Characterizing the Internal Architecture of Upper Bone Spring Limestone Turbidites and Mass-Transport Deposits (MTDs) Utilizing High-Resolution Image Log Technology

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CHARACTERIZING THE INTERNAL ARCHITECTURE OF UPPER BONE SPRING LIMESTONE TURBIDITES AND MASS-TRANSPORT DEPOSITS (MTDs) UTILIZING HIGH-RESOLUTION IMAGE LOG TECHNOLOGY

Jason J. Asmus, M.S.
Western Michigan University, 2012

Characterization of reservoir scale (less than 1 meter thick) turbidites and mass-transport deposits (MTDs) using conventional subsurface data is complex, due to millimeter-centimeter scale architectural heterogeneity exhibited by these deposits.

Limited studies of the Bone Spring carbonate turbidites and MTDs within the Delaware Basin subsurface emphasized the use of conventional wire-line log and seismic data to evaluate reservoir potential of such strata. As a result, limited resolution offered by these data sets do not allow for accurate characterization of reservoir, and sub-reservoir scale, architectural and compositional variations.

The present investigation integrates high-resolution (centimeter scale) electrical borehole image logs with conventional subsurface data as a means to: 1) enhance recognition of reservoir scale carbonate turbidites and MTDs and evaluate stratigraphic cyclicity of these deposits within the UBSL, and 2) provide detailed analysis of architectural attributes characterizing turbidite and MTD facies.

Results indicate that integrating electrical borehole image logs with conventional data improves recognition and characterization of sub-reservoir scale UBSL carbonate turbidites and MTDs, and enhances current understanding of basin-centered depositional processes occurring during the Late Leonardian.
CHARACTERIZING THE INTERNAL ARCHITECTURE OF UPPER BONE SPRING LIMESTONE TURBIDITES AND MASS-TRANSPORT DEPOSITS (MTDs) UTILIZING HIGH-RESOLUTION IMAGE LOG TECHNOLOGY

by

Jason J. Asmus

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Acknowledgments—continued

thesis to her, for its successful completion would not have been possible without her by my side every step of the way.

Jason J. Asmus
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INTRODUCTION

Summary of the Problem

Late Leonardian (Early Permian) Bone Spring carbonates are regionally-extensive, slope and basin deposits within the Delaware Basin of west Texas and southeast New Mexico. In a proximal foreslope setting, carbonate turbidites and mass-transport deposits (MTDs) of the 2nd and 3rd Bone Spring carbonate members are pervasively dolomitized and act as prolific hydrocarbon reservoir units. These reservoir units are conventionally targeted along an 8-24 km (5-15 mile) wide fairway rimming the northern Delaware Basin margins. Previous investigations, in response to common exploration strategies, have focused upon characterizing these deposits within a proximal foreslope setting (Gawloski, 1987; Mazzullo and Reid, 1987; Mazzullo and Reid, 1989; Saller et al., 1989; Wiggins and Harris, 1985).

These aforementioned studies provide a fundamental background concerning general aspects of slope and toe-of-slope turbidites and MTDs that are meters to tens of meters thick (i.e. mineralogical and biological compositions of matrix and clasts, textural fabrics, diagenetic alterations, and provenance), all utilizing conventional data sets. However, conventional data sets alone are inadequate for characterizing architectural attributes (i.e. sedimentary structures, textural fabric, composition, size and geometry of grains and intraclasts, bedding geometry, and stratigraphic stacking patterns) associated with these deposits at a reservoir-scale (less than 1.0 meter thick). This is due to the limited vertical resolution of most conventional wire-line log and seismic data in conjunction with the overall heterogeneity of turbidites and MTDs. Results from these investigations, as with many subsurface investigations within the
Permian Basin, have been compared to equivalent deposits in outcrop (Leonardian outcrops located in Apache Mountains, Glass Mountains, Sierra Diablo Mountains, Wylie Mountains, and Guadalupe Mountains – Amerman, 2009; Gawloski, 1987; Stoudt and Raines, 2004; French and Kerans, 2004; among others).

Previous studies of Bone Spring carbonate turbidites and MTDs have not addressed these deposits, and their associated architectural attributes, at a reservoir-scale (less than 1.0 meter thick) within a distal basin-centered depositional setting. Furthermore, detailed characterization of these deposits within the uppermost carbonate member (i.e. Upper Bone Spring Limestone (UBSL)) is limited. Thus, a more detailed investigation integrating non-conventional data is essential for addressing types, and associated petrophysical and depositional features, of basin-centered reservoir-scale turbidites and MTDs of the UBSL.

Objectives and Goals

This investigation characterizes reservoir-scale (less than 1.0 meter thick), architectural attributes of various interpreted turbidites and MTDs within the UBSL in a distal basin-centered depositional setting of the Delaware Basin. Electrical borehole image log data, in conjunction with conventional data sets (i.e. core, thin-sections and wire-line logs) are utilized in order to relate whole core and petrographic analysis to electrical borehole image log evaluations as a means to characterize and predict these deposits within the subsurface. Detailed analyses of such deposits will be developed from fundamental turbidite and MTD classification schemes, as well as a consideration of important factors controlling sediment transport and deposition.

The central hypothesis of this study is that utilization of electrical borehole image log data, in conjunction with core and conventional wire-line log data, will
enhance recognition of reservoir-scale flow deposits, and provide an alternative to
traditional methods of mapping the inter-well continuity of these deposits.
Furthermore, the vertical resolution offered by electrical borehole imagery (centimeter
to millimeter scale vertical resolution) should provide better resolution and allow for
accurate predictability when identifying turbidites and MTDs that do not have any
available core data.

The overarching questions to be addressed in this investigation are:
1. What types of reservoir-scale, turbidites and MTDs, characterize the
   UBSL member in a distal, basin-centered depositional setting?
2. What attributes characterize the internal architecture of reservoir-scale
   UBSL turbidites and MTDs?
3. How do architectural and sedimentologic observations of these
deposits in cores and thin-sections, compare to observations from non-
conventional borehole image logs?
4. Can borehole image logs be used to differentiate and predict turbidites
   and MTDs in wells that lack rock data (i.e. core, core plugs, drill
   cuttings)?
5. How do these deposits compare to Neogene deep-water strata from the
   Bahamas?

Geologic Background

Structural Setting

The Delaware Basin is the westernmost sub-basin of the Permian Basin (Figure
1). It spans approximately 33,500 km² (13,000 mi²) across southeastern New Mexico
and west Texas. Structural features bordering the Delaware Basin are the Central Basin Platform and Midland Basin to the East, the San Simon Channel to the northeast, the Northwest Shelf to the north and northwest, the Diablo Platform, Marfa Basin, and Hovey Channel to the west and southwest, and the Marathon-Ouachita fold and thrust belt and Sheffield Channel to the south and southeast (Hill, 1996). Figure 1 illustrates the approximate size and orientation of these structural elements in relationship to the Delaware Basin physiography.
Figure 1: Illustration of the Delaware Basin (~33,500 km² area) and surrounding structural elements. Grey regions represent ancient depression features, white represents uplifted regions, and yellow represents the ancient Central Basin Platform. Note location of the Permian Basin (grey region, top left inset map) positioned within New Mexico and Texas. Image modified from Fitchen, 1997.

Structure and Tectonics

The Delaware Basin, from Cambrian to Late Mississippian, was part of a much
larger sag basin, termed the Tabosa Basin (Hill, 1996). Beginning in Late Mississippian (~326 Ma), and continuing through much of the Permian (~253 Ma), a major tectonic episode began the formation, and subsequent deformation, of the Delaware Basin north of the Marathon-Ouachita orogenic fold and thrust belt. This tectonic event occurred during the aggregation of the Laurasia, Gondwana, and African continental plates forming Pangea (Hill, 1996; Hills, 1984; Schumaker, 1992).

Late Mississippian tectonism, characterized by east-west compressional stresses, caused reactivation of deep-seated Precambrian basement faults. This led to uplift of the Central Basin fault blocks and separation of the ancestral Tabosa Basin into two smaller sub-basins: 1) the westernmost Delaware Basin, and 2) the easternmost Midland Basin (Hill, 1996; Hills, 1984; Schumaker, 1992). Continued deformation and block-faulting within the Delaware Basin during this time led to formation of north-to-northwest trending Huapache and West Platform fault zones, and the east-to-west trending Mid-Basin fault (Hill, 1996).

Peak tectonic activity occurred during Early-to-Middle Wolfcampian (Sakmarian-to-Artinskian) time. Following peak tectonism, subsidence and isostatic adjustment along the margin of the West Platform fault zone allowed the Delaware Basin to reach a maximum structural depth adjacent to the Central Basin fault blocks. During Middle Wolfcampian-to-Early Leonardian time, subaerial exposure of uplifted fault blocks lining the Delaware basin margins allowed for mechanical degradation, erosion and subsequent deposition of sand, silt, and mud into the basin. This was followed by a marine transgression, resulting in basin-centered deposition of limestone, shale and mudstone in conjunction with prolific platform-margin carbonate reef growth (Hills, 1972; Silver and Todd, 1969).
Climate and Paleogeography

The Delaware Basin was located approximately 3° to 5° north latitude during Late Leonardian (Kungurian) time (Sageman et al., 1998; Fischer and Sarnthein, 1988 - Figure 2, Blakey, 2011). Therefore, the Delaware Basin was situated within the trade-wind belt of the northern hemisphere (Fischer and Sarnthein, 1988). Paleo-reconstruction of the Delaware Basin during this time indicates that paleo-winds blew from present day north-northeast to south-southwest, as hypothesized by Fischer and Sarnthein (1988). Sea water influx into the basin originated from the southwest (Hovey Channel) and northeast (San Simon Channel), possibly initiating counter-clockwise circulation of surface water within the basin (Fischer and Sarnthein, 1988; Fitchen, 1997). The presence of time-equivalent continental, terrigenous, clastic red beds and shelf evaporites of the Yeso Formation in the Guadalupe Mountains indicate arid-to-semi-arid climatic conditions during the Late Leonardian (Fischer and Sarnthein, 1988; Fitchen, 1997; Silver and Todd, 1969).
Figure 2: Paleogeographic reconstruction of Earth during the Late Leonardian (Kungurian). The Delaware Basin (red circle) was situated approximately 3° to 5° north of the equator resulting in a hot, arid to semi-arid climate. Image from Blakey, 2011.

Delaware Basin Stratigraphy

The Bone Spring Formation in the Delaware Basin is Early Permian (Leonardian) in age and is a mixed, carbonate-siliciclastic system consisting of three carbonate members and three siliciclastic sandstone members (Figure 3). These members are informally termed (from oldest to youngest): 3rd Bone Spring sand member, 3rd Bone Spring carbonate member, 2nd Bone Spring sand member, 2nd Bone Spring carbonate member, 1st Bone Spring sand member, and Upper Bone Spring Limestone (UBSL) member (i.e. 1st Bone Spring carbonate member). The UBSL is distinguished from the overlying Guadalupian and underlying Wolfcampian deposits by the inclusion of Early-to-Late Leonardian fusulinid foraminifera, including *Parafusulina* (*Parafusulina fountainia*, *Parafusulina* and *leonardensis*), *Schubertella*
sp. (*Schubertella melonica*), *Schwagerina sp.*, and *Boultonia sp.* (Fitchen, 1997; King, 1942; DiMichele et al., 2000; Reid et al., 1989; Skinner and Wilde, 1955). The Bone Spring in the Delaware Basin subsurface, is unconformably overlain by the Cutoff Formation, and conformably overlain by the Guadalupian age Delaware Mountain Group deposits comprising. From stratigraphically oldest/bottom to youngest/top, the Delaware Mountain Group comprises: the Brushy Canyon, Cherry Canyon, and Lamar Bell Canyon Formations; and overlies carbonate detritus of the Upper Wolfcamp Formation (Figure 3).

![Stratigraphy of the Delaware Basin subsurface. Image modified from Gawloski, 1987.](image)

Deposits of the Bone Spring Formation are slope and basinal time-equivalents to: 1) Yeso and lower-middle Victorio Peak shelf-margin strata, including the Drinkard, Tubb, Blineberry, and Paddock Formations located along the Northwest
Shelf and Central Basin Platform, 2) the Upper Clear Fork and Glorieta Formations along the Northern Shelf and Central Basin Platform, and 3) the Upper Spraberry and Lower San Andres Formations in the Midland Basin (Figure 4; Fitchen, 1997; Gawloski, 1987; Hill, 1996; Mazzullo and Reid, 1989; Saller et al., 1989).

Figure 4: Third-order sequence stratigraphic cycles (L1-L6 and W2-W3) representing platform and basin deposition of Latest Wolfcampian through Leonardian age strata within the Delaware Basin, Northwest Shelf, Central Basin Platform, and Diablo Platform. Outlined in red are cycles L5-L6 which represents UBSL basin deposition. Image modified from Playton and Kerans, 2006.

Bone Spring strata have been extensively studied in outcrop in the Glass

Turbidites and Mass-Transport Deposits (MTDs)

The complexity in characterizing reservoir-scale turbidites and MTDs from subsurface rock data makes it critical to evaluate historical classification schemes. It should be noted that the current investigation does not move to disprove, or argue against, previous classification schemes or assigned nomenclature related to turbidites and MTDs. However, accurate and precise application of such terms and attributes necessitates the critical evaluation of each.

Controversy and Debate

Deep-water mass-transport deposits (MTDs) constitute a large volume of strata within subaqueous slope and basinal settings, making them a dominant strata type in most deep-water basins around the world (up to 50%; Posamentier and Walker, 2006). It is for this reason that throughout the past decade, deep-water petroleum exploration efforts have focused much of their attention upon these deposits. This requires a more detailed understanding of their temporal and spatial distribution, depositional setting, and internal and external geometries. This rejuvenated interest has caused many authors to devise new classification schemes and terminology, specifically targeted towards certain characteristics of flows and their
resulting deposits. Overuse, or incorrect application of both new, and pre-established terms has led to much confusion and debate over: 1) the specific meaning of terms, 2) the basis for subdividing mass-transport processes (MTPs) and mass-transport deposits (MTDs), 3) the factors controlling MTP flow, 4) the structures and bedforms that are used to distinguish MTDs, and 4) at what point, in both time, and space, were these structures and bedforms developed (Amerman et al., 2011; Cook and Mullins, 1983; Lowe, 1979; Mulder and Alexander, 2001; Nardin et al., 1979; Posamentier and Martinsen, 2011; Reading and Richards, 1994; and Tripsanas et al., 2008).

MTD Classification and Subdivision

Classification and subdivision of subaqueous mass-transport processes (MTP) are commonly based upon: 1) rheology, 2) dominant sediment support mechanism, 3) initial flow mechanism, 4) concentration, 5) size, and 6) type of material transported (Dott, 1963; Lowe, 1979; Middleton and Hampton, 1976; Mulder and Alexander, 2001; and Nardin et al., 1979).

Initial classification and subdivision of MTPs are fundamentally dependent upon the application of the term “mass-transport”. Mass-transport, as used by many authors, refers to gravity-driven, down-slope movement of “en mass” sediment particles where the main sediment support mechanism is non-fluid turbulence (thus excluding turbidity currents, fluidized flows, liquefied flows, and other non-cohesive, frictional flows-Cook and Mullins, 1983; Lowe, 1979; Mulder and Alexander, 2001; Nardin et al., 1979; and Posamentier and Martinsen, 2011). Final emplacement or accumulation of sediment resulting from those processes, are termed mass-transport deposits (MTDs).
Rheology

Rheology, as applied in this study, considers the deformation and flow of carbonate and siliciclastic sediment. The rheologic nature of a subaqueous flow is related to the stress-strain relationship between the internal composition (sediment and interstitial water) of a flow and the shear stress applied to the flow body (Figure 5; Heimsund, 2007). Figure 5 shows how flows may be classified as Newtonian fluids, Non-Newtonian fluids, or Bingham plastics. Newtonian fluids (e.g. water) have no internal yield strength; however, they do exhibit a linear relationship between the rates of shear strain under an applied stress. Thus, Newtonian fluids deform instantaneously under an applied shear stress and are assumed to have a constant viscosity (Heimsund, 2007).
Figure 5: Rheological classification of subaqueous flows determined by stress versus strain relationships. Relationships are directly dependent upon a flow’s internal composition (sediment and interstitial water) versus the amount of stress applied to the flow body. Image modified from Heimsund, 2007.

Non-Newtonian fluids (e.g. liquid and/or fluidal flows) are those which display variable viscosities. Fluid viscosities vary as shear-strain rate increases or decreases with increasing stress.

Bingham plastics (e.g. debris flows, mud flows, some grain flows) are typically associated with flows having a finite internal yield strength which must be surpassed by an applied stress for the interstitial flow body sediment to deform, or for the interstitial sediment to become mobilized (Mulder and Alexander, 2001; Enos, 1977; Heimsund, 2007; Lowe, 1979). Bingham plastics exhibit a linear relationship between shear stress and applied strain, resulting in constant internal flow-body viscosities. As Figure 5
illustrates, however, changes in viscosity resulting from increased sediment and/or water content internal to the flow body may yield dilational or contractional non-Bingham plastics (Heimsund, 2007).

Two models explain the rheological relationship between shear stress, shear strain, and viscosity. These are the Coulomb-viscous model and the Bingham plastic model.

Initially applied to subaerial debris flows by Johnson (1965, 1970), and later extended to subaqueous debris flows by Hampton (1972) and Middleton and Hampton (1973, 1976), the Coulomb-viscous model shows that particle cohesion and matrix strength may be used to distinguish between plastics and fluids (i.e. debris flows from turbidity currents). The Coulomb-viscous model is expressed as (Mulder and Alexander, 2001):

\[ \tau = \sigma_n \tan \phi + c + \eta \left( \frac{\delta u}{\delta z} \right) \]

\( \tau \) = shear stress; \( \sigma_n \) = effective normal stress; \( \phi \) = angle of internal friction of grains; \( c \) = cohesive (non-frictional) yield strength component; \( \eta \) = dynamic viscosity of sediment-fluid mixture; and \( \frac{\delta u}{\delta z} \) = vertical rate of shear.

Similarly, the Bingham plastic model may be used to distinguish plastics from fluids by relating the material’s yield strength to viscosity. The Bingham plastic model is expressed as (Mulder and Alexander, 2001):

\[ \tau = K + \eta_b \left( \frac{\delta u}{\delta z} \right) \]

\( \tau \) = shear stress; \( K \) = Bingham yield stress; \( \eta_b \) = Bingham viscosity; \( \frac{\delta u}{\delta z} \) = vertical rate of shear.

Subdivision of various flow types based upon rheology can be accomplished by discerning internal mechanical behavior of the flows (elastic, plastic, fluid, or liquid) and particle cohesion within the flow bodies (cohesive, or non-cohesive (frictional)).
The former rheological subdivision, adopted by Middleton and Hampton (1976), Lowe (1979), Nardin et al. (1979), and Dott (1963); classifies rockfalls, translational slides (glides), and rotational slides (slumps) as elastic flows. It classifies debris flows, mud flows and viscous grain flows as plastic flows. Furthermore, non-viscous grain flows, fluidized flows, liquefied flows and turbidity currents are classified as fluid or liquid flows.

Distinction between fluidized or liquefied flow types has been established by analysis of particle cohesion (Mulder and Alexander, 2001). Cohesive flows tend to have high matrix strength during transport as cohesive particles resist interstitial fluid flow; thus, flow bodies maintain their external geometries. Non-cohesive flows, on the other hand, are characterized by discrete fluid-filled particles as a result of sediment concentrations (which are directly affected by flow origin, transport distance, and the sediment type being transported-Mulder and Alexander, 2001). According to the classification of flows by Mulder and Alexander (2001), “rheologically cohesive” flows include debris flows and mudflows. Those classified as “rheologically non-cohesive” include grain flows and turbidity currents.

**Dominant Sediment Support Mechanism**

Anti-gravitational forces are internal to flow bodies during downslope transportation, and support the entrainment of grains above the sediment-water interface. These forces are referred to as “dominant sediment support mechanisms” (Cook and Mullins, 1983). Lowe (1979), with a modification of the classification scheme developed by Middleton and Hampton (1976) classified five dominant flow types based upon the dominant sediment support mechanism: 1) turbidity currents, 2) debris flows, 3) fluidized flows, 4) liquefied flows, and 5) grain flows (Table 1; Lowe,
Turbidity currents consist of sediment supported by upward moving fluid turbulence during downslope transport. Debris flows are characterized by sediment supported by a matrix of fluid and sediment. Fluidized flows display upward intergranular fluid movement which appears to completely support sediment grains. Conversely, liquefied flows have upward displaced intergranular fluid movement which only partially supports grains as a result of grain dispersion and settling during run-out. Within grain flows, grains are supported by dispersive pressures as a result of cohesive sediment particles internal to the flow body.

