement after the deposition of the Rose Run Sandstone. Riley et al. (1993) stated that basinal brine caused the dolomitization of the unit at the initial depth of burial. Uplift and erosion by meteoric water during the formation of the Knox unconformity may have caused eroded grain boundaries, dissolution of carbonate cement causing a reduction in carbonate cement, and oversized pore spaces within the unit. These were also observed by Atha (1981) and Riley et al. (1993).

**Burial cement**

Re-burial of the unit at depth could have led to formation of quartz and feldspar overgrowths, and authigenic feldspars. Figure 27 shows that the quartz cements were precipitated before the feldspar cements. This stage of burial may have given rise to the precipitation of clay within the oversized pore spaces formed during the uplift stage. This stage is also marked by the
absence of dolomite cement as shown in Figures 27 and 28. However Figure 30 shows the presence of both quartz overgrowth and carbonate cement. This probably denotes secondary cementation, after the precipitation of quartz overgrowth. The late calcite cement precipitation may have been caused by changes in formation fluid compositions.

**Stratigraphic Correlation**

Based on core and geophysical logs, a stratigraphic correlation of the well was carried out. This was done by using the geophysical logs to delineate the top and bottom limits of the Rose Run Sandstone. After this, the delineated boundaries were then compared to the core attributes so as to assign lithofacies value to different depths of each of the cores. The core units were then correlated based on their similar log values (Figures 38 and 39).

By carrying out a stratigraphic correlation, the trend of the different facies association, and therefore their corresponding environment, was delineated within the study well; however, the accuracy of the correlation would first depend on the interpretation of the different facies association. Interpretation of depositional environment according to this author would depend on the experience and perspective of the interpreter.

For this type of study, sources of error would come mainly from inadequate experience as explained in the previous paragraph. Additional source of error would be the state of preservation of the cores during the time of their extraction from wells. In other words, how well preserved were the cores after extraction? Take for instance Figure 24, it would be difficult to interpret the structure as a herringbone cross-stratification because the crossbedding showing reverse direction, occurs in separate or broken core pieces.
Regardless of these shortcomings, stratigraphic correlations could be used to delineate an environmental trend by correlating lithofacies, as shown in this study. It usage is more accurate when used in association with marker beds such as shale which could help constrain the lithofacies correlation.
SUMMARY AND CONCLUSION

By studying the sedimentary structures from four cores within the Rose Run Sandstone, the paleoenvironment of the unit was interpreted as subtidal with associated tidal flat deposits and related subtidal channels with migrating sandbars/dunes.

Sedimentary structures such as ooids and intraclasts, mottling, algal lamination were found occurring in the dolostone; whereas lamination, flaser bedded, wavy bedded, lenticular bedded heterolithic sandstone and mudstone, current ripple lamination, and low-to medium-angle tabular cross bedding were found in sandstone. These structures in order of their succession were used to interpret both a clastic and carbonate shallowing-upward sequences in the Rose Run Sandstone. Tidal rhythmites, double mud drapes and possible herringbone cross stratification within the unit support a tidally influenced depositional environment.

Excellent core data, gamma-ray, density, and neutron porosity log coverage enabled a facies interpretation and correlation from wells 3409 to wells 2923. These subsurface facies were successfully correlated to their given gamma-ray, density, and neutron-porosity log signature slice by attributing a lithofacies from the core to a given geophysical log slice through a process called supervised classification. This modeling goes to prove that geophysical logs could be used to a certain extent to interpret the lithofacies from wells lacking cores.

The unit varies from glauconitic, calcareous to non-calcareous fine-to coarse-grained, rounded to subrounded, moderately sorted quartz arenite to quartz wacke. Using the polarized optical microscope and cathodoluminescence microscopy, the presence of dominantly monocryrstalline quartz, weakly luminescence quartz, and feldspars indicate an igneous and sedimentary provenance. Abraded quartz overgrowths indicate reworking of siliciclastic rocks at
low temperature. The cements are, in order of prominence, dolomite, quartz overgrowths, clay, and feldspar overgrowths.