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<tr>
<th>Flow Type</th>
<th>Sediment Support Mechanism</th>
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<td>Turbidity Current</td>
<td>Fluid Turbulence</td>
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<td>Fluidized Flow</td>
<td>(Full Support) Escaping pore fluid</td>
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<tr>
<td>Liquified Flow</td>
<td>(Partial Support) Escaping pore fluid</td>
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<tr>
<td>Grain Flow</td>
<td>Dispersive Pressure</td>
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<tr>
<td>Debris Flow</td>
<td>Matrix Strength</td>
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</table>

Table 1: Lowe’s (1979) classification scheme of subaqueous flows based upon a dominant sediment support mechanism.

It is critical to realize that multiple dominant sediment support mechanisms often operate simultaneously against gravitational forces, and may lead to partial or complete transformation of a single flow type during transportation (Lowe, 1979; Cook and Mullins, 1983; Mulder and Alexander, 2001; and Nardin et al., 1979). As such, it is critical to keep in mind that mass-transport processes form a continuum of processes, and the evaluation of MTDs must account for both syndepositional and post-depositional alterations that occur during, and after, transportation and deposition.
Turbidite and MTD Classification

Debris Flow

Debris flows are cohesive laminar flows. They may originate from both low relief (toe-of-slope and distal basin) and high relief (rimmed platform margins and upper slope) environments (Posamentier and Martinsen, 2011; and Cook and Mullins, 1983). Disaggregated and unstratified intraclasts within the flow body are fully supported by: 1) a high-density, cohesive mud-to-silt matrix, and 2) buoyant forces resulting from low density intraclasts contained within a greater density matrix. These types of flows may travel hundreds of kilometers across areas of low depositional relief ($1^\circ$ degree or less), transporting intraclasts 10-50 meters (33-164 feet) in diameter (Cook and Mullins, 1983). Erosive, down-slope transportation may increase sediment concentrations within the saturated flow body. This increased sediment volume enhances flow body rigidity, allowing flows to deposit thick volumes of sediment in either lobate sheets or channel-like geometric forms.

However, debris flow deposits (debrites) are often observed as non-erosive to slightly-erosive features (Mulder and Alexander, 2001). Both outcrop and laboratory observations indicate that abundant clay particles within a debris flow matrix act to increase flow strength by electrostatic attraction of clay particles, and by retaining interstitial pore pressure (Loucks et al., 2011). Increased flow strength leads to: 1) greater run-out distances, and 2) higher flow velocities. Dynamic pressures, at a certain velocity, along the leading edge of the flow reaches basal overburden pressures. This causes lift of the flow body during transport. This phenomenon is recognized as hydroplaning, and is thoroughly documented by De Blasio and Elverhoi (2011).
En mass deposition of debris flow sediment is due to “freezing” of the flow body when frictional shear forces equal downslope gravitational forces. Observations of debris flow MTDs document unstratified, randomly oriented clasts supported by dense mud, silt, or clay matrix. Mulder and Alexander (2001), recognize debris flow matrices consisting of greater than 5% by volume of gravel-sized sediments. These clasts, variable in both size and composition, exhibit little-to-no fabric within beds, deformational shearing along flow margins and base, and often consist of both shoal-water and basin fauna (Cook and Mullins, 1983; and Mulder and Alexander, 2001). Inverse grading of clasts and matrix, as well as clast protrusion into overlying deposits is often observed within debris flows (Mulder and Alexander, 2001). Deposits may preserve original sedimentary fabric and textures that existed during transport, provided sediment has undergone minimal post-depositional deformation (Mulder and Alexander, 2001). Figure 6 illustrates the above attributes likely associated with debris flow deposits, as observed in Devonian foreslope strata of Alberta, Canada by Cook et al. (1972).
Figure 6: Illustration of an Upper Devonian carbonate debris flow layer observed by Cook et al. (1972) in the Rocky Mountains of Alberta, Canada. Architectural observations from this unit may be typical of most carbonate debris flow deposits originating from platform or slope settings. No exact scale is intended for layers or debris flow elements. Image modified from Cook and Mullins, 1983.

**Slide**

Slides are either translational (glide), or rotational (slump), during down-slope transport. They exhibit elastic and/or plastic internal mechanical flow behavior over steep to gentle slope declivities (greater than 30° to less than 1° - Posamentier and Martinsen, 2011).

Translational slide deposits exhibit continuous internal bedding, planar basal surfaces, and little to no internal plastic deformation as shown in Figure 7B (Nardin et al., 1979). Tensinal and compressional deformation throughout portions of the flow body may result in both faulting (strike-slip and listric), and folding of sediments, generally located along the base and margins of the flow body (Posamentier and
Martinsen, 2011; Amerman, 2009; Nardin et al., 1979). Sediment shear strength at basal and marginal positions of the flow body is either met or surpassed. Cook and Taylor (1977) suggests that as shear strength of the sediment is surpassed, part of the flow transforms into a viscous debris flow, which may be initiated by intense plastic deformation occurring within those portions of the flow (Cook and Mullins, 1983).

Rotational slide deposits differ from translational slide deposits by the fact that basal surfaces, in rotational bodies, exhibit a convex down-slope, or spoon-shaped geometry as shown in Figure 7A (Posamentier and Martinsen, 2011; and Nardin et al., 1979). This geometry results from extensional forces acting at the head (or front) of the flow body, while compressional forces act at the tail (or back) of the flow (Posamentier and Martinsen, 2011). Rotational deposits, similar to translational deposits, may exhibit continuous bedding with little-to-no internal deformation within central regions of the flow body, and deformational folding and faulting within upper, lower and marginal surfaces of the flow body (Nardin et al., 1979). Individual slide blocks observed in Quaternary slope deposits exhibit similar attributes (Grammer et al., 1993). These Quaternary slide blocks have been observed to reach 10 meters in diameter, and displaced 100’s of meters basinward. Fold crests tend to indicate sediment transport direction, although post-depositional deformation, and multiple shear stress directions during transportation make interpretations of paleo-flow direction difficult (Amerman, 2009; and Cossey, 2011).
Figure 7: Illustration showing the differences between translational and rotational slides. A) Rotational slides (slumps) exhibit a convex down-slope basal shear surface with intense deformation and faulting along basal and marginal surfaces. B) Translational slides (glides) exhibit continuous internal bedding planes with little-to-no internal deformation and minor faulting and folding along basal and marginal surfaces.

Liquified Flow and Fluidized Flow

The distinction between liquefied flows and fluidized flows, as previously
mentioned, is based upon cohesive sediment concentrations within the flow body. Both may be regarded as fluid flows (i.e. non-Newtonian fluids) (Lowe, 1979). The two flow types may be distinguished from each other based upon the degree of cohesive strength between grains, in comparison to turbulent fluid forces. Lowe (1979) suggests that within fluidal flows, cohesion between grains creates full grain support as a result of fluid dispersion during flow transportation. Liquefied flows, in contrast, do not permit the grains to be fully supported by dispersive fluid pressures during flow transportation. Using grain size and sorting, erosional features, bedforms and sedimentary structures, Mulder and Alexander (2001) suggest the terms “hyperconcentrated density flows” and “concentrated density flows” to distinguish between these two subaqueous flow types (Figure 8).
Figure 8: Mulder and Alexander’s (2001) classification scheme of subaqueous flow deposits. This classification scheme utilizes elements of rheology and dominant sediment support mechanisms for flow classification, allowing for the distinction between cohesive and frictional flow types. Image from Mulder and Alexander, 2001.
It must be remembered, however, that at any given point in time and space, part of the flow body may be characterized by turbulent flow, while another part may be characterized by laminar flow. This is most likely the case in most flows as they continuously attain and disperse sediment throughout transport distances, successively transforming from fluidized (or hyperconcentrated density) flow, to liquefied (or concentrated density) flow. Sedimentary structures and bedforms such as: 1) fluid escape structures, 2) collapse structures, 3) slight to moderate grading, and 4) load structures are often observed within both flow types (Cook and Mullins, 1983; Lowe, 1979; Mulder and Alexander, 2001; and Nardin et al., 1979). Mulder and Alexander (2001) suggest that liquified flows travel longer distances relative to fluidized flows, due to the abundance of fine grain sizes concentrated within the flow, and that this a distinguishing characteristic between these two flow types.

**Grain Flow**

Grain flows may be cohesive or non-cohesive (fluidized to liquified) sediment gravity flows. The distinction depends upon the relative amount of cohesive grains within the flow body. It has been suggested that grain flows require steep slopes (greater than 20°) to maintain flow by overcoming grain interactions that produce strong frictional forces against down-slope gravitational forces (Lowe, 1979). Cook and Mullins (1983) suggest slope angles of 18° to 30° to maintain grain flow movement in modern environments. They hypothesize that these high slope angles partially explain the limited field observations of ancient deposits. This hypothesis is supported by Grammer and Ginsburg (1992), recognizing Quaternary rockfall and grain flow strata deposited on slope angles of 35° to 40° in the Tongue of the Ocean, Bahamas. Grain flows exhibit massive bedding, sharp upper surface contacts, basal
erosional features, local inverse grading, and are predominantly composed of sand, silt, and gravel-sized sediment (Cook and Mullins, 1983; Mulder and Alexander, 2001; and Middleton and Hampton, 1976). Upper slope Quaternary deposits in the Bahamas are observed as approximately 0.5 meter thick lenses that exhibit laterally discontinuous geometries, and display internal heterogeneity (Grammer and Ginsburg, 1992; Grammer et al., 1993).

It is hypothesized here, that the paucity of grain flows observed in ancient outcrops may be due to our inability in distinguishing: 1) the relative abundance of cohesive material present within the flow body during gravitational transport, and 2) the likelihood of these deposits rapidly evolving during transport as a result of cohesive grain deposition.

**Turbidity Current**

Turbidity currents are sediment gravity flows in which the sediment is supported by fluid turbulence within the flow body. Many authors (e.g. Cook and Mullins, 1983; Lowe, 1979; Mulder and Alexander, 2001; and Nardin et al., 1979) exclude turbidity currents from MTP classification schemes based upon this dominant sediment support mechanism. However, these same authors also postulate that many MTPs likely exhibit multiple sediment support mechanisms at any one time (including fluid turbulence), or experience a shift in support mechanisms as flows transform during downslope transport (e.g. grain flow to turbidity current). The latter is based upon the widely accepted idea of a “flow process continuum”. This idea is interpreted to suggest that turbidity currents may be included in MTP classification schemes. Many authors observe and/or infer fluid turbulence in modern and ancient deposits (Eberli, 1988; Bernet et al., 2000; Cook, 1979; Crevello and Schlager, 1980).
Initiation of turbidity currents are due to: 1) contour currents, 2) storm or wave re-working of slope deposits, 3) rapid sedimentation by a different flow, 4) flow transformation, where turbidity currents represent the waning stages of a flow (Cook and Mullins, 1983; and Mulder and Alexander, 2001). The abundance of generating mechanisms for turbidity currents complicates spatial correlation of reservoir-scale (less than 1.0 meter thick) turbidites, especially when utilizing conventional wire-line log and core data with limited vertical and lateral resolution. This is due primarily to the variability in depositional geometry and transport distances exhibited by differing MTPs (e.g. slumps, debris flows, grain flows, etc. - Shanmugam, 2000). Turbidites (turbidity current deposits) exhibit variable sediment size and composition as a function of flow origin and transport distance. Fine sand-to-silt sized sediment is commonly indicative of basinal settings, while coarser-grained sediment is more indicative of shallow-water settings (Cook and Mullins, 1983).

Turbidites are often characterized using the Bouma sequence model (Figure 9). Arnold Bouma (1962) developed this model while studying outcrop deposits in the western Alps (Annot Sandstone Fm.) and northern Apennines (Marnoso-Arenacea and Macigno Fms.) (Mutti et al., 1999). This model characterizes sequences of traction (Bouma sequences T$_a$-T$_d$) and suspension (Bouma sequences T$_d$-T$_e$) sedimentation resulting from decreasing turbidity current transport velocity. However, complete Bouma sequences are not always present, as a result of successive sedimentation, erosion, post-depositional deformation, and biogenic re-working.
Figure 9: Bouma sequences ($T_a$-$T_e$) depicting divisional sedimentation of granule to clay-sized grains transported by turbidity currents. Partial or complete Bouma sequences may be observed within turbidite accumulations. Preliminary Bone Spring core observations indicate basin-centered strata are dominated by partial Bouma sequences possibly as a result of long (greater than 20.0 kilometers) transport distances. Image modified from Mutti et al., 1999.

Turbidites generally exhibit the following sedimentary structures and bedforms: 1) thin to thick bedding (millimeter to meter), 2) basal scour (flute) marks, 3) dewatering structures, 4) partial or complete Bouma sequences (Figure 9), 5) long travel distances (100’s of kilometers), and 6) cyclical stratigraphic occurrence (i.e. multiple turbidites stratigraphically stacked in one location) (Mulder and Alexander, 2001; Cook and Mullins, 1983; Mutti et al., 1999; Bernet et al., 2000; Heimsund, 2007; Shanmugam, 1997). Previous work (Mulder and Alexander, 2001; Cook and Mullins, 1983; Nardin et al., 1979; among others) suggests turbidity currents may likely originate as a result of MTP transformation during sediment transport. Turbidite accumulations resulting from evolving, in-transit flows may also include similar
textures and sedimentary structures diagnostic of other flow deposits. Characteristics of debris flows, grain flows, liquefied flows, and fluidized flows, are particularly similar, especially as these flows become quickly diluted during downslope sedimentation (Mulder and Alexander, 2001).

This investigation will utilize nomenclature and associated attributes related to the internal architecture of turbidites and MTDs as outlined in Table 2.
<table>
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<tr>
<th>Flow Type</th>
<th>Glide (Elastic/Plastic)</th>
<th>Debris Flow (Elastic/Plastic)</th>
<th>Grain Flow (Elastic/Plastic)</th>
<th>Liquified Flow (Fluid/Plastic)</th>
<th>Fluidized Flow (Fluid/Plastic)</th>
<th>Turbidity Current (Elastic/Plastic)</th>
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<td>(volume % of solid grains)</td>
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<td>Massive bedding</td>
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<tr>
<td>Sharp upper and lower bedding contacts; local inverse grading; and sediment concentrations dominated by gravel-, sand-, and silt-sized grains.</td>
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<td><strong>Architectural Elements</strong></td>
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<td>Continuous bedding</td>
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<tr>
<td>Planar basal surfaces</td>
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<tr>
<td>Minimal internal deformation of bedding along central axis of flow body; internal deformational shearing; local inverse grading; and clast protrusion into underlying and/or overlying strata.</td>
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<td><strong>Sediment Abundance</strong></td>
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<td>Sharp upper and lower bedding contacts; local inverse grading; and sediment concentrations dominated by gravel-, sand-, and silt-sized grains.</td>
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Table 2: Terminology and architectural attributes to be utilized in this investigation associated with turbidites and MTDs. Table 2 data are synthesized from Middleton and Hampton (1976), Lowe (1979, 1982), Nardin et al. (1979), Cook and Mullins (1983), Posamentier and Martinsen (2011), Tripsanas et al. (2008), and Mulder and Alexander (2001).

Previous Investigations – Bone Spring Formation

Previous workers (Gawloski, 1987; Saller et al., 1989; Wiggins and Harris, 1985) utilized conventional subsurface data sets to analyze turbidites and MTDs of the 2nd and 3rd Bone Spring carbonate members. Figure 10 shows the location of these investigations in proximity to Airstrip, Scharb and Mescalero Escarpe Fields located approximately 8-24 kilometers (5-15 miles) south of the Abo-Yeso shelf-margin. These studies conclude that only three sedimentation processes occurred during Bone Spring deposition of shelf margin and slope strata. The following section discusses observed attributes for these three styles of sedimentation, 1) debris flow, 2) slump, and 3) turbidity current.
Figure 10: Previous subsurface investigations focusing upon 2nd and 3rd Bone Spring carbonate members are restricted to a 10-15 kilometer wide fairway (main map; Abo Reef Trend-Purple; Yeso Shelf Margin-Blue) along the northern margins of the Delaware Basin (see indicator map). Airstrip, Scharb, and Mescalero Escarpe Fields (shown in green on the main map) are major oil fields that produce from these carbonate members, specifically from shelf margin and slope detritus reservoirs where these units create up-dip stratigraphic traps for hydrocarbon accumulation. Outlined in red on the indicator map is the approximate basin-centered location of the present study (located in southern Eddy and Lea counties, New Mexico). The study area is approximately 20 kilometers from the Central Basin Platform (CBP), and approximately 30-40 kilometers from the northern-northwestern margins of the Delaware Basin (DB). East of the Central Basin Platform is the Midland Basin (MB), illustrated for regional referencing. Image modified from Fitchen, 1997; and Saller et al., 1989.
Debris Flows in the Bone Spring

Debris flow deposits are pervasively dolomitized (dominated by rhombohedral dolomite crystals), and are characterized by various textures including: 1) dolomitized megabreccias, 2) skeletal packstones to grainstones, and 3) skeletal wackestones to packstones (Gawloski, 1987). These deposits range from thin (less than 5.0 centimeters thick) to very thick (greater than 24.0 meters thick) and are often cyclically stacked (Gawloski, 1987). Clasts are one to tens of centimeters in diameter, angular to subangular, exhibiting stylolitic, micritized, and/or irregular margins (Saller et al., 1989; Gawloski, 1987; Wiggins and Harris, 1985). Texturally, clasts are characterized as consisting of: 1) quartz-rich sandstone, 2) crystalline dolomite, 3) peloidal packstone to grainstone, 4) skeletal wackestone to packstone, 5) bioclast packstone to grainstone, and 6) algal boundstone (Saller et al., 1989). Depositional attributes associated with these deposits are: 1) poor grain sorting, 2) irregular clast geometry, 3) overall fining upward clast size, and 4) sharp to gradational bedding contacts with clasts protruding into the underlying micritic mudstone facies (Saller et al., 1989; Gawloski, 1987; Wiggins and Harris, 1985). Angular to subangular, skeletal and non-skeletal grain types are present within both the debris flow clasts and the matrix. Crinoids, brachiopods, bryozoans, pelecypods, corals, fusulinids, sponge spicules, and phylloid algae are the most abundant skeletal grain types present. The abundance of this neritic skeletal material within the clasts indicates a shallow-water shelf margin origin (Saller et al., 1989; Gawloski, 1987; Wiggins and Harris, 1985).

Turbidity Currents in the Bone Spring

Turbidites are thin (one to tens of centimeters thick) and occur in close
proximity to debris flows (often as overlying units relative to debris flows) (Gawloski, 1987). Gawloski (1987) postulates that stacking of turbidites over top of debris flows may be representative of turbidity current deposition occurring during the waning stages of debris flow sedimentation. Texturally, turbidites range from wackestones to skeletal packstones, and fine to very fine grained quartz-rich sandstones to siltstones (Gawloski, 1987). Architectural attributes characteristic of these deposits include: 1) thin, graded beds, 2) complete and/or partial Bouma sequences, 3) abrupt basal contacts, and 4) a lack of shallow-water grains (Gawloski, 1987; Saller et al., 1989). Saller et al. (1989) additionally observed burrows, wavy laminations, and rippled cross-bedding within these same turbidite deposits.

**Slumps in the Bone Spring**

Slump deposits have only been documented in the Bone Spring Formation by Wiggins and Harris (1985). Wiggins and Harris (1985) observed slump deposits in core samples taken from the Gulf Lea “YH” State #4 well, located in the Airstrip Field of Lea County, New Mexico (Figure 10). Based upon core observations, they indicate that slump deposits: 1) are approximately one foot thick, 2) texturally consist of dolomitic mudstone to wackestone, very fine-grained sandstone to siltstone, and megabreccia, and 3) include vertical and horizontal fracturing, burrows, convoluted bedding, and ripple laminations. Based upon core and wire-line log analysis, Wiggins and Harris (1985) suggest that slump deposits represent the re-working of slope strata.

Previous workers conclude that deposition of shelf margin and slope strata occurred as a result of: 1) decreased accommodation space due to increased production of carbonate sediment, 2) hydraulic degradation and over-steepening of a vertically aggrading shelf margin, 3) oversaturation of unconsolidated slope strata, and
4) winnowing of sediment by strong bottom currents (Gawloski, 1987; Saller et al., 1989; Wiggins and Harris, 1985).