The primary porosity within the unit is dominantly intergranular with some of it being cemented by dolomite. The dolostones have intercrystalline porosity. The dissolution and alteration of feldspar tends to affect porosity, with alteration causing a reduction in porosity and dissolution giving rise to an increase in porosity. Dissolution of feldspars within the sandstone unit created moldic porosities. The dolostone interbedded within the unit are vuggy and fractured.

This research is important for those interested in exploring for hydrocarbon within the unit, as it helps determine which lithofacies can serve as a guide for hydrocarbon exploration and, when the conditions (trap, seal, and maturity) for hydrocarbon exploration are right.
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APPENDIX

Thin section description

Core 2898

C-01

Depths of 4528.8ft

This sample comprises fine to coarse grained, rounded to subrounded quartz wacke. Feldspars such as orthoclase and microcline also occur. Monocrystalline quartz dominantly makes up the frame work of the sample, with polycrystalline quartz occurring in insignificant amount. The cements are dominantly dolomite-to-calcite, with quartz cement.

Core 3409

C-06

Depths of 4191ft.

The sample comprises concentric ooids that have been siliceously cemented by coarse cherts.

C-02

Depths of 4204ft

This sample consists of very fine to medium grained, rounded to subrounded, moderately sorted quartz arenite. The cements are dominantly quartz overgrowth and clay. This sample also shows feldspar reaction plane. The feldspars seem to be dissolving and altering at different parts of the sample. Most of the feldspars seem to be etched out by the quartz.

C-11
Depths of 4219ft

This sample consist of coarse grained crystalline sparry calcite

C-16

Sample occurs as a very fine crystalline sparite.

C-15

Depths of 4243.6ft

Sample occurs as clast. Clast is a very fine grained quartz wacke. The sample contains feldspar.

From estimation, the percentage composition of minerals making up the frame work of the sample is giving as Quartz (89%), feldspars (7%), and clay (4%).

C-14

Depths of 4246.4ft

Calcereous very fine grained, rounded to subrounded, quartz arenite. Dominantly calcite cement. Within the arenaceous dolostone are clay stringers filling porosity trends. The clay are attributed to have infiltrated the pores or probably due to pressure solution. This clay laminae tend to occur at intervals of the unit, forming a sort of rhythmitic pattern. Graded bedding of the arenecous dolostone occurs within the sample. From estimation, the percentage composition of minerals making up the frame work of the sample is giving as Quartz (89%), feldspars (7%), and clay (4%).
Core 2989

C-05
Depths 6587.7ft
Dominantly fine grained arenaceous dolostone. Alternation of grainstone to mud. Presence of graded bedding from very fine to very fine grain stone. The clay within the mud might have infiltrated into the unit or occurred due to pressure solution.

C-12
Depth 6593ft
Calcareous very fine to fine grained, well rounded to subrounded quartz wacke. The sample is dominantly carbonate cemented. This thin section comprises Dolomite to calcite cement (90%), quartz (95%), orthoclase (3%), and Polycrystalline quartz (<1%).

C-10
Depths 6594.4ft
Arenaceous dolostone, dominantly carbonate cement (sparry calcite). Possible occurrence of graded bedding. Quartz and feldspars are suspended within sparry calcite. Quartz is 40%, K-feldspar is 3%, while Na – feldspar comprises 3%.

Core 2923

C-13
Depths 6484ft
Fine to medium grained, rounded to subrounded, moderately sorted quartz arenite. The sample contains authigenic feldspars; the cements are dominantly quartz overgrowth and clay.

C-09
Depths of 6497.5ft.
This sample comprises very fine crystalline sparite.

C-07
Depth of 6500.2ft.
This sample comprises mostly of very fine crystalline sparry calcite with minor very fine to medium grained, rounded to subrounded quartz suspended within the sparry calcite. From estimation, the percentage composition of quartz is <20%.

C-03
Depths 6511ft
This sample consists of micitized concentric ooids that have been siliceously cement by fine to coarse cherts. Within the sample are also ghost ooids that have been dolomitized. Speckled greenish glauconites are also locally conspicuously present within the sample.

C-08
Depth of 6519ft
This sample consists of very fine crystalline sparry calcite.
C-04

Depths 6594.4ft

Very fine to fine grained, well rounded to subrounded quartz wacke. Cements are dominantly clay and quartz overgrowth.