Utilizing conventional well and seismic data, Gawloski (1987) and Saller et al. (1989) determined that turbidites and MTDs exhibit a high degree of lateral heterogeneity between wells. Inter-well heterogeneity is attributed to the abrupt lateral termination of MTD lenses, MTD amalgamation, and/or intense dolomitization of turbidite and MTD strata. Gawloski (1987) states that identifying, and correlating individual turbidite and MTD deposits with conventional data is often problematic, necessitating the correlation of sedimentary packages, rather than individual units.

METHODS

Selection of Cores

Two conventional cores within the Delaware Basin were selected for investigation. During analysis, these cores were being housed at the Michigan Geological Repository for Research and Education (MGRRE) facility at Western Michigan University in Kalamazoo, Michigan. The Well A core is located in western Lea County, and the Well B core is located in central Eddy County, New Mexico (Figure 11).
Selection of core was based upon the following criteria (Table 3):

1. Cores located in a basin-centered position.
2. Core recovered sufficient samples representative of the UBSL member (greater than 50% UBSL coverage).
3. Availability of associated electrical borehole image logs as well as a full coverage...
log suite consisting of a gamma-ray log, a shallow and deep resistivity log, a neutron-porosity log, and a neutron-density log.

4. Associated dipmeter data for interpreting approximate source terrains for zones of suggestive turbidites or MTDs.

5. Presence of abundant zones suggestive of either turbidites or MTDs spanning the upper and lower vertical resolution limits of image log coverage.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>State</th>
<th>County</th>
<th>Formation</th>
<th>Core Footage (Ft)</th>
<th>Full Log Suite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well A</td>
<td>New Mexico</td>
<td>Lea</td>
<td>UBSL</td>
<td>726.0’</td>
<td>Yes</td>
</tr>
<tr>
<td>Well B</td>
<td>New Mexico</td>
<td>Eddy</td>
<td>UBSL</td>
<td>500.0’</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3: UBSL core utilized in this investigation.

Core and Thin-Section Analysis

The two cores (A and B; 1226.0 total linear feet of core) were analyzed at a centimeter scale for evaluation of probable turbidite or MTD compositions, textures, fabrics, sedimentary structures, and stratigraphic stacking patterns. Core and thin-sections were described by broadly following the methodology presented in the Sample Examination Manual by Swanson (1981).

Examination of 204 thin-sections sampled from textural lithofacies identified throughout each of the two cored wells, were compared to core observations for
further refinement of textural lithofacies. Thin-sections utilized in this study were standard size (27 mm by 46 mm), vacuum impregnated with blue epoxy to illustrate the presence of porosity, and oriented relative to up-section (i.e. up-hole).

Lithofacies were defined at the centimeter scale using Dunham’s (1962) classification scheme of carbonate rocks. Use of this scheme, emphasizing the textural distinction between mud-dominated versus grain-dominated lithofacies, aids interpretations of probable turbidite and MTD sedimentation processes by indicating dominant grain types, the presence of intraclasts, whether grains and/or intraclasts are mud-supported versus grain-supported, and key sedimentary structures. Lithofacies were then grouped into facies associations, reflecting sedimentation processes as interpreted from observed architectural attributes. Architectural attributes used for defining facies associations include sedimentary structures, textural fabric, composition, size and geometry of grains and intraclasts, bedding geometry, and stratigraphic stacking patterns. Previous works utilizing similar architectural attributes for turbidite and MTD classification have been established by Middleton and Hampton (1976), Lowe (1979, 1982), Mulder and Alexander (2001), Cook and Mullins (1983), Nardin et al. (1979), Tripsanas et al. (2008), and Posamentier and Martinsen (2011), and served as a template for classifying interpreted turbidites and MTDs during this investigation. This classification scheme is outlined in Table 2.

Following evaluation of core and thin-section data for the two cored wells, numerical codes were assigned to each lithofacies, facies association, and Dunham (1962) rock texture. Also, existence of certain fauna and/or allochems, diagnostic of a particular depositional setting, were noted (i.e. “1” if present and “0” if absent). Numerical codes were then entered into a Microsoft Excel database and depth calibrated to core and conventional wire-line log depths. These Excel databases were
then uploaded into Petra® data integration software for direct comparison to conventional wire-line logs and electrical image logs (Figure 12). Analysis of these data sets within a single display provides a means to compare variations in wire-line log responses and image log resistivity patterns to variations in textural lithofacies and sedimentation processes.

Figure 12: Petra display module correlating core, image log, and conventional wire-line log data sets.
Conventional Wire-Line Log Analysis

Application of conventional wire-line logs serves as a means for correlating rock data to image log data, and evaluating petrophysical properties of textural lithofacies and sedimentation processes identified from core and thin-section analysis.

Conventional wire-line log suites utilized for each of the two cored wells consists of a gamma ray log (GR), a caliper log (CALI), a neutron-porosity log (NPHI), a density-porosity log (DPHI), and shallow (LLS, RLA3), and deep (LLD, AT90_PRE) resistivity logs.

Gamma ray and shallow and deep resistivity logs were found to be the most applicable for this investigation. Gamma ray logs allow for proper depth calibration of core and image logs, as well as highlighting “clean” carbonate-rich zones (low GR values) versus “dirty” carbonate-poor zones (high GR values). Resistivity logs record resistivity of rock formations similar to FMI and XRMI image logs. Thus, resistivity logs assist in depth calibration of core and image log data, and aid in making interpretations of possible turbidite or MTD sedimentation processes from image logs. A detailed overview of wire-line log properties and their responses to dominant rock formations are explained in depth by Asquith and Krygowski (2004), Doveton (1994), and Lucia (2007).

Borehole Image Log Analysis

Borehole image logs are either electrical or acoustic well logs that image the rock face within a well bore at high vertical and lateral (azimuth) resolution (millimeters to centimeters). This allows for accurate identification of sub-meter scale fractures, folds, bedding, and sedimentary structures that are normally beyond
resolution by conventional wire-line logging tools (Hammes, 1997). When calibrated with core, image logs serve as a primary tool in many reservoir characterization studies (Hammes, 1997; Hurley, 2004).

Electrical borehole image logs utilized in this investigation include Schlumberger’s Fullbore Formation Micro Imager (FMI) and Halliburton’s X-Tended Range Micro Imager (XRMI). Schlumberger’s Formation Microscanner (FMS) log was utilized at ODP Leg 166 Sites 1003 and 1006 in the Bahamas, and is compared to results from FMI and XRMI analysis. All of these logs measure micro-resistivity of the rock face within a wellbore. Once processed and orientated, these micro-resistivity measurements render a 2-D image of almost complete three hundred and sixty degree borehole coverage at a vertical resolution of approximately ~0.5 centimeters (~5 millimeters). Table 4 provides an overview of FMI, XRMI, and FMS tool specifications utilized during this investigation.
Table 4: Summary of electrical borehole image log tools utilized in this investigation.

<table>
<thead>
<tr>
<th>Tool</th>
<th>FMS</th>
<th>FMI</th>
<th>XRMI</th>
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<tbody>
<tr>
<td>Number of Arms</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Number of Pads/Arm</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Number of Electrodes/Pad</td>
<td>16</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Total Electrodes</td>
<td>64</td>
<td>192</td>
<td>150</td>
</tr>
<tr>
<td>Logging Speed (ft/hr)</td>
<td>1,600</td>
<td>1,800</td>
<td>1,800</td>
</tr>
<tr>
<td>Borehole Coverage (~8 in. hole)</td>
<td>40%</td>
<td>80%</td>
<td>67%</td>
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<tr>
<td>Sampling Rate (inches)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Vertical Resolution (inches)</td>
<td>0.2</td>
<td>0.2</td>
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Electrical image tools are composed of an accelerometer (records tool speed variation), a magnetometer (records borehole deviation and formation dip), and high micro-resistivity electrodes (emit electrical current - Hurley, 2004; Lagraba et al., 2010). Figure 13 shows a typical, electrical borehole imaging tool (Schlumberger’s FMI tool) utilized in the current investigation.
During up-hole logging, micro-resistivity sensors attached to pads located on four separate tool arms (right) are pressed against the borehole wall, emitting and recording variations in resistivity. Bedding features approximately ~0.5 centimeters thick (~5 millimeters) may be resolved for roughly 80% of the entire wellbore. Image modified from Schlumberger, 2011.

During logging, micro-resistivity electrodes, attached to pads at the base of the logging tool, are pressed against the borehole wall. As the tool is pulled upward, a constant electrical potential is emitted into the formation while, at the same time, micro-resistivity electrodes are recording drops in current (Hurley, 2004). Current drop is a response of electrical current traveling from the tool, into the rock, and back to the tool. Therefore, electrical borehole image logs (i.e. FMI, FMS, XRMI logs) must be run in a conductive, water-based mud (e.g. brine), to allow current emission into the formation being contacted by the tool (Lagraba et al., 2010). Current drop reflects micro-conductivity variations within the rock. Recorded as curves, these
variations are then processed and displayed as images (Hammes, 1997). Post-
acquisition processing of the magnetometer, accelerometer, and resistive nodes applies
corrections for borehole deviation, tool speed, tool sticking, emitter exciter (EMEX)
and magnetic inclination and declination variability encountered during logging
(Hurley, 2004; Lagraba et al., 2010). Image processing is provided by either the
logging service company, or by any individual with the appropriate processing
software.

The resulting processed images display a nearly 360° degree view of the
borehole wall, transmitted by a range of resistivity values. Values are assigned pre-
determined color pixels during image processing and analysis (Hurley, 2004). Logs
utilized in this study are all displayed using a heated color scheme. This heated color
scheme (Figure 14) exhibits micro-resistivity variations using shades of white, yellow,
orange and brown. Low conductivity (high resistivity) features are represented as
lighter colors (i.e. white and yellow), and high conductivity (low resistivity) features
are represented as darker colors (i.e. orange and brown). Examples of low
conductivity features are carbonates, dolomitic muds, and heavily compacted and/or
cemented carbonate zones (Hammes, 1997; Hurley, 2004). High conductivity features
are typically shales, siliciclastics, heavy minerals (e.g. pyrite), mud-filled fractures,
heavily bioturbated zones, and solution-enhanced and/or open fractures (Hammes,
1997; Hurley, 2004). Prior to geological evaluation, borehole images are converted to
2D by splitting the “borehole” open along a vertical axis relative to magnetic north
(Figure 15). This allows for interpretation of intersecting fault angles, bedding dip,
maximum stress-direction, sediment transport direction, and/or paleo-current direction
(Hammes, 1997; Hurley, 2004).
Figure 14: FMS image log recorded at Site 1003 along the leeward margin of Great Bahama Bank, Bahamas. Turbidites from Site 1003 exhibit complete to partial Bouma sequences with resistive bases and conductive tops as a result of fining-upward grain sizes and/or differential compaction of carbonate grains during sediment transport and deposition (Eberli, 1997). The FMS log has been oriented relative to magnetic north within the wellbore and displayed using a heated color scheme. Image modified from Williams and Pirmez, 1999.
Figure 15: Image log processing steps commonly completed prior to geological evaluation (A-C). A) Resistivity measurements are displayed as images using a black-white, or color scheme. B) Borehole images are oriented, and split open along a vertical axis, relative to magnetic north. C) 2D orientation will always show (from left to right) N-E-S-W-N. Image modified from Thompson, 2009.

It is important to note that caution must be taken when interpreting image logs without direct comparison to core and conventional log data. Otherwise, artifacts encountered within the borehole (e.g. rugosity, mud cake, borehole breakouts) may be interpreted on the image logs as structural or sedimentary features (Lagraba et al., 2010; Hammes, 1997). Figure 16 displays suggested guidelines to consider during image log interpretation of carbonate rocks (originally outlined by Serra, 1989; and later modified by Hammes, 1997).
Figure 16: Hammes (1997) suggests utilizing of such guidelines when interpreting depositional features in carbonate rocks from electrical image logs. These guidelines were originally based upon Serra’s (1989) FMS image evaluation of carbonate rocks and were later modified by Hammes (1997) for interpreting carbonate depositional features within the Ellenburger Formation, a highly brecciated shallow water carbonate deposit. Image from Hammes, 1997.

For the two cored wells, observations of turbidites and MTDs, and their architectural features, recorded during core and thin-section analysis were directly compared to observations recorded during FMI and XRMI image log analysis. Direct comparison of observations provides a means to interpret the relative applicability of image logs for discerning suggestive reservoir-scale turbidites and MTDs. Both FMI and XRMI logs incorporate natural gamma-ray tools, automated dip-picking of beds,
while also being oriented relative to magnetic north. These attributes allow for correct depth tracking and direct correlation of core and image log observations to conventional wire-line log data. It also provides a means for interpreting approximate paleo-transport directions.

Data Limitations

The fundamental limitation of this investigation is the limited vertical and lateral spatial distribution of core data throughout the study area (only two cores located approximately 24.5 miles (~40.0 kilometers) apart). Core recovery from Well A totals 726.0 feet (~76.0% of the 950.0 feet thick UBSL section), and 500.0 feet from Well B (~55.0% of the 915.0 feet thick UBSL section).

Other data limitations include processing and interpretation of image logs. Processing (i.e. filtering, application of a color scheme, removal of unwanted data, among additional quality control steps) and interpretation of dip measurements (automated dip values for sedimentary features, bedding planes, faults, fractures, and joint sets interpreted from software) were completed by service companies prior to the start of this investigation. This resulted in interpretations being made solely on the basis of analyzing cropped images of FMI and XRMI image logs. Also, many of the turbidites identified during core analysis were less than a few centimeters thick, which made identification of these deposits difficult during analysis of conventional wire-line logs, which, at the centimeter and sub-centimeter scale, do not fully resolve such features.
RESULTS AND INTERPRETATIONS

Facies Associations

In this investigation, lithofacies, defined at the centimeter scale, were identified by examining 1226.0 total linear feet from two cores, and 204 thin-sections. This was done to aid in the interpretation of sedimentation processes, and to better characterize the internal architecture of various deposits. Seven facies associations, reflecting interpreted sedimentation processes, were defined by this analysis: 1) pelagic and hemipelagic suspension settling, 2) bioturbation of pelagic and hemipelagic suspension sediments, 3) slump, 4) turbidity current, 5) turbidity current and/or liquified flow, 6) grain flow, and 7) debris flow. Appendix G provides a detailed summary of each facies association and the lithofacies grouped within them. Furthermore, Table 5 summarizes petrophysical values for all lithofacies as determined from conventional wire-line log analysis.
Table 5: Petrophysical values for lithofacies as determined from conventional wire-line logs.

Diagnostic fauna and allochems for this investigation include the presence of fusulinids and/or ooids (identified by a “1” if present and a “0” if absent). Fusulinids

<table>
<thead>
<tr>
<th>Facies Associations (Primary &amp; Secondary Sedimentation Processes)</th>
<th>Lithofacies (Dunham (1962) classification)</th>
<th>Gamma Ray (GR API)</th>
<th>Neutron Porosity (NPHI - %)</th>
<th>Density Porosity (DPHI - %)</th>
<th>Shallow Resistivity (LLS, RL13 - ohm-m)</th>
<th>Deep Resistivity (LLD, AT90 - ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies Association #1 - Pelagic/Hemipelagic Suspension Settling</td>
<td>Lithofacies 1.1 - Argillaceous Mudstone - Sporillic Wackestone</td>
<td>Mean: 85.0</td>
<td>Mean: 0.15</td>
<td>Mean: 0.15</td>
<td>Mean: 108.8</td>
<td>Mean: 214.5</td>
</tr>
<tr>
<td></td>
<td>Mode: 144.0</td>
<td>Mode: 0.23</td>
<td>Mode: 0.14</td>
<td>Mode: 103.6</td>
<td>Mode: 177.8</td>
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<tr>
<td></td>
<td>SD: 41.0</td>
<td>SD: 0.08</td>
<td>SD: 0.05</td>
<td>SD: 1.92</td>
<td>SD: 3.00</td>
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</tr>
<tr>
<td>Facies Association #2 - Bioturbation of Pelagic-Hemipelagic Suspension Sediment</td>
<td>Lithofacies 1.2 - Silstone - Carbonaceous Shale</td>
<td>Mean: 95.9</td>
<td>Mean: 0.18</td>
<td>Mean: 0.12</td>
<td>Mean: 125.3</td>
<td>Mean: 233.7</td>
</tr>
<tr>
<td></td>
<td>Mode: 112.5</td>
<td>Mode: 0.23</td>
<td>Mode: 0.08</td>
<td>Mode: 200.0</td>
<td>Mode: 177.8</td>
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<tr>
<td></td>
<td>SD: 36.2</td>
<td>SD: 0.07</td>
<td>SD: 0.06</td>
<td>SD: 3.03</td>
<td>SD: 4.44</td>
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</tr>
<tr>
<td>Facies Association #3 - Slump</td>
<td>Lithofacies 3.1 - Argillaceous Mudstone - Sporillic Wackestone</td>
<td>Mean: 56.3</td>
<td>Mean: 0.11</td>
<td>Mean: 0.09</td>
<td>Mean: 199.9</td>
<td>Mean: 1032.5</td>
</tr>
<tr>
<td></td>
<td>Mode: 58.9</td>
<td>Mode: 0.08</td>
<td>Mode: 0.11</td>
<td>Mode: 200.0</td>
<td>Mode: 562.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD: 27.28</td>
<td>SD: 0.06</td>
<td>SD: 0.04</td>
<td>SD: 1.82</td>
<td>SD: 2.94</td>
<td></td>
</tr>
<tr>
<td>Facies Association #4 - Turbidity Current</td>
<td>Lithofacies 4.1 - Argillaceous Mudstone - Sporillic Wackestone</td>
<td>Mean: 79.9</td>
<td>Mean: 0.15</td>
<td>Mean: 0.13</td>
<td>Mean: 134.9</td>
<td>Mean: 242.9</td>
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<td>Mode: 37.5</td>
<td>Mode: 0.23</td>
<td>Mode: 0.17</td>
<td>Mode: 103.6</td>
<td>Mode: 177.8</td>
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<td>SD: 35.25</td>
<td>SD: 0.07</td>
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<td>SD: 2.08</td>
<td>SD: 2.73</td>
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<td>Facies Association #5 - Turbidity Current and/or Liquified Flow</td>
<td>Lithofacies 4.2 - Skeletal Wackstone - mud-rich Packstone</td>
<td>Mean: 72.9</td>
<td>Mean: 0.13</td>
<td>Mean: 0.11</td>
<td>Mean: 121.9</td>
<td>Mean: 188.8</td>
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<td>Mode: 50.4</td>
<td>Mode: 0.11</td>
<td>Mode: 0.11</td>
<td>Mode: 200.0</td>
<td>Mode: 177.8</td>
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</tr>
<tr>
<td></td>
<td>SD: 33.9</td>
<td>SD: 0.08</td>
<td>SD: 0.05</td>
<td>SD: 1.99</td>
<td>SD: 2.41</td>
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<td>Facies Association #6 - Grain Flow</td>
<td>Lithofacies 4.3 - Oolitic, Skeletal Wackstone - Packstone</td>
<td>Mean: 97.3</td>
<td>Mean: 0.11</td>
<td>Mean: 0.06</td>
<td>Mean: 198.4</td>
<td>Mean: 4800.6</td>
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<td>Mode: 91.1</td>
<td>Mode: 0.14</td>
<td>Mode: 0.09</td>
<td>Mode: 200.0</td>
<td>Mode: 5620.4</td>
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<td>SD: 32.4</td>
<td>SD: 0.05</td>
<td>SD: 0.04</td>
<td>SD: 1.26</td>
<td>SD: 2.35</td>
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<tr>
<td>Facies Association #7 - Grains</td>
<td>Lithofacies 4.4 - Silstone - Carbonaceous Shale</td>
<td>Mean: 116.7</td>
<td>Mean: 0.18</td>
<td>Mean: 0.13</td>
<td>Mean: 103.6</td>
<td>Mean: 188.1</td>
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<td>Mode: 144.6</td>
<td>Mode: 0.20</td>
<td>Mode: 0.11</td>
<td>Mode: 200.0</td>
<td>Mode: 562.3</td>
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<td>SD: 30.17</td>
<td>SD: 0.06</td>
<td>SD: 0.06</td>
<td>SD: 2.74</td>
<td>SD: 4.53</td>
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<td>Facies Association #8 - Grains and/or Liquid Flow</td>
<td>Lithofacies 5.1 - Argillaceous Mudstone - Sporillic Wackestone</td>
<td>Mean: 60.1</td>
<td>Mean: 0.12</td>
<td>Mean: 0.10</td>
<td>Mean: 142.4</td>
<td>Mean: 455.2</td>
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<td>Mode: 26.8</td>
<td>Mode: 0.03</td>
<td>Mode: 0.06</td>
<td>Mode: 103.6</td>
<td>Mode: 562.3</td>
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<td>SD: 40.0</td>
<td>SD: 0.09</td>
<td>SD: 0.05</td>
<td>SD: 1.32</td>
<td>SD: 2.32</td>
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<td>Facies Association #9 - Grains and/or Slug Flow</td>
<td>Lithofacies 5.2 - Skeletal Wackstone - mud-rich Packstone</td>
<td>Mean: 69.8</td>
<td>Mean: 0.13</td>
<td>Mean: 0.11</td>
<td>Mean: 188.3</td>
<td>Mean: 609.8</td>
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<td>Mode: 37.5</td>
<td>Mode: 0.09</td>
<td>Mode: 0.03</td>
<td>Mode: 200.0</td>
<td>Mean: 177.8</td>
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<tr>
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<td>SD: 46.2</td>
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<td>SD: 0.07</td>
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<td>Facies Association #10 - Grains and/or Slug Flow</td>
<td>Lithofacies 6.1 - Skeletal Wackstone - mud-rich Packstone</td>
<td>Mean: 43.7</td>
<td>Mean: 0.07</td>
<td>Mean: 0.07</td>
<td>Mean: 115.0</td>
<td>Mean: 232.0</td>
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<tr>
<td></td>
<td>Mode: 48.2</td>
<td>Mode: 0.09</td>
<td>Mode: 0.06</td>
<td>Mode: 103.6</td>
<td>Mode: 562.3</td>
<td></td>
</tr>
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<td>SD: 6.26</td>
<td>SD: 0.03</td>
<td>SD: 0.02</td>
<td>SD: 1.32</td>
<td>SD: 2.32</td>
<td></td>
</tr>
<tr>
<td>Facies Association #11 - Debris Flow</td>
<td>Lithofacies 6.2 - Oolitic Wackstone - Packstone</td>
<td>Mean: 66.6</td>
<td>Mean: 0.06</td>
<td>Mean: 0.03</td>
<td>Mean: 198.7</td>
<td>Mean: 4491.2</td>
</tr>
<tr>
<td></td>
<td>Mode: 48.2</td>
<td>Mode: 0.03</td>
<td>Mode: 0.06</td>
<td>Mode: 200.0</td>
<td>Mean: 1778.3</td>
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<td>SD: 36.5</td>
<td>SD: 0.05</td>
<td>SD: 0.03</td>
<td>SD: 1.39</td>
<td>SD: 3.93</td>
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<tr>
<td>Facies Association #12 - Debris Flow</td>
<td>Lithofacies 7.1 - Intracratic, Skeletal Wackstone - Packstone</td>
<td>Mean: 37.4</td>
<td>Mean: 0.05</td>
<td>Mean: 0.07</td>
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<td>Mean: 361.2</td>
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<td>Mode: 26.8</td>
<td>Mode: 0.03</td>
<td>Mode: 0.06</td>
<td>Mode: 103.6</td>
<td>Mean: 177.8</td>
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<td>SD: 14.7</td>
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<td>SD: 0.04</td>
<td>SD: 1.39</td>
<td>SD: 3.19</td>
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</table>

Table 5: Petrophysical values for lithofacies as determined from conventional wire-line logs.
are good environmental indicators, inhabiting paleo-water depths between 30.0 to 100.0 feet (10.0 to 30.0 meters) representing mid-, to outer-ramp and shelf margin settings (Flügel, 2004; Phelps et al., 2008; Fitchen, 1997). Ooids, similar to fusulinids, are good environmental indicators. Depositional settings characteristic of ooid formation include tidal and marine bars, tidal deltas and beach environments (Flügel, 2004). These environments are characteristic of shallow, warm, tropical marine waters located adjacent to supersaturated seas with respect to CaCO₃, and form under constant hydraulic agitation (Flügel, 2004; Tucker and Wright, 1990).

Facies Association #1 – Pelagic and Hemipelagic Suspension Settling

Facies association #1 includes those deposits which accumulated on slope and basin floor settings primarily by pelagic and hemipelagic suspension settling with intermittent bottom current (i.e. contour current) re-working. Two lithofacies have been grouped into this facies association:

1) Lithofacies 1.1

2) Lithofacies 1.2

Lithofacies 1.1 is a dark gray to black, massive to horizontally laminated mudstone to spiculitic wackestone. This lithofacies consists of micrite, radiolarians, sponge spicules, and organic matter with lesser amounts of peloids, fine silt-sized quartz grains, pyrite and chert nodules (Figure 17A-B). Grains range between medium silt to clay size (31.0 µm to 0.06 µm), are well sorted, and exhibit a subrounded to well rounded, moderate to high sphericity morphological character. Gradational mudstone to wackestone lithofacies shifts are common as concentrations of planktonic organisms vary throughout this lithofacies. No visible porosity is present within this lithofacies. Pyrite and chert nodules are locally present throughout, and are often
found in association with one another. Chert nodules and silt-sized quartz grains are interpreted to result from the dissolution of biogenic silica (Opal-A) derived from sponge spicules and radiolarians (Scholle and Ulmer-Scholle, 2003). Pyrite is a product of bacterial reduction of organic matter, indicating formation under reducing (anoxic) environmental conditions (Tucker and Wright, 1990).

At both core locations, Lithofacies 1.1 is characterized by a high gamma ray response, a moderate to low neutron-porosity response, a moderate density-porosity response, and a variable shallow, and deep, resistivity responses (see Table 5 for petrophysical values for all lithofacies). This lithofacies is interpreted to represent a deep-water, lower slope and basin floor depositional setting, which was deposited during periods of transgressive and highstand relative sea level conditions when carbonate sediment was actively being produced by the shallow-water carbonate factory (Tucker and Wright, 1990). Similar lithofacies have been recognized by Wiggins and Harris (1985), Saller et al. (1989), Gawloski (1987), Janson et al. (2007), Fitchen (1997), and Mazzullo and Reid (1989).

Lithofacies1.2 is a gray to light brownish gray, massive to horizontally laminated siltstone to carbonaceous shale, composed of micrite, organic matter, and medium-fine silt-sized (31.0 µm to 7.8 µm) siliciclastic grains, with lesser amounts of sponge spicules, radiolarians, peloids, pyrite and chert nodules (Figure 17C-D). Grains range between medium silt to clay size (31.0 µm to 7.8 µm), exhibiting angular to subrounded, low to high sphericity morphological character. Similar to Lithofacies 1.1, this lithofacies commonly exhibits gradational texture shifts from siltstone to carbonaceous shale or mudstone, depending upon the concentration of siliciclastic grains, carbonate mud and organic matter present. No visible porosity is present within this lithofacies. Pyrite, localized chert nodules, and silt-sized quartz grains are
interpreted to have a similar diagenetic (authigenesis) origin as in argillaceous mudstone to wackestone lithofacies.

At each of the two core locations, this lithofacies is characterized by a high gamma ray response, a high neutron-porosity response, a low density-porosity response, and low shallow and deep resistivity responses. Conventional wire-line log response for this lithofacies is highly variable, making interpretations of characteristic log responses difficult. This is attributed to the high-degree of variability of shale, detrital siliciclastic grains, micrite and organic content throughout this lithofacies. Lithofacies 1.2 is interpreted to represent detrital deposits originating from outside of the basin (extrabasinal), and transported basinward by eolian processes (Lorenz and Brooks, 1990) during lowstand periods of relative sea level conditions. A low sea level position on ramp and rimmed-platform settings, of which are suggested to characterize the northernmost margins of the Delaware Basin (Saller et al., 1989; Fitchen, 1997), would allow for siliciclastics, previously trapped in a more landward setting, to be transported seaward into deeper water (Tucker and Wright, 1990).
Figure 17: A) Lithofacies 1.1 (argillaceous mudstone to spiculitic wackestone) with faint horizontal laminations (h-lams) indicating pelagic and hemipelagic suspension settling of sediment vertically out of the water column. B) Thin-section from core photo (A) showing pelagic mudstone to wackestone (mdst-wckst) composition consisting of radiolarians (rad), sponge spicules (sp spic), and pyrite (pyr). C) Lithofacies 1.2 (siltstone to carbonaceous shale) with faint, finning upward (fu h-lams) horizontal laminations (h-lams) indicating pelagic and hemipelagic suspension settling. D) Thin-section from core photo (C) showing siltstone to carbonaceous shale composition (slst-csh) consisting of quartz (qtz) grains, radiolarians (rad), sponge spicules (sp spic), and organic matter (org).
Facies Association #1 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity

Facies association #1 deposits are variable in thickness (less than 1.0 centimeter to greater than 9.0 meters thick), and exhibit massive to planar laminated (less than 1.0 centimeter thick) internal depositional fabrics. Laminations are less than 1.0 centimeter thick, horizontally layered, and locally exhibit normal and inverse grading (increasing and/or decreasing in thickness up-section). Slight deformation of bedding laminations occurs locally around chert nodules and where contourites are present. Contourites (less than 1.0 centimeter thick) occur locally throughout both lithofacies. Contour currents are recognized by: 1) light gray to gray color in core resulting from the significant increase in abundance of sponge spicules and a change in texture from mudstone to spiculitic wackestone, 2) sharp bedding contacts relative to adjacent suspension deposits, 3) small (centimeter thick) ripple laminations, and 4) reworking and deformation of adjacent suspension deposits (Shanmugam, 2000). In the Well A core, suspension deposits account for 51.0% of the entire cored interval (375.1 feet of 726.0 total linear feet of core), and 65.0% (322.0 feet of 500.0 total linear feet of core) in the Well B core.

Based on these observations from core and thin-section analysis, facies association #1 deposits are interpreted to represent sedimentation by pelagic and hemipelagic suspension settling with intermittent contour current deposition, accumulating on slope and basin floor settings under reducing environmental conditions. Evidence supporting deposition by suspension settling include: 1) less than 1.0 centimeter thick horizontal laminations, indicating vertical accumulation of sediment, 2) lack of diverse sedimentary structures, interpreted as indicating low hydraulic energy during sediment accumulation, 3) localized (less than 1 centimeter
thick) contourites, and 4) a lack of coarse-grained skeletal and non-skeletal debris, interpreted to indicate abundant sediment was derived from deep-water open marine setting (Scholle et al., 1983).

**Facies Association #2 – Bioturbation of Pelagic and Hemipelagic Suspension Sediment**

Facies association #2 includes those deposits which accumulated on slope and basin floor settings by pelagic and hemipelagic suspension settling and were then subsequently re-worked syndepositionally by burrowing organisms. One lithofacies has been grouped into this facies association:

1) Lithofacies 2.1

Lithofacies 2.1 is a dark gray to black, massive, bioturbated mudstone to spiculitic wackestone consisting of micrite, sponge spicules and radiolarians, with lesser amounts of organic matter, peloids, pyrite, and undifferentiated skeletal grains. Grains range between medium silt to clay size (31 µm to 0.06 µm), are well sorted, and exhibit a subrounded to well rounded, moderate to high sphericity morphological character. No visible porosity is present within this lithofacies.

At both core locations, this lithofacies is characterized by a high gamma ray response, a high neutron-porosity response, a moderate density-porosity response, and variable shallow, and deep, resistivity responses. These deposits are interpreted to represent a deep-water, lower slope and basin floor depositional setting, accumulating as suspension deposits during periods transgressive and highstand relative sea level conditions (Tucker and Wright, 1990). These sediments are interpreted to have been re-worked by burrowing organisms during periods of increased oxygenation caused by bottom currents (Tucker and Wright, 1990). Bioturbation is interpreted to have been syndepositional due to the presence of burrows throughout entire deposit thicknesses.
Similar lithofacies have been recognized by Saller et al. (1989), Fitchen (1997), Mazzullo and Reid (1989), Phelps et al. (2008), among others.

Facies Association #2 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity

Facies association #2 deposits occur as thick (3.0 to 6.0 meters thick), isolated deposits (i.e. do not occur as cyclically stacked deposits) and exhibit a massive, structureless, internal depositional fabric. Original depositional fabric is that of Lithofacies 1.1 suspension sediments, and is locally preserved in core. These deposits are characterized by the presence of small (less than 1.0 centimeter long) sediment-filled burrows that are horizontally oriented. The horizontal orientation of burrows resemble those of Planolites, which are thought to be made by a deep-water worm-like organism (Figure 18A-B – Scholle et al., 1983), and their presence suggests periods of increased oxygenation on slope and basin floor settings (Tucker and Wright, 1990). Facies association #2 appears to occur at random locations within each of the cored intervals, but is typically present where turbidite and MTD frequency decreases. In the Well A core, these deposits account for 13.6% of the entire cored interval (99.5 feet of 726.0 total linear feet of core), and 8.4% (40.4 feet of 500.0 total linear feet of core) in the Well B core.

Facies association #2 is interpreted to represent a primary sedimentation process with syndepositional modifications to the primary sediment. Accumulation of facies association #1 mudstone to wackestone suspension sediment occurred as a primary sedimentation process. This sediment was then re-worked syndepositionally by burrowing organisms, or shortly following deposition. The former is suggested here due to the presence of burrows occurring throughout the entirety of these
deposits.

Figure 18: A) Core photo of Lithofacies 2.1 (bioturbated argillaceous mudstone to spiculitic wackestone) with horizontal centimeter-scale burrows (bur). B) Thin-section from core photo (A) showing sediment-filled burrows (bur) within a mudstone to wackestone matrix (mdst-wckst) consisting of micrite (mic), organic matter (org), and sponge spicules (sp spic). This lithofacies represents deposition by suspension settling, and became reworked syndepositionally by burrowing organisms.

Facies Association #3 – Slump

Facies association #3 include those deposits which accumulated on slope and basin floor settings by pelagic and hemipelagic suspension settling and were then remobilized or redeposited further basinward by slumping. One lithofacies has been grouped into this facies association:

1) Lithofacies 3.1

Lithofacies 3.1 is a dark gray to black, intensely deformed mudstone to spiculitic wackestone, consisting of micrite, sponge spicules and radiolarians, with
lesser amounts of peloids and chert concretions (Figure 19A-B). Skeletal fragments are locally abundant within these deposits, and represent the presence of crinoids, brachiopods, bryozoans, phylloid algae, and undifferentiated skeletal grains. Grains range between fine-silt to very fine sand size (0.06 µm to 125 µm), are poor to moderately sorted, and exhibit an angular to subrounded, low to moderate sphericity morphological character. No visible porosity is present within this lithofacies. At each of the two core locations, analysis of conventional wire-line logs indicate that slump deposits are characterized by a low gamma ray response, a low neutron-porosity response, a low density-porosity response, and significant increasing spikes in shallow, and deep, resistivity responses.

Figure 19: A) Core photo of Lithofacies 3.1 (argillaceous mudstone to spiculitic wackestone) deposited by slump processes as indicated by highly deformed and overturned bedding (def) and foliated bedding layers (foli). B) Thin-section from core photo (A) illustrating mudstone to wackestone (mdst-wkst) composition dominated by radiolarians (rad), sponge spicules (sp spic), and organic matter (org).
Facies Association #3 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity

Slump deposits are characterized by 0.3 to 1.0 meter thick deposits composed of alternating argillaceous mudstone, spiculitic wackestone and skeletal wackestone bedding layers, and exhibit intensely folded and fluidal deformed (convoluted) internal depositional fabrics. Deformation of bedding (represented by folds and faults) progressively increases upward within slump deposits, interpreted to indicate upward propagation of shear stresses along individual bedding laminae as well as from a basal shear surface (Tripsanas et al., 2008).

Slump deposits comprise 2.5% of all sediments from both cored wells (30.1 feet of 1226.0 total linear feet of core). Of the 30.1 cumulative feet of slump deposits, 23.0 feet (76.0%) occur within the Well A core, and 7.1 feet (24.0%) occur within the Well B core. Within the Well A core, slump deposits are most prevalent at depth intervals 10106.0’ to 10072.0’, 9456.0’ to 9453.0’, 9392.0’ to 9390.0’ and 9375.0’ to 9374.0’. These depth intervals closely correspond to intervals of increasing turbidite and coarse grained MTD frequency. Within the Well B core, slumps exhibit analogous architectural attributes as those observed in the Well A core, but are less abundant and do not occur within close association to other flow deposits.

Architectural attributes typifying slump architecture observed within the two UBSL cores are illustrated in Figure 20. These architectural attributes include: 1) mudstone to wackestone texture, dominated by micrite, sponge spicules, and radiolarians, 2) sharp erosive basal shear surface overlying slight to undeformed mudstone to wackestone strata, 3) fluidal deformation of bedding (convoluted bedding) above basal shear surface, 4) increasing deformation of bedding near central portions of deposit, 5) beds exhibit centimeter scale folds (asymmetric, recumbent and
recumbent isoclinal) and faults (listric), 6) plastic deformation of intraclasts (when present), preferentially aligned parallel to deformed bedding layers, and 7) decreasing deformation upwards with a gradational upper bedding contacts (Posamentier and Martinsen, 2011; Amerman, 2009; Nardin et al., 1979; Cook and Mullins, 1983; Tripsanas et al., 2008; Mulder and Alexander, 2001; Lowe, 1979, 1982).

Figure 20: Core photo and core traces illustrating diagnostic architectural elements observed in facies association #3 slump deposits. Size of schematic elements are exaggerated in order to emphasize key architectural and compositional features.

Slump deposits are often present as upper and lower units relative to thick intervals (10.0 to 20.0 feet thick) of cyclically stacked turbidity current and/or liquefied flow deposits of similar composition (mudstone to spiculitic wackestone),
suggesting a genetic relationship between them. The erosive nature of turbidity currents and liquefied flows, of which is attributed to high transport velocities of these flows, are interpreted to have initiated slumps through liquefaction of mud-dominated sediment along lower slope and basin floor settings (Mulder and Alexander, 2001). In the Monterey Submarine Canyon located off the west coast of California, Xu et al. (2004) documented turbidity current transport velocities of 0.5 m/s to 2.0 m/s at depths up to 1450 meters and transport distances greater than 1.10 miles away from where the turbidity currents were initiated. Wiggins and Harris (1985) also suggest slumping by liquefaction as a result of traction sedimentation, which is interpreted to further support the interpretation of slumps being initiated by turbidity current or liquefied flow processes. Similar relationships between slumps and turbidites have been proposed by Eberli (1988) for slope strata analyzed from ODP Leg 101 drill sites along northern Little Bahama Bank. Analysis of turbidites at these drill sites, which are dominated by periplatform ooze and shallow-water grains (between 0.01 to 2.0 meters thick), indicate that instability horizons exists between these deposits and surrounding strata, leading to initiation of turbidites and small-scale slumping events.

Based upon these observations, slump deposits are interpreted to represent a deep-water lower slope and basin floor depositional setting, accumulating as suspension sediments during periods of transgressive and highstand relative sea level conditions when carbonate sediment was actively being produced by the shallow-water carbonate factory (Tucker and Wright, 1990). These deposits were then subsequently redeposited and re-worked syndepositionally, or shortly following suspension settling, by slumping based on: 1) similar composition and texture of suspension deposits, 2) fluidal deformation of bedding, and 3) closely associated with turbidites and/ liquefied flow deposits of similar composition (Wiggins and Harris, 1985; Mulder and
Facies Association #4 – Turbidity Current

Facies association #4 includes those deposits which were transported into the basin, and/or re-worked and redeposited by turbidity current sedimentation processes. Four lithofacies have been grouped into this facies association:

1) Lithofacies 4.1
2) Lithofacies 4.2
3) Lithofacies 4.3
4) Lithofacies 4.4

Lithofacies 4.1 is a light to dark gray, mudstone to spiculitic wackestone, consisting of micrite, sponge spicules, peloids and radiolarians, with lesser amounts of organic matter, pyrite and fine silt-sized quartz grains. Grains range between medium silt to clay size (31 µm to 0.06 µm), are moderately to poorly sorted, and exhibit subangular to subrounded, low to moderate sphericity morphological characteristics. Localized skeletal debris is observed within this lithofacies, located at the base of Bouma sequences. No visible porosity is present within this lithofacies (Figure 21A-B).
Figure 21: A) Core photo illustrating turbidite deposit of Lithofacies 4.1. B) Thin-section from core photo (A) illustrating Lithofacies 4.1 (mudstone to wackestone) texture (mdst-wckst). Note fluid escape structure (fld esc). C) Core photo illustrating turbidite deposit of Lithofacies 4.2. D) Thin-section from core photo (C) showing Lithofacies 4.2 (skeletal wackestone to packstone) texture (skel wckst-pckst) with large concentrations of skeletal material including brachiopods (brach), bryozoans (bry), crinoids (crin), and sponge spicules (sp spic).

This lithofacies accounts for 9.2% (67.3 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 19.8% (94.9 feet of 500.0 total linear feet
of core) of all sediments within the Well B core. At each of the two core locations, analysis of conventional wire-line logs indicate that this lithofacies is characterized by a moderate gamma ray response, a moderate neutron-porosity response, a moderate density-porosity response, and variable, abruptly increasing, shallow, and deep, resistivity responses. Similar to Lithofacies 1.1, this lithofacies is interpreted to represent a deep-water lower slope and basin floor depositional setting, deposited during periods of transgressive and highstand relative sea level conditions when carbonate sediment was actively being produced by the shallow-water carbonate factory (Tucker and Wright, 1990). These deposits are interpreted to have been re-worked and redeposited further basinward by turbidity currents (Saller et al., 1989; Gawloski, 1987; Mazzullo and Reid, 1989; Loucks et al., 2011).

Lithofacies 4.2 is a light to dark gray, skeletal wackestone to mud-rich packstone, consisting of micrite, and broken and fragmented skeletal grains (crinoid ossicles, ostracods, brachiopods, phylloid algae, gastropods, bryozoans, minor fusulinid tests, sponge spicules, radiolarians and undifferentiated skeletal grains), with lesser amounts of organic matter and peloids. Skeletal grains often exhibit complete micritization or significant replacement by calcite, dolomite or quartz cement (Scholle and Ulmer-Scholle, 2003). Grains range between very fine sand and silt to medium sand size (63 µm to 500 µm), are poorly to moderately sorted, and exhibit very angular to subrounded, low sphericity morphological characteristics. No visible porosity is present within this lithofacies (Figure 21C-D).

This lithofacies accounts for 1.2% (9.0 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 1.1% (5.7 feet of 500.0 total linear feet of core) of all sediments within the Well B core. At both cored wells, conventional wire-line logs indicate this lithofacies is characterized by a moderate gamma ray response, a
moderate neutron-porosity response, a moderate density-porosity response, and low, abruptly increasing shallow, and deep, resistivity responses. This lithofacies is interpreted to represent deposition in an outer ramp to shelf margin setting within storm wave base. These deposits are interpreted to have been redeposited basinward by turbidity currents during periods of highstand and early lowstand relative sea level conditions (Flügel, 2004; Tucker and Wright, 1990). Similar lithofacies have been recognized by Wiggins and Harris (1985), Saller et al. (1989), Gawłoski (1987), Janson et al. (2007), Fitchen (1997), Phelps et al. (2008), and Mazzullo and Reid (1989).

Lithofacies 4.3 is a light gray, oolitic, skeletal wackestone to packstone, consisting primarily of ooids, aggregate grains, peloids, micrite and fragmented skeletal grains (crinoid ossicles, ostracods, bryozoans, brachiopods, phylloid algae, gastropods, fusulinid tests, planktonic foraminifera, sponge spicules, radiolarians and undifferentiated skeletal grains), with lesser amounts of organic matter and fine silt-sized detrital quartz grains. Ooids range between very fine sand to fine sand size (63 µm to 125 µm), are subspherical to spherical in shape, and locally exhibit partial destruction of internal concentric laminae by micritization, or calcite and dolomite cementation (Scholle and Ulmer-Scholle, 2003). Within these deposits, visible porosity is 3.0% (2.0% intraparticle and 1.0% moldic (oomoldic)) with a majority of pores filled with organic matter. Aggregate grains range from fine sand to medium sand size (125 µm to 250 µm), are subangular to subrounded and consist of cemented peloids, ooids and skeletal fragments. Grains are poorly sorted within this lithofacies (Figure 22A-D).
Figure 22: A and C) Core photos of turbidite deposits of Lithofacies 4.3. B) and D) Thin-sections from core photos (A) and (C) showing abundance of micritized ooids (ooid) with lesser amounts of skeletal fragments including planktonic foraminifera (foram) and brachiopod (brach). Note presence of intraparticle porosity (intra poro) partially filled with organic matter (org). E) Core photo of Lithofacies 4.4. F) Thin-section of core photo (E) illustrating coarse siltstone texture (crs slst) with horizontal laminations (h-lams) and cross-bedding (x-lams). Note presence of finning upward grains and laminations overlain by cross-bedded laminations and finally, pelagic suspension sediments, indicating turbidity current deposition.
This lithofacies is only present within the Well A core, and accounts for 1.6% (11.5 feet of 726.0 total linear feet of core) of all sediments. This lithofacies is easily distinguished from other turbidite lithofacies in core by the presence of visible ooids and aggregate grains on the core face. Analysis of conventional wire-line logs characterizes this lithofacies by a high gamma ray response, a moderate neutron-porosity response, a low density-porosity response, and high, abruptly increasing, shallow, and deep, resistivity responses. This lithofacies is interpreted to represent deposition within a shallow marine ramp crest to middle ramp depositional setting (i.e. beach barrier, tidal delta, shoal complexes) within fair-weather wave base (Flügel, 2004; Tucker and Wright, 1990). Within this setting, grains were likely subject to alternating conditions of intermittent hydraulic energy regimes allowing for formation of ooids and aggregate grains (Flügel, 2004; Tucker and Wright, 1990). Grains are interpreted to have been mobilized basinward during periods of high hydraulic energy (i.e. storm generated waves and spring tides) during highstand and early lowstand relative sea level conditions (Tucker and Wright, 1990). Similar lithofacies have been recognized by Janson et al. (2007), Fitchen (1997), Ruppel and Ariza (2002), Ruppel et al. (2000), Stoudt and Raines (2004), French and Kerans (2004), and Pranter et al. (2004).

Lithofacies 4.4 is a yellowish gray to light olive gray, siltstone to carbonaceous shale, and has a similar composition to that of Lithofacies 1.2 suspension deposits, except for localized occurrences of fragmented skeletal grains (crinoid ossicles, brachiopods, bryozoans and undifferentiated skeletal grains). Non-skeletal grains range between fine to medium silt size (7.8 μm to 31 μm), exhibiting very angular to subrounded, low sphericity morphological characteristics. Skeletal grains (when present) range between very fine sand to fine sand size (63 μm to 125 μm), are poorly
sorted, and exhibit subangular to subrounded low sphericity morphological characteristics. No visible porosity is present within this lithofacies (Figure 22E-F).

This lithofacies accounts for 4.1% (30.0 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 4.7% (22.6 feet of 500.0 total linear feet of core) of all sediments within the Well B core. For both cores, conventional wire-line log responses indicate that this lithofacies is characterized by a high gamma ray response, a moderate neutron-porosity response, a moderate density-porosity response, and low, abruptly increasing, shallow, and deep, resistivity responses. Lithofacies 4.4 is interpreted to have a similar extrabasinal origin as Lithofacies 1.2, being transported basinward by eolian processes during lowstand periods of relative sea level conditions (Tucker and Wright, 1990; Lorenz and Brooks, 1990). Similar lithofacies have been recognized by Saller et al. (1989), Gawloski (1987), Janson et al. (2007), Fitchen (1997), Mazzullo and Reid (1989), and Lorenz and Brooks (1990).

**Facies Association #4 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity**

Turbidity current deposits (turbidites) are characterized as relatively thin (less than 0.3 to 0.6 meters thick) isolated units, but often exhibit cyclical stacking patterns with multiple deposits occurring within 0.3 to 3.0 meter thick intervals. Architectural attributes characteristic of turbidites observed within the two UBSL cores are illustrated in Figure 23. These architectural attributes include: 1) normal grading, 2) ripple cross-laminations, 3) sharp basal contacts with loadcasts structures, 4) gradational upper contacts with fluid escape structures, 5) planar laminations, and 6) partial to complete Bouma sequences (Cook and Mullins, 1983; Mulder and Alexander, 2001; Lowe, 1979, 1982). These architectural elements are interpreted to
indicate traction ($T_{ac}$) and suspension ($T_{ce}$) sedimentation by a non-cohesive flow, where sediment grains were supported within the flow body by upward directed forces of fluidal turbulence (Lowe, 1979, 1982; Mulder and Alexander, 2001; Cook and Mullins, 1983). Grain-to-grain dispersive pressures may have also existed within Lithofacies 4.2 and 4.3, due to an increased abundance of solid grain components relative to Lithofacies 4.1 and 4.4 (Mulder and Alexander, 2001).
Figure 23: Core photo and core traces illustrating diagnostic architectural elements observed for facies association #4 turbidity current deposits. Size of schematic elements are exaggerated in order to emphasize key architectural and compositional features.

Lithofacies 4.2 and 4.3 turbidites have relatively high sediment concentrations (10.0% to 20.0%), consisting of shallow-water and deep-water fauna, shallow-water allochems (ooids and aggregate grains) and relatively high concentrations of carbonate mud (35.0% to greater than 50.0%). These observations are interpreted to indicate
increasing transport velocities downslope to allow for the long transport distances from shelf margin and slope source terrains (33.0 to 34.0 miles (53.0 to 55.0 kilometers) away from Well B and 19.0 to 20.0 miles (30.5 to 32.0 kilometers) away from Well A) (Mulder and Alexander, 2001). Increasing transport velocities promote basal erosion of underlying strata, preserved in turbidites in the form of scour marks (flute marks) and loadcasts (Lowe, 1979, 1982; Mulder and Alexander, 2001; Cook and Mullins, 1983). These structures were often observed within Lithofacies 4.2 and 4.3 turbidites.

Lithofacies 4.1 and 4.4 turbidites consist of relatively low sediment concentrations of solid grains (less than 10.0%) and exhibit slight to non-erosive basal contacts, fluid-escape structures at gradational upper bedding contacts and cyclically stacked partial Bouma sequences. These observations are interpreted to indicate decreasing transport velocities of sediment grains that were fully supported by upward directed fluid turbulence (Mulder and Alexander, 2001).

Possible mechanisms for initiation of turbidity currents include tectonic activity, storm generated waves and currents, slumping, liquefaction, remobilization of sediment from an overlying flow, or they may represent the latter stages of a different flow (Heimsund, 2007). This study interprets that turbidity current initiation was predominantly related to sediment transport by other flow processes. Thick intervals (0.3 to 3.0 meters thick) of cyclically stacked turbidites overlying 0.6 to 0.9 meter thick MTDs of similar composition occur frequently throughout both of the cored wells, interpreted to indicate that turbidity currents were initiated by underlying MTDs. Furthermore, decreasing thicknesses and increasing frequencies of these stacked turbidites up-section, is interpreted to indicate the waning stages of sedimentation related to underlying MTDs (Mutti et al., 1999; Mulder and Alexander,
Overall, turbidite deposits comprise 19.6% of all sediments within both cored wells (240.9 feet of 1226.0 total linear feet of core). Of the 240.9 cumulative feet of turbidites, 117.8 feet (49.0%) occur within the Well A core and 123.1 feet (51.0%) occur within the Well B core. Turbidites within Well A are mainly those dominated by shallow-water fauna and allochems (i.e. Lithofacies 4.2 and 4.3), and predominantly occur at depth intervals 9253.0’ to 9286.0’, 9295.0’ to 9367.0’, 9642.0’ to 9679.0’ and 10030.0’ to 10123.0’. These depth intervals closely correspond to intervals dominated by slumps and coarse grained MTDs, and are interpreted to represent basinal transport and redeposition during highstand and lowstand periods of relative sea level (Tucker and Wright, 1990). Turbidites in the Well B core are dominated by mudstones and siltstone deficient of shallow-water grains (i.e. Lithofacies 4.1 and 4.4), and are most prevalent at depth intervals 7367.0’ to 7372.0’, 7549.0’ to 7614.0’ and 7658.0’ to 7721.0’. Unlike the depth intervals in the Well A core, these intervals closely correspond to depth intervals dominated by pelagic and hemipelagic suspension deposits. These intervals are interpreted to represent basinal transport during transgressive and early highstand periods of relative sea level (Tucker and Wright, 1990).

**Facies Association #5 – Turbidity Current and/or Liquified Flow**

Facies association #5 includes those deposits which were transported into the basin, and/or re-worked and redeposited by turbidity current and/or liquefied flow sedimentation processes. Two lithofacies have been grouped into this facies association:

1) Lithofacies 5.1
2) Lithofacies 5.2

Lithofacies 5.1 is characterized as a light to dark gray, mudstone to wackestone mainly composed of micrite, sponge spicules, radiolarians and organic matter, with lesser amounts of peloids, pyrite and fine silt-sized detrital quartz grains. Grains range between medium to fine silt size (31 μm to 7.8 μm), are moderately to well sorted, and exhibit subangular to subrounded, moderate to low sphericity morphological characteristics. No visible porosity is present within this lithofacies (Figure 24A-B).
Figure 24: A) Core photo of turbidite and/or liquified flow deposit of Lithofacies 5.1.  
B) Thin-section from core photo (A) showing Lithofacies 5.1 (mudstone to wackestone) texture (mdst-wckst) dominated by sponge spicules (sp spic), radiolarians (rad), and peloids (pel).  C) Core photo of turbidite and/or liquified flow deposit of Lithofacies 5.2.  D) Thin-section from core photo (C) illustrating Lithofacies 5.2 (skeletal wackestone to packstone) texture (skel pckst) dominated by ostracods (ostr), fusulinids (fus), bryozoans (bry), and brachiopods (brach).
This lithofacies accounts for 5.3% (38.6 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 0.2% (0.9 feet of 500.0 total linear feet of core) of all sediments within the Well B core. Analysis of conventional wire-line logs at both core locations indicates that Lithofacies 5.1 is characterized by a low gamma ray response, a moderate neutron-porosity response, a moderate density-porosity response, and highly variable, abruptly increasing, shallow, and deep, resistivity responses. Lithofacies 5.1 is interpreted to represent a deep-water slope and basin floor depositional setting, accumulating as suspension deposits during transgressive and highstand relative sea level conditions and were subsequently re-worked and redeposited basinward by turbidity current and/or liquefied flow processes (Tucker and Wright, 1990).

Lithofacies 5.2 is characterized as a light to dark gray, wackestone to mud-rich packstone mainly composed of micrite, skeletal grains (sponge spicules, radiolarians, crinoids, brachiopods, bryozoans, ostracods, gastropods, fusulinids, planktonic foraminifera, and undifferentiated skeletal grains), with lesser amounts of organic matter, peloids, and pyrite. Grains range between coarse sand to fine silt size (500 μm to 7.8 μm), are poorly sorted, and exhibit very angular to subrounded, low sphericity morphological characteristics. No visible porosity is present within this lithofacies (Figure 24C-D).

This lithofacies accounts for 2.0% (14.9 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 1.6% (7.8 feet of 500.0 total linear feet of core) of all sediments within the Well B core. At each of the two core locations, conventional wire-line log analysis indicates that Lithofacies 5.2 is characterized by a low gamma ray response, a moderate neutron-porosity response, a moderate density-porosity response, and high, abruptly increasing, shallow, and deep, resistivity
responses. Similar to Lithofacies 4.2, this lithofacies is interpreted to represent deposition in an outer ramp to shelf margin setting within storm wave base. These deposits were then later re-worked and redeposited basinward by turbidity current and/or liquified flows during periods of relative sea level highstand and early lowstand (Flügel, 2004; Tucker and Wright, 1990).

Facies Association #5 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity

Turbidity current and/or liquefied flows (turbidites and/or liquefied flow deposits) are characterized as relatively thick (typically 0.6 to 1.2 meters thick) deposits with massive to slightly graded internal depositional fabrics. Concentration of solid grain components is between 10.0% to 40.0%, but typically exceeds greater than 20.0% sediment concentrations by volume. Architectural attributes characteristic of turbidite and/or liquefied flow deposits observed within the two UBSL cores are illustrated in Figure 25. These architectural attributes include: 1) normal grading, 2) sharp, moderately to non-erosive basal contacts, 3) gradational, non-erosive upper bedding contacts, 4) fluid escape structures, 5) planar bedding laminations, 6) fluidal deformation of bedding, 7) pressure solution seams, 8) high-angle bedding, and 8) partial Bouma sequences (Mulder and Alexander, 2001; Lowe 1979, 1982; Cook and Mullins, 1983).
Figure 25: Core photo and core traces illustrating diagnostic architectural elements observed for facies association #5 turbidity current and/or liquified flow deposits. Size of schematic elements are exaggerated in order to emphasize key architectural and compositional features.

These architectural attributes indicate traction and suspension sedimentation by non-cohesive flows, whereby sediment grains are fully supported by a combination of upward directed fluidal turbulence, escaping pore fluids, grain-to-grain dispersive...
pressures and buoyant forces (Lowe 1979, 1982; Mulder and Alexander, 2001). These deposits exhibit architectural attributes characteristic of both turbidity currents and liquefied flows, indicating that these deposits likely represent transitional sedimentation processes (Lowe, 1979, 1982; Mulder and Alexander, 2001). The occurrence of these deposits as underlying units to cyclically stacked turbidites of similar composition suggests a genetic relationship between the two, representing different stages of sedimentation from a single flow process (Mutti et al., 1999; Mulder and Alexander, 2001).

Overall, turbidite and/or liquefied flow deposits comprise 5.1% of all sediments within both cored wells (62.3 feet of 1226.0 total linear feet of core). Of the 62.3 cumulative feet of turbidites and/or liquefied flow deposits, 53.5 feet (86.0%) occur within the Well A core and 8.8 feet (14.0%) occur within the Well B core. Turbidites and/or liquefied flow deposits within the Well A core mainly occur at depth intervals 9313.0’ to 9343.0’ and 9747.0’ to 9789.0’. These depth intervals closely correspond to intervals dominated by turbidites and MTDs, and are interpreted to represent basinal transport and redeposition during highstand and early lowstand periods of relative sea level (Tucker and Wright, 1990). Turbidites and/or liquefied flow deposits within the Well B core predominantly occur at depth intervals 7687.0’ to 7694.5.0’ and 7721.5’ to 7723.0’. Unlike the depth intervals in the Well A core, these intervals closely correspond to depth intervals dominated by pelagic and hemipelagic suspension deposits and mud-dominated turbidites. These intervals are interpreted to represent basinal transport and redeposition during transgressive and early highstand periods of relative sea level (Tucker and Wright, 1990).
Facies Association #6 – Grain Flow

Facies association #6 includes those deposits which were transported into the basin, and/or re-worked and redeposited by grain flow processes. Two lithofacies have been grouped into this facies association:

1) Lithofacies 6.1

2) Lithofacies 6.2

Lithofacies 6.1 is characterized as a light to dark gray, wackestone to packstone mainly composed of micrite and skeletal grains (sponge spicules, radiolarians, crinoids, fusulinids, brachiopods, bryozoans, ostracods, gastropods, phylloid algae, and undifferentiated skeletal grains), with lesser amounts of organic matter and silt-sized detrital quartz grains. Grains range between coarse sand to fine sand size (750 \( \mu \text{m} \) to 125 \( \mu \text{m} \)), are moderately to poorly sorted, and exhibit very angular to subrounded, low to moderate sphericity morphological characteristics. No visible porosity is present within this lithofacies (Figure 26A-B).
Figure 26: A) Core photo of grain flow deposit of Lithofacies 6.1. B) Thin-section from core photo (A) illustrating Lithofacies 6.1 (skeletal wackestone to packstone) texture (skef wckst-pckst) dominated by fusulinids (fus), foraminifers (foram), sponge spicules (sp spic), brachiopods (brach), ostracods (ostr) and crinoids (crin) with millimeter-scale mudstone intraclasts (clast). C) Core photo of grain flow deposit of Lithofacies 6.2. D) Thin-section from core photo (C) showing Lithofacies 6.2 (packstone to grainstone) texture (pckst-grnst) dominated by ooids (ooid) and aggregate grains (aggr grn) with minor skeletal material. Note the presence of intraparticle porosity (intra poro) and oomoldic porosity (oomoldic poro) with partial filling of pores by organic matter (black).
This lithofacies accounts for 0.5% (3.5 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and 0.0% (0.2 feet of 500.0 total linear feet of core) of all sediments within the Well B core. Analysis of conventional wire-line log responses for grain flow deposits was completed only for Well A due to the lack of these deposits within Well B (only one grain flow observed less than 0.2 feet thick). Lithofacies 6.1 is characterized by a very low gamma ray response, a low neutron-porosity response, a low density-porosity response, and moderate to high, abruptly increasing, shallow, and deep, resistivity responses. This lithofacies, similar to Lithofacies 5.2, is interpreted to represent an outer ramp to shelf margin depositional setting within storm wave base (Flügel, 2004; Tucker and Wright, 1990). Transport and redeposition of these deposits basinward is interpreted to have occurred during periods of relative sea level highstand and early lowstand (Flügel, 2004; Tucker and Wright, 1990).

Lithofacies 6.2 is characterized as a light to dark gray, oolitic wackestone to packstone mainly composed of ooids, aggregate grains and peloids, with lesser amounts of micrite, skeletal grains, organic matter, and silt-sized detrital quartz grains. Ooids range between fine sand to very fine sand size (250 μm to 63 μm), are moderately to well sorted, and exhibit spherical to subspherical, moderate to high sphericity morphological character. Aggregate grains consists of cemented ooids, peloids, and skeletal fragments and range between very coarse sand to medium sand size (750 μm to 250 μm), are poorly sorted, and exhibit a subangular to subrounded, moderate to low sphericity morphological character. Estimated visible porosity within this lithofacies is 3.0% (2.0% intraparticle porosity and 1.0% moldic porosity), with pores, primarily occurring within ooids and aggregate grains, being partially filled by organic matter (Figure 26C-D).
This lithofacies accounts for 2.2% (16.1 feet of 726.0 total linear feet of core) of all sediments within the Well A core, and was not observed within the Well B core. Analysis of conventional wire-line logs from Well A indicate that Lithofacies 6.2 is characterized by a very low gamma ray response, a low neutron-porosity response, a low density-porosity response, and very high, abruptly increasing, shallow, and deep, resistivity responses. High resistivity responses from conventional wire-line logs strongly agrees with an extremely high resistivity response on image logs (see Figure 41). Similar to Lithofacies 4.3, Lithofacies 6.2 is interpreted to have been initially deposited in a shallow-marine ramp crest to middle ramp depositional setting (i.e. beach barrier, tidal delta, shoal complexes) within fair-weather wave base (Flügel, 2004; Tucker and Wright, 1990). Within this setting, grains were likely subjected to alternating conditions of intermittent hydraulic energy regimes allowing for formation and cementation of ooids and aggregate grains, particularly during transgressive and highstand relative sea level conditions (Janson et al., 2007; French and Kerans, 2004; Pranter et al., 2004; Flügel, 2004; Tucker and Wright, 1990). Grains are interpreted to have been mobilized basinward during periods of high hydraulic energy (i.e. storm generated waves and spring tides) during highstand and early lowstand relative sea level conditions (Tucker and Wright, 1990; French and Kerans, 2004; Stoudt and Raines, 2004). This is supported by the occurrence of these deposits within the uppermost 50.0’ of the UBSL member, which is overlain by lowstand siliciclastics of the Brushy Canyon Formation. Furthermore, the association of these deposits with increased siliciclastics of Lithofacies 1.2 is interpreted to indicate a basinward shift in facies related to falling sea level position within the basin. Similar lithofacies have been recognized by Janson et al. (2007), Fitchen (1997), Ruppel and Ariza (2002), Ruppel et al. (2000), Stoudt and Raines (2004), French and Kerans (2004), and
Grain flow deposits are characterized by relatively thick individual deposits (0.3 to 0.6 meters thick) that are locally associated with slumps, but also occur as cyclically stacked deposits (0.3 to 0.9 meters thick). Grain flows exhibit massive to inversely graded internal depositional fabrics. Concentrations of solid grain components are typically in excess of greater than 25.0% but do not exceed 90.0% (~75.0% solid grain components for Lithofacies 6.2). Architectural attributes characterizing grain flow deposits observed within the two UBSL cores are illustrated in Figure 27. These architectural attributes include: 1) normal and inverse grading, 2) sharp upper and lower bedding contacts, 3) slight to non-erosive basal contacts with localized loadcasts, 4) localized chaotic grain orientation alternating with parallel oriented grains relative to bedding, and 5) localized intraclasts of composition similar to that of Lithofacies 1.1 and display an elongated geometry (less than 1.0 centimeter diameter) (Mulder and Alexander, 2001; Lowe, 1979, 1982; Cook and Mullins, 1983). These intraclasts were observed to occur only at the base of grain flow deposits.
Figure 27: Core photo and core traces illustrating diagnostic architectural elements observed for facies association #6 grain flow deposits. Size of schematic elements are exaggerated in order to emphasize key architectural and compositional features.

Sedimentation by grain flow processes is interpreted to have resulted from frictional “freezing”, caused by frictional shear forces (located at the base of the flow) surpassing downslope gravitational forces (Lowe, 1979). Frictional shear forces are the result of grain-to-grain collisions internal to the flow body (Lowe, 1979). These forces are interpreted to have been significantly greater within Lithofacies 6.2 relative to Lithofacies 6.1, due to higher-sediment concentrations of grains (greater than 75%)
and less than 5.0% micrite (Mulder and Alexander, 2001). This is interpreted to suggest that grains had not been completely lithified in the shallow-water environment prior to transport.

Possible mechanisms for initiation of grain flows from a shallow-water source terrain include mechanical degradation by storm generated waves and spring tides, tectonic activity, slumping, liquefaction, or remobilization of sediment from an overlying flow (Heimsund, 2007; Tucker and Wright, 1990). Although exact initiation mechanisms cannot be definitively determined, it is suggested that wave and tidal activity in the shallow water environment caused mechanical perturbation of shallow-water grains resulting in basinward expulsion of multiple grain flows (Tucker and Wright, 1990). This is supported by the occurrence of cyclically stacked grain flow deposits observed within the uppermost 50.0’ of core from Well A. Furthermore, hydroplaning of grain flows promotes increased transport distances over relatively shallow slope angles (less than 5° degrees) and is suggested as a process to explain the presence of basin-centered grain flows observed within this investigation (Mulder and Alexander, 2001; De Blasio and Elverhoi, 2011).

Overall, grain flow deposits account for 1.6% of all sediments within both cored wells (19.8 feet of 1226.0 total linear feet of core). Of the 19.8 cumulative feet of grain flow deposits, 19.6 feet (99.0%) occur within the Well A core and 0.2 feet (1.0%) occur within the Well B core. Grain flow deposits within the Well A core are mainly those dominated by shallow-water fauna and allochems (i.e. Lithofacies 6.2), and primarily occur at depth intervals 9213.5’ to 9215.5’ and 9235.0’ to 9253.0’. These depth intervals indicate that deposition of grain flows was limited to within the upper 75.0 feet of the UBSL member, with one isolated grain flow deposit overlying thick debris flow deposits. The occurrence of grain flow deposits at these depth
intervals is interpreted to correspond to periods of transgressive and highstand relative sea level conditions (Flügel, 2004; Tucker and Wright, 1990).

**Facies Association #7 – Debris Flow**

Facies association #7 includes those deposits which were transported into the basin, and/or re-worked and re-deposited by debris flow processes. One lithofacies has been grouped into this facies association:

1) **Lithofacies 7.1**

Lithofacies 7.1 is characterized as a dark gray to black, intraclastic, skeletal wackestone to packstone composed of skeletal-rich matrix and intraclasts. The term intraclast is used here to represent lithified sediment which have been eroded and transported from a nearby depositional setting from within the basin (Scholle and Ulmer-Scholle, 2003). Intraclasts are both matrix-supported and grain-supported, are greater than 30.0 centimeters to less than 5.0 millimeters in diameter, and exhibit very angular to subrounded and elongated geometries of moderate to low sphericity. Intraclast textures include: 1) mudstone to wackestone, 2) siltstone to shale, and 3) skeletal wackestone to packstone, with skeletal components being predominantly fusulinids and crinoids with lesser amounts of brachiopods, bryozoans, phylloid algae, ostrocods, planktonic foraminifera, sponge spicules, radiolarians, and undifferentiated skeletal grains. Matrix material consists of varying concentrations of micrite and fragmented skeletal grains, with lesser amounts of silt-sized detrital quartz grains. Intraclasts consisting of abundant skeletal material often exhibit localized burrows along their margins. Based on previous works by Wiggins and Harris (1985), Gawlowski (1987), and Saller et al. (1989), these intraclasts were lithified and biologically eroded from shelf margin and slope settings prior to being transported into
the basin.

This lithofacies accounts for 4.9% (36.1 feet of 726.0 total linear feet of core) within Well A core, and was not observed within Well B core. Analysis of conventional wire-line logs from Well A indicate that Lithofacies 7.1 is characterized by an extremely low gamma ray response, a low neutron-porosity response, a low density-porosity response, and moderate to high shallow, and deep, resistivity responses. All resistivity logs exhibit sharp increasing spikes near the basal portion of deposits, with a sharp turnaround (i.e. decrease), and gradual decrease in resistivity upwards. No visible porosity is present within this lithofacies.

This lithofacies is interpreted to have been initially deposited in an outer ramp, shelf margin, or upper slope depositional setting within storm wave base (Flügel, 2004). Fusulinid abundance in both matrix and intraclasts suggest maximum water depths of 10.0 to 30.0 meters (Fitchen, 1997). Similar lithofacies have been recognized by Wiggins and Harris (1985), Saller et al. (1989), Gawloski (1987), Janson et al. (2007), Fitchen (1997), Phelps et al. (2008), Mazzullo and Reid (1989), Ruppel et al. (2000), Ruppel and Ariza (2002), French and Kerans (2004), and Stoudt and Raines (2004).

**Facies Association #7 – Architectural Attributes, Bedding Geometry, and Stratigraphic Cyclicity**

Debris flow deposits are characterized as thick (2.0 to 4.0 meters thick), isolated units, typically overlain by slumps or cyclically stacked turbidites. These deposits exhibit massive, structureless internal depositional fabrics. Debris flow deposits exhibit two distinct depositional patterns (denoted as “Type #1” and “Type #2”) based on observed architectural attributes. “Type #1” debris flows exhibit large,
skeletal-rich intraclasts chaotically arranged within, and fully supported by, a mud-rich to skeletal-rich matrix (Figure 28A-B). “Type #2” debris flows exhibit significantly deformed, elongate (stringer-like) mud-rich and skeletal-rich intraclasts preferentially arranged within, and fully supported by, a skeletal-rich matrix (Figure 28C-D). Matrix material of “Type #1” and “Type #2” debris flow deposits are compositionally identical, with only minute variations in abundance of skeletal grains present occurring throughout a single debris flow deposit. Thus, division of debris flow deposits into multiple lithofacies was deemed unnecessary.
Figure 28: A) Core photo of “Type 1” debris flow deposit of Lithofacies 7.1. Notice skeletal-rich intraclasts (indicated by red arrows) within skeletal-rich matrix. B) Thin-section from core photo (A) showing Lithofacies 7.1 (skeletal wackestone to packstone) texture (skel wekst-pckst) of intraclasts (clasts) consisting of fusulinids (fus), foraminifera (foram), and crinoids (crin). C) Core photo of “Type 2” debris flow deposit of Lithofacies 7.1. Notice both skeletal-rich and mud-rich intraclasts preferentially aligned parallel across the core face. D) Thin-section from core photo (C) illustrating mudstone and skeletal wackestone-packstone intraclasts (clasts) supported by a skeletal-rich matrix (skel pckst) dominated by brachiopods (brach), crinoids (crin), and fusulinids (fus).
Architectural attributes characterizing debris flows observed within the two UBSL cores are illustrated in Figures 29-30. These architectural attributes include: 1) chaotic, unstratified grains and intraclasts, 2) sharp, slightly to non-erosive upper and lower bedding contacts, 3) intraclasts of variable size (greater than 30.0 centimeters to less than 5.0 millimeters in diameter) and geometry (very angular to subrounded and elongate stringer-like in shape) completely and partially supported by non-cohesive matrix material, 4) variable intraclasts composition (mudstone to spiculitic wackestone, siltstone to carbonaceous shale, and skeletal wackestone to packstone), 5) protrusion of intraclasts into underlying and overlying layers, 6) normal and inverse grading locally present, and 7) sutured and fractured intraclasts contact boundaries (Mulder and Alexander, 2001; Lowe, 1979, 1982; Cook and Mullins, 1983). These architectural attributes are interpreted to indicate sedimentation by a slightly cohesive to non-cohesive debris flow originating from shelf margin and upper slope settings (Mulder and Alexander, 2001; Lowe, 1979, 1982). The low clay content within mudstone to skeletal wackestone-packstone matrices are interpreted to indicate that intraclasts were not fully supported by cohesive matrix strength (Mulder and Alexander, 2001). Intraclasts were likely supported by buoyancy, dispersive pressure from intraclasts collisions, and escaping pore fluids (Mulder and Alexander, 2001; Lowe, 1979, 1982).
Figure 29: Core photo and core traces illustrating diagnostic architectural elements observed for Lithofacies 7.1 “Type 1” debris flow deposits. Size of schematic elements are exaggerated in order to emphasize key architectural and compositional features.
Debris flows are interpreted to have accumulated on the basin floor by frictional “freezing”, which may also have contributed to intraclast deformation (Mulder and Alexander, 2001). Long transport distance of these deposits from a shelf margin source terrain (19.0 to 20.0 miles (30.5 to 32.0 kilometers) east to northeast of
Well A is likely due to hydroplaning, reducing frictional shear forces that would have been present at the base of the flow body (Mulder and Alexander, 2001; De Blasio and Elverhoi, 2011). Turbidites and slump deposits are often associated with these debris flow deposits, interpreted to indicate a genetic relationship between them.

Overall, debris flow deposits account for 2.9% of all sediments within both cored wells (36.1 feet of 1226.0 total linear feet of core). Of the 36.1 cumulative feet of debris flow deposits, all 36.1 feet (100.0%) occur within the Well A core. Debris flow deposits in Well A are dominated by shallow-water fauna (fusulinids and crinoids) and intraclasts, and occur at depth intervals 10046.4’ to 10047.5’, 10075.0’ to 10077.0’, 9626.5’ to 9686.5’. These depth intervals indicate debris flow deposition predominantly occurred within the lower half of the UBSL member (see Figure 46).

Image Log Analysis and Comparison to Rock Data

Facies Association #1 – Pelagic and Hemipelagic Suspension Settling

Lithofacies resulting from pelagic and hemipelagic suspension settling were difficult to discern from one another on image logs (Figure 31). This is interpreted to be a result of both lithofacies: 1) containing sub-centimeter scale laminations, 2) exhibiting gradational lithofacies shifts from one another, 3) consisting of high concentrations of quartz and organic material, and 4) exhibiting massive to slightly planar laminated depositional fabrics. As a result, both facies appear similar on image logs.
Figure 31: Correlation of core and image log intervals for facies association #1 pelagic and hemipelagic suspension sediments. Figures (A) and (C) illustrate Lithofacies 1.1 and 1.2 represented in core and dynamic FMI image logs, from Well A. Figures (B) and (D) illustrate Lithofacies 1.1 and 1.2 represented in core and XRMI image logs from Well B. A) Green arrows indicate planar-laminated, moderate to high resistivity, mudstone to spiculitic wackestone facies. Blue arrows indicate high resistivity chert concretions commonly associated with these deposits. B) Green arrows indicating massive, moderate resistivity, mudstone to spiculitic wackestone facies. Blue arrows represent alternating moderate, and high resistivity, mudstone and spiculitic wackestone deposits. Increased skeletal content within spiculitic wackestones yields increased resistivity responses. C) Green arrows showing high resistivity chert concretion and slightly deformed, moderate resistivity bedding around concretion margins. Blue arrows show planar-laminated, moderate resistivity, siltstone to carbonaceous shale deposits. D) Green arrows (siltstone to carbonaceous shale) and blue arrows (mudstone to spiculitic wackestone) indicate similar planar-laminated, low to moderate resistivity responses.

Architectural attributes resolved during image log analysis for pelagic and hemipelagic suspension deposits (Figure 31) include: 1) massive to planar laminated depositional fabrics represented by a low to moderately resistive pattern, 2) highly resistive planar laminations greater than 2.0 to 5.0 centimeters thick, indicating increased concentrations of sponge spicules and radiolarians, and thus, high concentrations of biogenic silica (i.e. quartz and chert), 3) chert nodules represented as highly resistive features, and 4) deformed bedding of low to moderate resistivity around high resistivity chert nodules.

Pelagic and hemipelagic suspension sediments often exhibit resistivity patterns that are similar to bioturbated suspension sediments, as well as thin-bedded (centimeter scale) turbidites and liquified flow deposits (see Figure 43E). This is due to localized preservation of original planar laminated fabric within bioturbated deposits, and centimeter scale turbidites and liquified flow deposits resembling centimeter thick high resistivity planar laminations of pelagic and hemipelagic
suspension sediments.

Pelagic and hemipelagic suspension sediments are easily identified when separating highly resistive deposits such as slumps, debris flows (see Figure 42A), and ooid-rich turbidites and grain flows (see Figure 41), due to highly contrasting resistivity responses relative to moderate to low resistivity suspension sediments. Furthermore, suspension sediments may be readily discerned from cyclically stacked turbidites (see Figure 34) and liquefied flow deposits (see Figure 38). Cyclical stacking of these deposits results in cyclical, high resistivity responses at a centimeter scale, which is a characteristic image log response for turbidites and liquefied flow deposits.

Pelagic and hemipelagic suspension deposits are interpreted to have a poor to moderate correlation potential primarily due to highly gradational, low to moderate resistivity responses, and the presence of highly resistive planar laminations. These features may be easily mistaken for bioturbated sediments or thin-bedded turbidites and liquefied flow deposits if not properly calibrated with core.

Facies Association #2 – Bioturbation of Pelagic and Hemipelagic Suspension Sediment

Architectural attributes resolved during image log analysis for bioturbated pelagic and hemipelagic suspension deposits (Figure 32) include: 1) massive to slightly laminated deposits represented by a moderate to low resistive pattern, of which exhibits a highly mottled texture, 2) thin intervals (0.3 to 0.9 meters thick) of highly resistive discontinuous planar laminations, indicating localized preservation of original, depositional fabric, and 3) high resistivity chert nodules (when present).
As discussed above, localized preservation of planar laminations within these deposits yields similar resistivity responses as pelagic and hemipelagic suspension sediments, as well as, centimeter scale turbidites and liquified flow deposits (see Figure 43E). As a result, it is suggested that these deposits may only be interpreted with a high degree of confidence when greater than 3.0 meters thick, or when separated by an abrupt depositional boundary. Based on core and image log analysis, when these deposits exceed a thickness of 3.0 meters, they are easily discerned from other facies association deposits due to the overall mottled texture on image logs, which is a characteristic pattern associated with these deposits.

Bioturbated pelagic and hemipelagic suspension sediments are interpreted to have a poor to moderate correlation potential primarily due to the high degree of similarity between non-bioturbated pelagic and hemipelagic suspension sediments, of which exhibit nearly identical low to moderate resistivity responses when original depositional fabric is preserved.

**Facies Association #3 – Slump**

Architectural attributes resolved during image log analysis for slump deposits (Figure 33) include: 1) sharp, high resistivity, erosive basal shear surface overlying
slight to undeformed mudstone to wackestone strata of low to moderate resistivity, 2) deformation of bedding (foliated bedding) above basal shear surface represented by deformed layers of alternating high, and low, resistivity, 3) increasing deformation of bedding near central portions of deposit represented by significant folding and deformation of high and low resistivity bedding layers, 4) alternating high and low resistivity beds exhibit centimeter scale folds (asymmetric, recumbent and recumbent isoclinal) and faults (listric), 5) plastic deformation of high resistivity intraclasts (when present) preferentially aligned parallel to deformed bedding layers, and 6) decreasing deformation of bedding upward with gradational upper bedding contacts relative to overlying low resistivity suspension sediments or high resistivity turbidites.
Figure 33: Figures (A) and (B) illustrate observed facies association #3 slump deposits (i.e. Lithofacies 3.1) from Well A, and Well B. A) Red arrows illustrate sharp, non-erosive base of slump deposit. High-resistivity patterns of slump deposits are easily discerned from moderately resistive laminated mudstones due to increased skeletal content, as well as, increased bedding deformation resulting in high resistivity contrasts. Blue arrows show internal plastic deformation and folding of bedding (moderately resistive mudstones and highly resistive skeletal wackestones). Green arrows illustrate highly resistive, plastically deformed, intraclasts supported within a skeletal wackestone matrix. Purple arrows indicate sharp, non-erosive upper bedding contacts. B) Blue arrows indicate a sharp, non-erosive, plastically deformed basal contact with underlying moderate to low resistivity mudstones. As indicated above, these mudstones are easily differentiated from overlying high-resistivity spiculitic wackestone to skeletal wackestone slump deposits.

Slump deposits are easily differentiated from all other turbidites and MTDs due to characteristic architectural features (see Figure 43F). Image log analysis of slump deposits allow for clear identification of all architectural features observed in core, as well as lithology contrasts between bedding layers (not able to discern exact lithology, but able to differentiate between mud-rich/low resistivity and skeletal-rich/high resistivity sediments).

Slump deposits are interpreted to have a high correlation potential. This is attributed to the high degree of correlation of architectural attributes observed in core and in image logs. It is interpreted that diagnostic features of slump deposits, if known, can easily be resolved from image logs alone in nearby wells without the use of rock data.

Facies Association #4 – Turbidity Current

Lithofacies 4.1, 4.2, and 4.4 (i.e. argillaceous mudstone to spiculitic wackestone, siltstone to carbonaceous shale, and skeletal wackestone to mud-rich
packstone) resulting from turbidity current deposition are difficult to discern from one another on image logs (Figure 34; Figure 35; Figure 37). This is interpreted to be a result of: 1) high to moderate resistivity response exhibited by each lithofacies indicating increased concentrations of carbonate (calcite and dolomite) and silica (quartz and chert) cement, and 2) similar architectural attributes exhibited by each lithofacies deposit. As a result, each facies appears similar on image logs. As mentioned above, Lithofacies 4.3, of which is dominated by ooids and aggregate grains, is easily differentiated from other turbidity current lithofacies due to an extremely high resistivity response (Figure 36). This resistivity response is attributed to high concentrations of limestone and carbonate cement (calcite and dolomite), which are observed to completely, or partially, replace ooids and aggregate grains.

Architectural attributes resolved during image log analysis for turbidity current deposits (Figures 34-37) include: 1) normal grading of Bouma sequences represented by a gradational resistivity response from high resistivity (at base) to low resistivity (at top), 2) high resistivity sharp basal bedding contact relative to underlying mudstones and siltstones of low to moderate resistivity, 3) gradational upper bedding contact represented by gradual decrease in resistivity, 4) high to moderate resistivity planar laminations, 5) high to moderate resistivity angled bedding and fluidal deformation of bedding layers at gradational upper bedding contact, 6) cyclically stacked turbidites represented as cyclically stacked high resistivity beds of centimeter thickness, and 7) individual Bouma sequences. Bouma sequences are difficult to resolve in most turbidity current deposits, and were only locally identified in Lithofacies 4.2 turbidites, interpreted to be due to greater reductions in resistivity, from base of deposit to top, as skeletal debris grades upward (Figure 35).
Figure 34: Figures (A) and (B) illustrate Lithofacies 4.1 (mudstone to wackestone) turbidites observed from Well A, and Well B. A) Red arrows indicating highly resistive, cyclically stacked turbidites separated by thin layers (5.0 – 10.0 centimeter thick) of moderately resistive laminated mudstone deposits. Note that turbidites less than one to two inches thick in core are very difficult to resolve in image logs. Blue arrows illustrate upward decreasing resistivity of cyclically stacked turbidites, likely due to decreasing skeletal content, or increasing mud content. Also, note that finning upward turbidites display a slight increase in fluidal deformation, as indicated by fluid escape structures. B) Overall, clear resolution of highly resistive, cyclically stacked turbidite deposits (green arrows) separated by moderate to low resistivity laminated mudstones (blue arrows).
Figure 35: Figures (A) and (B) represent Lithofacies 4.2 (skeletal wackestone to mud-rich packstone) turbidites as observed in core from Well A, and Well B. A) Complete Bouma cycle easily identified in both core, and image logs. “Tc” Bouma sequence is difficult to distinguish in core, but is clearly resolved in image logs by high to low resistivity ripple-laminated bedding. Blue arrows indicate sharp, erosive base with loadcast structures. This sharp bed boundary is represented on image logs by an abrupt change in resistivity between moderate to low resistivity mudstones underlying a highly resistive skeletal-rich turbidite. B) Similar to (A), complete Bouma sequence is able to be identified in both core, and image logs.
Figure 36: Core to image log correlation of Lithofacies 4.3 (oolitic-skeletal wackestone to packstone) turbidite deposits as observed in Well A. Black arrows indicate individual turbidite deposits characterized by an extremely high resistivity pattern. These turbidites are separated by moderate to low resistivity mudstones, of which allow for distinguishing individual turbidites. This extremely high resistivity response enhances the difficulty in identifying internal architectural attributes, however, this response is characteristic of ooid-dominated turbidites, allowing for these deposits to be easily distinguished from all other turbidite lithofacies.
Figure 37: Figures (A) and (B) represent Lithofacies 4.4 (siltstone to carbonaceous shale) turbidites as observed from Well A, and Well B. A) Black arrows indicate normal grading (i.e. grading from high resistivity base to moderate resistivity top) of individual turbidites that are separated by moderate resistivity mudstones. Although slight variations in resistivity response exists between the four turbidite lithofacies, all show similar patterns of highly resistive bases that gradually decrease in resistivity upward. This grading is interpreted to be due to normal grading of Bouma sequences. Blue arrows indicate slight tilting of turbidite layer, possibly indicating the erosive nature of turbidity currents during downslope sediment transport. B) Black arrows, similar to those in (A), indicate normal grading (high to moderate resistivity response) of individual turbidites separated by moderate resistivity laminated mudstones. Note, dynamic XRMI image log significantly enhances image resolution relative to static XRMI image log, allowing for architectural attributes to be resolved with less difficulty.

As previously discussed (see image log analysis of suspension sediments and bioturbated suspension sediments above), centimeter scale turbidites are difficult to differentiate from pelagic and hemipelagic suspension sediments and bioturbated suspension sediments due to similar, high resistivity planar laminated responses on image logs (Figure 43A-E).

Turbidites are easily identified, and differentiated from, most facies association deposits when cyclically stacked (Figure 34; Figure 36; Figure 37). These deposits exhibit a cyclically stacked resistivity pattern of highly resistive bases grading to moderate to low resistivity tops. This style of deposition is also illustrated by repetitive, small amplitude, decreasing spikes in gamma ray response (Figure 53). Recognition of this stacking pattern is enhanced when turbidites are separated by low resistivity, mudstones to spiculitic wackestones.

Turbidites are interpreted to have a moderate correlation potential. These deposits may be easily identified when occurring as cyclically stacked deposits, which is characteristic of most turbidite units observed from the two UBSL cores.
Facies Association #5 – Turbidity Current and/or Liquified Flow

Lithofacies 5.1 and 5.2 (i.e. argillaceous mudstone to spiculitic wackestone and skeletal wackestone to mud-rich packstone) resulting from turbidity current and/or liquified flow deposition are difficult to discern from one another on image logs (Figures 38-39). Similar to the turbidite lithofacies, this is interpreted to be a result of: 1) high to moderate resistivity response exhibited by each lithofacies indicating increased concentrations of carbonate (calcite and dolomite) and silica (quartz and chert) cement, 2) and similar architectural attributes exhibited by each lithofacies deposit. As a result, each lithofacies appear similar on image logs.

Architectural attributes resolved during image log analysis for turbidity current and/or liquified flow deposits (Figures 38-39) include: 1) massive to slightly graded (normal and inverse grading) bedding represented by a high resistivity base which gradually transitions to a moderate resistivity top (normal grading) or from moderate resistivity base to high resistivity top (inverse grading), 2) sharp, upper and lower bedding contacts relative to adjacent low resistivity mudstones to siltstones, 3) fluidal deformation of discontinuous bedding layers, 4) gravel-sized basal loadcasts represented as low resistivity intraclasts within high resistivity matrix at the base of the deposit, and 5) partial Bouma sequences (locally present).
Figure 38: Figures (A) and (B) represent Lithofacies 5.1 (mudstone to wackestone) turbidites/liquified flow deposits as observed in core from Well A, and Well B. A) Red arrows indicate erosive basal contacts, interpreted to indicate high flow velocities during sediment transport, sediment support by fluidal turbulence, and/or greater flow duration (i.e. long transport distances), all of which are conducive of both turbidity currents and liquefied flow sedimentation processes. Blue arrows show fluid-escape structures at the top of deposits as a result of escaping pore fluids. These structures indicate partial grain support from escaping pore fluids, as well as, fluidal turbulence as the dominant sediment support mechanisms. Black arrows illustrate normal grading (i.e. Bouma sequence T_a) of lower half of deposit overlain by horizontal laminations (i.e. Bouma sequence T_b) for upper half of deposit. These architectural attributes are indicative of turbidity current deposition. Green arrows show basal load structures, indicating the erosive nature of transported sediment. B) Similar to figure (A), red arrows illustrate erosive basal contacts and black arrows indicate normal grading of Bouma sequence T_a. Green arrows indicate gravel-sized mudstone intraclasts located at the base of a deposit, indicating deposition by liquefied flow because turbidity currents do not have the competency to transport such coarse-grain material.
Figure 39: Figures (A) and (B) represent Lithofacies 5.2 (skeletal wackestone to mud-rich packstone) turbidites/liquified flow deposits as observed in core from Well A, and Well B.  A) Green arrows indicate sharp, slightly-erosive basal contacts which separate moderate to high resistivity turbidite and/or liquified flow deposit from underlying low resistivity mudstones.  Blue arrows show fluid-escape structures, indicating deposition by either turbidity currents or liquified flows.  B) Blue arrows show sharp, slight-to-non-erosive basal contacts.  Black arrows indicate normal grading (high to low resistivity response), followed by inverse grading (low to high resistivity response), interpreted to indicate sedimentation by liquified flow rather than turbidity current, however, Mulder and Alexander (2001) suggest alternating, normal, and inverse grading, to be characteristic of quasi-steady turbidity current sedimentation.

Centimeter scale architectural attributes identified during core analysis, which allowed for differentiating facies association #5 deposits from those of facies association #4 turbidites, were only locally resolved from image log analysis. These features include gravel-sized loadcasts located at the base of deposits (Figure 38B) and inverse grading (Figure 39B). Thus, differentiating facies association #5 deposits from facies association #4 turbidites was met with a high degree of difficulty.

Turbidites and/or liquefied flow deposits are interpreted to have a moderate correlation potential. Similar to turbidites, these deposits may be easily identified, and differentiated from other sedimentation processes, when occurring as cyclically stacked units. It is suggested that, without direct comparison to core, interpreting transitional sedimentation processes, such as these, for deposits at a centimeter scale from image logs alone is not likely.

Facies Association #6 – Grain Flow

Grain flow lithofacies (skeletal wackestone to mud-rich packstone and oolitic wackestone to packstone) are easily differentiated from one another due to high contrasts in resistivity response, as well as key differences in architectural attributes.
exhibited by each (Figures 40-41).

Figure 40: Core to image log correlation of Lithofacies 6.1 (skeletal wackestone to packstone) grain flow deposit from Well A. Green arrows indicate a sharp, moderately erosive and slightly deformed lower bedding contact separating the overlying grain flow deposit from underlying low resistivity mudstones. Blue arrows illustrate a massive, high resistivity depositional fabric indicative of grain flow sedimentation. Black and red arrows show moderately resistive siltstone intraclasts, and low resistivity mudstone intraclasts within highly resistive skeletal matrix material.
Figure 41: Core to image log correlation of cyclically stacked Lithofacies 6.2 (oolitic wackestone to packstone) grain flow deposits from Well A. Red and blue arrows illustrate low resistivity (high conductivity), laminated mudstone intervals separating extremely high resistivity grain flow deposits. Notice four separate black arrows in core and image log photos correspond to four separate grain flow deposits. These four grain flows are only able to be resolved on image logs because they are separated by low resistivity mudstone layers. The extremely high resistivity response of these deposits is characteristic of an ooid-dominated composition, similar to that of observed ooid-rich turbidites. A negative aspect of this high resistivity response is the fact that no internal architectural elements can be clearly defined, which enhances the difficulty in trying to discern between ooid-dominated grain flows and ooid-dominated turbidites in image logs.
Lithofacies 6.1 (skeletal wackestone to mud-rich packstone) is represented by a moderate to high resistivity response with localized, low resistivity mudstone intraclasts present at the base of grain flow deposits. Local grading is slightly visible, with gradational resistivity shifts from high to low (normal grading), or low to high (inverse grading). Lithofacies 6.1 also has clearly visible upper and lower bedding contacts which have a high resistivity contrast with low resistivity mudstones (Figure 40), making interpretations of upper and lower deposit boundaries easy to identify.

Lithofacies 6.2 (oolitic wackestone to packstone) is represented by an extremely high resistivity response, appearing massive on image logs. Due to this high resistivity response, internal architectural attributes were not able to be resolved. Cyclically stacked grain flows of Lithofacies 6.2 were only able to be identified when separated by low resistivity mudstones (Figure 41; Figure 43A). Although no internal architectural features were able to be resolved, this high resistivity response is interpreted to be characteristic of ooid-dominated grain flow deposits, and thus, a characteristic feature in their identification.

Architectural attributes resolved during image log analysis for grain flow deposits (Figures 40-41) include: 1) massive to slight inverse graded bedding represented by increasing upward resistivity response, 2) sharp, slightly erosive upper and lower bedding contacts relative to adjacent low resistivity mudstones, 3) local, low resistivity mudstone intraclasts present at basal portion of deposits (limited to Lithofacies 6.1), and 4) moderate to high resistivity deformed bedding (limited to Lithofacies 6.1).

Grain flows are able to be clearly identified from image logs when correlating architectural and lithological features observed directly in core, suggesting that these deposits have a high correlation potential. This is due to characteristic architectural
attributes clearly identified in core, and image log, as well as the extremely high resistivity response of ooid-dominated grain flow deposits.

**Facies Association #7 – Debris Flow**

Image log analysis of debris flow deposits indicates that two distinct depositional patterns (“Type #1” and “Type #2” debris flow deposits as observed from core analysis) are present, and the architectural attributes associated with each clearly identifiable.

“Type #1” architectural attributes resolved during image log analysis (Figure 42A-42C) include: 1) moderate to high resistivity matrix, 2) high resistivity intraclasts chaotically arranged within, and fully supported by, moderate to high resistivity matrix, 3) sharp, slightly erosive upper and lower bedding contacts, 4) high resistivity intraclasts protruding into underlying low resistivity mudstones, 5) slight deformation of low to moderate resistivity bedding and high resistivity intraclasts, and 6) locally present low resistivity mudstone intraclasts. Variations in matrix resistivity is attributed to variations in skeletal material present as observed in core.
Figure 42: Figures (A), (B) and (C) illustrate Lithofacies 7.1 “Type 1” debris flows, and Figure (D) illustrates Lithofacies 7.1 “Type 2” debris flows as observed in core from Well A. A) Red arrows indicate sharp, erosive basal contacts with intraclasts protruding into underlying, low resistivity, mudstone deposits. Green and purple arrows illustrate skeletal-rich wackestone to packstone intraclasts of variable size and composition, which are chaotically arranged within, and fully-supported by, a moderate to high resistivity skeletal-rich matrix (skeletal-rich matrix indicated by blue arrows). Intraclasts exhibit no sharp boundaries (i.e. subrounded geometry), suggesting that they were transported over relatively long distance from a shallow-water origin (outer ramp to upper-middle slope). This interpretation is also supported by the presence of abundant shallow-water fauna. B) Blue arrows indicate the sharp upper bedding contact of a debris flow deposit that is overlain by highly resistive, cyclically stacked turbidite deposits, interpreted to indicate a genetic relationship between the two (i.e. cyclically stacked turbidites likely initiated by debris flow). C) Green arrows represent highly to moderately resistive, cyclically stacked turbidites that underlie debris flow deposits, interpreted to suggest a genetic relationship exists between the two. Blue arrows indicate sharp, erosive basal contacts with skeletal-rich intraclasts protruding into underlying low resistivity mudstones. Black arrows show skeletal-rich wackestone to packstone intraclasts of variable size and composition, chaotically arranged within, and fully-supported by, a moderate to high resistivity skeletal-rich matrix (skeletal-rich matrix indicated by red arrows). Yellow arrows represent significantly deformed mudstone intraclasts represented by a low resistivity pattern. Purple arrows (in figures (C) and (D)) indicate 30.5 centimeter thick, horizontally laminated mudstone intervals of low resistivity, separating two distinct debris flow deposits. During core analysis, these mudstones were interpreted to represent mudstone intraclasts within a single debris flow deposit. D) Green arrows represent moderately resistive siltstone to carbonaceous shale intraclasts. Blue arrows show skeletal-rich matrix consisting of abundant shallow-water skeletal material. Black arrows represent low resistivity, elongate mudstone intraclasts. Yellow arrows represent high resistivity, elongate skeletal wackestone-packstone intraclasts. These intraclasts appear to be significantly deformed and preferentially oriented within a skeletal-rich matrix. Significant deformation of mudstone and skeletal wackestone-packstone intraclasts is interpreted to suggest that this material was still soft when incorporated within the debris flow.
“Type #2” architectural attributes resolved during image log analysis (Figure 42D) include: 1) moderate to high resistivity matrix, 2) intraclasts of variable lithology and shape, preferentially aligned within, and fully supported by, moderate to high resistivity matrix, 3) fractured and deformed intraclasts, and 4) sharp, slightly erosive upper and lower bedding contacts.

“Type #1” and “Type #2” debris flow deposits are easily differentiated from each other, as well as from all other turbidites and MTDs due to characteristic architectural features. Image log analysis of debris flow deposits allow for clear identification of all depositional features observed in core, as well as lithologic contrasts between intraclasts and matrix (not able to discern exact lithology, but able to differentiate between mud-rich (low resistivity) and skeletal-rich (high resistivity) sediments) (Figure 43D).

Debris flow deposits, similar to slumps, are interpreted to have a high correlation potential. This is attributed to the high degree of correlation between architectural attributes and contrasting lithologies resolved from both core, and image log analysis. Diagnostic features of debris flow deposits, if known, are likely to be resolved from image logs alone in nearby wells when rock data is unavailable.
Figure 43: Core and image log comparisons illustrating: 1) characteristic sedimentation patterns that aid in discerning between different sedimentation processes, and 2) the similarity between one or more sedimentation processes in image logs. Represented in each figure above (A-F) are: facies associations (far left), lithofacies (middle), and image log (far right) as observed during core analysis.

Sediment Source Terrain from Dipmeter Data

Interpretation of paleo-transport directions for turbidites and MTDs identified from the two cored wells is based upon the analysis of automated strike and dip measurements of sedimentary features, and bedding planes, picked during image log processing. Dip values are derived from resistivity measurements recorded from each tool arm, with azimuth values derived from resistivity measurements recorded from a single tool arm (Pad 1 Azimuth, Figure 44), which is geographically referenced to magnetic north within the borehole.
Figure 44: XRMI image log for Well B. This figure illustrates dip and azimuth measurements displayed as “tadpoles” that were used for interpreting turbidite and MTD paleo-transport directions and approximate source terrains.

Dip and azimuth measurements are plotted as “tadpoles” within a separate track, recording depth on the vertical axis, and dip (0° at far left to 90° at the far right) on the horizontal axis. Tadpole “heads” (i.e. circles) are positioned vertically at depth locations where resistivity measurements are recorded, and horizontally on the dip axis based upon calculated dip of the resistive feature. As a quality-check, color-filled tadpoles indicate high confidence measurements, and hollow tadpoles indicate measurements of lesser confidence. Tadpole “tails” (i.e. sticks) are oriented relative to the azimuth of calculated dip, located between 0° to 360° (relative to magnetic north)
around the tadpole “head”, always pointing in a down-dip direction. Thus, it is inferred that down-dip azimuth directions indicate paleo-transport direction for turbidites and MTDs. Conversely, opposite of this down-dip direction is inferred to indicate direction of approximate sediment source regions.

Frequency plots (i.e. rose diagrams), spaced at 3.0 meter intervals, record the total number of calculated azimuth directions within each interval. Similar to tadpole “tails”, triangles point in the calculated azimuth direction. As frequency of a particular azimuth direction increases, triangles expand farther outward from a central point. These plots provide a “quick look” method for determining main azimuth directions within each 3.0 meter interval.

Analysis of automated dip values from the two cored wells indicate that sedimentary features and bedding planes recorded within pelagic and hemipelagic suspension sediments have a maximum dip angle of 1.0°. Consistency of this dip magnitude at both well locations is interpreted to indicate that these values represent structural dip.

Azimuth directions were analyzed for only those measurements that corresponded to observed turbidites and MTDs. In Well A, turbidites and MTDs exhibit little variation in paleo-transport direction, predominantly being to the south, southwest, west, and northwest. This is interpreted to indicate that turbidites and MTDs were primarily sourced from the north, northeast, east, and southeast (Figure 45).
Figure 45: Regional 3D structure map for the base of the UBSL member within the Delaware Basin. Location of wells utilized in this investigation are marked on the map by green and red circles. Approximate regions and directions of turbidite and MTD sediment source (green and red shaded regions) are displayed on top of the 3D structure map. Map limits mark the maximum shelfal extent of the UBSL member within the Delaware Basin.

At Well B, turbidites and MTDs exhibited greater variation in paleo-transport direction than within Well A. Azimuth values indicate paleo-transport directions were to the south, southeast, east, northeast, and north, interpreted to indicate that turbidites and MTDs were sourced from the south, southwest, west, northwest, and north (Figure 45).

Dipmeter analysis from image logs are interpreted to indicate that: 1) Well A sediments were predominantly sourced from the Central Basin Platform with minor input originating from the Northern Delaware Basin margin, and 2) Well B sediments were sourced from a broad region, predominantly originating from the southwest, west, northwest, and north Delaware Basin margins. This difference in approximate sediment source regions is interpreted to be attributed to differences in foreslope morphology for the eastern, northern and western Delaware basin margins. Regional depth profiles, for the base of the UBSL member, were created as a means of approximating slope angles, and detailing variations in slope angle across the western, northern, and eastern Delaware Basin margins. These depth profiles indicate that along the western basin margin, foreslopes are characterized as low angle (2.0° to 4.0°) ramps, where facies shifts are expected to be laterally extensive during changes in relative sea level (Read, 1985; Tucker and Wright, 1990). This means that a larger region is affected by relative sea level fluctuations, causing sediments to be transported into the basin over a much greater area (Read, 1985). Conversely, along the eastern
basin margin, foreslopes are characterized by higher angle (3.0° to 6.0°), distally-steepened ramps to rimmed-platforms, where channelization of deposits through reentrants may cause strike-parallel facies shifts and an increase in turbidite and MTD sedimentation further basinward (Read, 1985; Playton and Kerans, 2006).

DISCUSSION

Facies Associations

Core and thin-section analysis allowed for the identification of seven facies associations comprising the UBSL member within a distal basin-centered depositional setting:

1) pelagic and hemipelagic suspension settling
2) bioturbation of pelagic and hemipelagic suspension sediments
3) slump
4) turbidity current
5) turbidity current and/or liquified flow
6) grain flow
7) debris flow

Pelagic and hemipelagic suspension deposits (i.e. mudstone to wackestone, and siltstone to carbonaceous shale lithofacies) are the most abundant within the two cored intervals and represent a deep-water slope and basin floor depositional setting, accumulating during transgressive and highstand relative sea level conditions. These deposits are interpreted have been secondarily re-worked by burrowing organisms and/or transported and redeposited further basinward by slump, turbidity current and liquified flow sedimentation processes.
Turbidity current (Lithofacies 4.2), turbidity current and/or liquified flow (Lithofacies 5.2), grain flow (Lithofacies 6.1), and debris flow (Lithofacies 7.1) deposits are dominated by shallow-water fauna, namely fusulinids and crinoids, indicative of being derived from a shallow-water outer ramp to shelf margin depositional setting, accumulating in the basin during highstand and early lowstand relative sea level conditions.

Turbidity current (Lithofacies 4.3) and grain flow (Lithofacies 6.2) deposits consist mainly of ooids and aggregate grains, indicative of being derived from a shallow-water ramp crest to outer ramp/shelf margin depositional setting, accumulating in the basin during highstand and early lowstand relative sea level conditions.

Deposits resulting from facies association #3-#7 sedimentation processes exhibit consistent gamma ray and resistivity log responses. These log responses are indicated by sharp decreases in gamma ray (often with GR less than 75 API) and sharp increases in shallow, and deep, resistivity. These conventional log responses are interpreted to be indicative of decreasing shale content, or conversely, and increase in limestone content attributed to an increase in skeletal material relative to mud-dominated suspension deposits (Asquith and Krygowski, 2004). Sharp increases in resistivity on conventional wire-line logs is supplemented by high resistivity response exhibited by image logs (discussed below).

Image Log Analysis and Comparison to Rock Data

Direct correlation of cores to image logs revealed that most turbidites and MTDs identified during core analysis were able to be successfully identified directly from image logs, albeit with different levels of confidence.
Image logs were not always able to successfully resolve architectural, or lithologic features at the millimeter scale and were only locally able to resolve these features at the centimeter scale. This is interpreted to be due to minor contrasts in lithology between multiple facies association deposits, in addition to, deposits of multiple facies associations exhibiting similar architectural attributes at relatively identical depositional scales (centimeter scale). The latter is particularly true for pelagic and hemipelagic suspension sediments, bioturbated suspension sediments, and thin-bedded turbidites and turbidites and/or liquefied flow deposits (i.e. facies associations #1, #2, #4 and #5). Cases when resolution of centimeter scale attributes was conducted with minimal difficulty include: 1) for highly contrasting lithologies (oolitic wackestone to packstone and argillaceous mudstone), 2) for intraclasts and matrix, 3) for cyclically stacked turbidites; and 4) for slump and debris flow deposits exhibiting significant internal deformation resulting in highly contrasting resistivity patterns.

Facies association #3 and #7 deposits (i.e. slumps and debris flows) were the only types of sedimentation processes identified from core analysis where all architectural and lithologic features were able to be resolved by image logs, allowing for these deposits to be easily differentiated from all other facies associations (i.e. sedimentation processes). This is interpreted to be due to these deposits exhibiting a high degree of internal deformation and lithologic heterogeneity, resulting in highly contrasting resistivity patterns on image logs. These observations suggest that the degree of deformation exhibited by MTDs controls how well a deposit is able to be identified on image logs.

Only those lithofacies dominated by ooids and aggregate grains (Lithofacies 4.3 and 6.2) and skeletal intraclasts (Lithofacies 7.1) were able to be easily discerned
from all other lithofacies during image log analysis. Lithofacies 4.3 and 6.2 exhibit extremely high resistivity responses as a result of high concentrations of limestone and carbonate cement (calcite and dolomite). Intraclasts within Lithofacies 7.1 (i.e. debris flow deposits) exhibit highly contrasting resistivity responses relative to matrix material (low resistivity mud-rich intraclasts and/or high resistivity skeletal-rich intraclasts) within an individual deposit, significantly enhancing identification of centimeter scale variations in depositional features in image logs. Furthermore, at two separate locations, image logs were able to distinguish two distinct debris flows separated by thin (less than 0.15 meter thick), horizontally oriented, mudstone layers, which had been previously interpreted to be single debris flow deposits during core analysis (mudstone layers were interpreted to be large intraclasts) (Figure 42C-D).

Gamma ray, as well as shallow and deep resistivity logs significantly enhanced recognition of turbidites and MTDs observed during core and image log analysis. Gamma ray response for these deposits typically exhibits a sharp decrease when these deposits are encountered, interpreted to indicate an increase in limestone and/or decrease in shale content (Asquith and Krygowski, 2004). Resistivity logs often exhibited a sharp increase when encountered, which directly corresponds with moderate to high resistivity responses on image logs.

Core photographs and corresponding image log intervals utilized during this investigation can be found in Appendix (B). Figure 46 illustrates a two-well cross-section for the cored well utilized in this investigation with all core, conventional wire-line log, and image log data shown for the entire UBSL member.
Depositional Analog – Great Bahama Bank, Bahamas

Geologically-constrained subsurface reservoir models utilizing outcrop and/or core data from both modern and ancient analogs provide a basis for the interpretation of vertical and lateral reservoir heterogeneity. Moreover, modern depositional analogs provide an additive value by constraining the temporal and spatial distribution of reservoir facies, and enhance the understanding of sedimentation processes that deposited these facies (Grammer et al., 2004).

Traditionally, developing a fundamental understanding of the factors controlling sedimentation processes, facies distribution, and vertical stacking patterns has been accomplished through incorporating outcrop data sets. Outcrops allow for 2-D, and possibly 3-D visualization (dependent on aerial coverage and exposure along strike and dip directions), of continuous turbidites and MTDs within modern and ancient depositional systems (Grammer et al., 2004). Diverging from traditional methods, this investigation utilized subsurface borehole image logs and rock data sets collected from the leeward margin of Great Bahama Bank, Bahamas as a means to compare depositional and petrophysical characteristics for Neogene age deposits. These deposits have resulted from similar deep-water sedimentation processes as interpreted for UBSL strata.

Along the leeward margin of Great Bahama Bank, Bahamas, core and log data were collected from seven drill sites along a platform-to-basin transect extending 30.0 kilometers (~18.5 miles) basinward during Ocean Drilling Program (ODP) Leg 166.
expedition (Figure 47). During E. Miocene to E. Pliocene (seismic sequences p-f), basin and lower-slope drill sites 1006 and 1003, recorded cyclical sedimentation of turbidites and suspension sediments, with minor slumps locally present. Similar to interpretations of UBSL sedimentation from this investigation, these deposits are interpreted to have been transported basinward during transgressive to highstand, and early lowstand sea level conditions on a low angle (maximum slope angle of 4°) ramp, to distally-steepened ramp setting (Bernet et al., 2000; Betzler et al., 1999; Rendle and Reijmer, 2005).
Figure 47: A) Regional map of Bahamas with inset map (top right) illustrating the location of ODP Leg 166 transect located along the leeward margin of Great Bahama Bank. Image modified from Grammer et al., 2004. B) A dip-oriented seismic section shows the location of seven drill sites, where core and log data were collected (Sites 1003-1007, Clino and Unda). Note Sites 1003 and 1006 are highlighted red to indicate utilization of core and log data from these sites into the present investigation. Core and log data utilized include only those which were collected throughout the E. Miocene to E. Pliocene (i.e. seismic sequences p-f). Image modified from Betzler et al., 1999.

Deposits identified at these two drill sites are dominated by: 1) alternating light and dark gray wackestones to packstones consisting of autochthonous pelagic sediments (planktonic foraminifera, calcareous nannofossils, and micrite), 2) periplatform ooze, and 3) calcareous turbidites (Bernet et al., 2000; Betzler et al., 1999). Turbidite composition varies, due to deposition during highstand and lowstand sea level conditions (Bernet et al., 2000; Betzler et al., 1999). Bernet et al. (2000) indicate that highstand turbidites consist of poorly-sorted, shallow-water grains dominated by red and green algae, benthic foraminifera, and intraclasts. Conversely, they indicate that lowstand turbidites consist of well-sorted, pelagic sediments dominated by planktonic foraminifera and micrite (Figure 48; Bernet et al., 2000).
Figure 48: Core and thin-section photomicrographs of pelagic and hemipelagic suspension sediment from Site 1006 (far left core photo and upper thin-section), and carbonate turbidite deposit from Site 1003 (far right core photo and lower thin-section). Core photos from Eberli, 1997. Thin-section photomicrographs from Bernet et al., 2000.

Utilizing FMS image logs, Bernet et al. (2000) and Williams and Pirmez (1999) have documented these deposits in detail at drill sites 1003 and 1006. Results from these studies indicate that dark gray wackestones to packstones, and periplatform ooze deposits are represented as low resistivity (conductive) features on image log (Figure 49A) with low-resistivity conventional wire-line log responses. Cyclically alternating with these deposits, the light gray wackestone to packstones are represented on image logs as moderate to high resistivity features (Figure 49B). Locally, these light gray wackestone to packstones are bioturbated, exhibiting a mottled texture and moderate to highly conductive resistivity response (Figure 49B). These deposits closely resemble deposits identified in this study: 1) massive to planar laminated, low resistivity pelagic and hemipelagic suspension sediments, and 2) mottled, moderate to high resistivity bioturbated suspension sediments identified from core and image log analysis.
Williams and Pirmez (1999) recognize turbidites as highly resistive, massive to planar laminated features on image logs (Figure 49C). They suggest that the high resistivity response on image logs is attributed to high calcite and/or aragonite cement concentrations. They indicate that turbidites, and cemented pelagic sediments (referred to as hardgrounds), exhibit identical high resistivity responses on image logs. Although difficult to distinguish from one another on image logs, these sediments are suggested to be easily discerned from light gray wackestone to packstone deposits due to the lack of a mottled texture (Williams and Pirmez, 1999). However, bioturbation is noted to be only locally present within these light gray wackestones to packstones, suggesting that the presence, or absence, of a mottled, moderate to high resistivity response on image logs is not a definitive characteristic for distinguishing between these deposits (Williams and Pirmez, 1999). This is also the case for bioturbated suspension deposits identified from the two UBSL cores, where original planar-laminated fabric is locally preserved, exhibiting similar moderate to high resistivity responses that are easily confused with thin bedded turbidites and/or planar-laminated suspension deposits (Figure 43E – Williams and Pirmez, 1999).
Figure 49: FMS image log responses for (A) dark gray and light gray (B) wackestone to packstone suspension sediments. Dark gray suspension sediments display a massive, low to moderate resistivity response. Light gray suspension deposits exhibit a massive, moderate to high resistivity response and are locally bioturbated, exhibiting a mottled texture (as shown in B). C) Carbonate turbidites display a massive, to slightly graded, high resistivity response on image logs. Compared with image log responses for suspension sediments, bioturbated suspension sediments, and turbidites of the UBSL member, these deposits exhibit almost identical image log resistivity responses. Images modified from Eberli, 1997.
Bernet et al. (2000) utilized FMS image logs to record frequency, and thickness, of highstand and lowstand turbidites at drill site 1003 when core recovery was poor. Similar to observations recorded by Williams and Pirmez (1999), Bernet et al. (2000) observed that turbidites exhibit massive to slightly graded, high resistivity responses on image logs (Figure 49C). Normal, and inverse grading (only locally observed), are represented on image logs as gradational shifts from high to low resistivity responses (normal grading), and low to high resistivity responses (inverse grading). Furthermore, they indicate that differentiating between: 1) moderate to low resistivity fine-grained (mudstones to wackestones) turbidites, and 2) low resistivity pelagic suspension sediments were met with a high degree of difficulty. Similarly, turbidites identified from the two UBSL cores often exhibit high to moderate resistivity responses, as pelagic and hemipelagic suspension sediments, making interpretations of these sediments from image logs difficult if not directly calibrated with core.

It is apparent from the above comparison that pelagic and hemipelagic suspension sediments, bioturbated suspension sediments, and turbidites exhibit very similar resistivity responses on image logs despite their compositional differences. Furthermore, difficulties in recognizing and distinguishing between these deposits, due to variations in bedding geometry and/or limited resolution capabilities of image logs, were similar to those encountered during this investigation. These observations indicate that: 1) image logs should always be calibrated with core data when possible, and 2) when core data is not available, literature review of image log responses for analogous sediments will provide a better understanding of sediment types encountered within the wellbore.
CONCLUSIONS

1. UBSL deposits consists of argillaceous mudstones to spiculitic wackestones, siltstones to carbonaceous shales, bioturbated argillaceous mudstones to spiculitic wackestones, skeletal wackestones to mud-rich packstones, oolitic, skeletal wackestones to packstones, oolitic wackestones to packstones, and intraclastic, skeletal wackestones to packstones.

2. UBSL deposits accumulated in a distal, basin-centered setting via suspension settling, slump, turbidity current, liquified flow, grain flow, and debris flow sedimentation processes.

3. Image logs are not able to distinguish between each lithofacies described in core. However, image logs are able to differentiate between mud-rich (low resistivity) and skeletal-rich (moderate to high resistivity) lithologies due to highly contrasting resistivity responses.

4. All turbidites and MTDs identified in core could be identified from image logs when these data sets were directly compared with one another, indicating that image logs can be used to enhance core-based interpretations of turbidites and MTDs.

5. Millimeter scale architectural, and lithologic, features were not able to be resolved by image logs, and only locally were able to resolve centimeter scale features. Centimeter scale features were able to be resolved when deposits exhibited:
   a. Highly contrasting resistivity responses (e.g. low resistivity mudstone versus high resistivity ooid-rich wackestones to packstones).
   b. Multiple lithologies within an individual deposit (e.g. mudstone and siltstone intraclasts floating within a skeletal-rich wackestone to
packstone matrix).

c. Significant internal deformation (i.e. slump and debris flow deposits) resulting in highly contrasting resistivity patterns.

6. Cyclical stacking of turbidites and liquified flow deposits occurs numerous times throughout the UBSL member at both well locations. These deposits, which increase in frequency and decrease in thickness up-section, are commonly underlain by thick (greater than 0.3 meters (1.0’) thick) MTDs (i.e. slumps and debris flows), indicating a genetic relationship exists between these deposits. Most of these intervals (i.e. of cyclically stacked deposits) were able to be clearly resolved on image logs.

7. Slumps, debris flows and ooid-dominated turbidites and grain flows are interpreted to have the highest correlation potential due to characteristic image log responses. For slumps and debris flows, all architectural attributes were able to be correlated from core to image logs. Ooid-dominated turbidites and grain flows exhibit extremely high resistivity responses on image logs that are distinctly dissimilar to all other deposits.

8. Suspension sediments, bioturbated suspension sediments, turbidites (excluding ooid-dominated turbidites), and liquified flow deposits are interpreted to have the lowest correlation potential due to these deposits locally exhibiting similar resistivity responses at various intervals throughout both cored intervals.

9. Analysis of dipmeter data indicates that:

   a. Turbidites and MTDs identified in the Well A core are primarily sourced from the western margin of the Central Basin Platform and Northern Delaware Basin margin.

   b. Turbidites and MTDs identified in the Well B core are sourced from a
much broader region along the southern, southwestern, western, northwestern, and northern margins of the Delaware Basin.

10. Comparison of observations recorded herein, to those from previous investigations in the Bahamas, indicates that suspension sediments, bioturbated suspension sediments, and turbidites exhibit identical resistivity responses on image logs despite compositional differences. This suggests that by having a fundamental understanding of image log responses for analogous sediments can significantly aid in image log interpretations when core data is not available.

Future Considerations

This study has thoroughly addressed architectural and compositional characteristics of deep-water turbidites and MTDs comprising the UBSL member, and how these deposits can be recognized at a sub-reservoir scale utilizing high-resolution electrical image logs. However, further investigation is required to address the application of electrical image logs in characterizing deep-water turbidites and MTDs, specifically, their application in characterizing UBSL turbidites and MTDs. Questions and topics for future investigations include:

1. Use results from this investigation to begin developing a detailed database of characteristic image log responses for turbidites and MTDs based upon the classification schemes and terminology used herein.

2. Compare and contrast image log response of distal versus proximal turbidites and MTDs within the UBSL member.

3. Analyze UBSL turbidites and MTDs in a proximal setting along the western margin of the Central Basin Platform. How do these deposits compare (with
respect to composition and depositional architecture) with those documented elsewhere in the Delaware Basin?

4. What ranges of image log resistivity for UBSL turbidites and MTDs correspond to specific wire-line log responses? Is there a relationship between these data sets that can be applied basin-wide?

5. What level of cyclicity do UBSL turbidites and MTDs, characterized herein, represent?

6. Can reservoir-scale turbidites and MTDs within the UBSL be correlated from well-to-well utilizing electrical image logs?
BIBLIOGRAPHY


Lowe, D. R., 1979, Sediment Gravity Flows: Their Classification and Some Problems of Application to Natural Flows and Deposits, SEPM Special Publication 27, p. 75-82.


APPENDIX A

Core Description Tables
Microsoft Excel spreadsheets containing core descriptions for the two wells used in this thesis may be obtained by contacting Jason J. Asmus via e-mail (jason.j.asmus@wmich.edu).
APPENDIX B

Thin-Section Photographs
Each page consists of one to two thin-section photographs taken under plane polarized light, unless otherwise indicated.

Thin-sections are oriented relative to up-stratigraphic section, and impregnated with blue epoxy to illustrate the presence of pore spaces.

Thin-section depths (measured depth in feet) are shown within a white box located in the top left corner of each thin-section photograph. White scale bars, located in the bottom right corner of each thin-section photograph, represent 1) 300 µm, 2) 200 µm, or 3) 100 µm.
Well A
Well B
APPENDIX C

Core-to-Image Log Comparison
Well A
Well B
### Extended Range Micro Imager

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
</tr>
</thead>
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<td>Gamma API</td>
<td>0-150</td>
</tr>
<tr>
<td>Borehole Diam Max</td>
<td>0-16 inches</td>
</tr>
<tr>
<td>Borehole Diam Min</td>
<td>0-16 inches</td>
</tr>
<tr>
<td>MD</td>
<td>1:20 ft</td>
</tr>
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</table>

#### X-Sec
- Static Image
- Autodip Result: Degrees

#### Horizon Filter
- Degrees

#### Pad 1 Azimuth
- Degrees
APPENDIX D

Graphical Core Descriptions
Well A
Well B
Well B
APPENDIX E

Analysis of Lithofacies and Facies Associations
Lithofacies Comparison (Feet) for Cored Wells

Well A: 221.9 153.2 99.5 23.0 67.3 9.0 11.5 36.0 38.6 34.9 3.5 36.1 36.1
Well B: 197.7 124.3 40.4 7.1 94.9 5.7 0.0 22.6 0.9 7.8 0.2 0.0 0.0
Dunham Texture Comparison (Feet) for Cored Wells

<table>
<thead>
<tr>
<th></th>
<th>Well A</th>
<th>Well B</th>
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<tr>
<td>Mudstone-Siltstone (1.0)</td>
<td>135.7</td>
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<td>Mudstone-Wackestone (1.5)</td>
<td>423.6</td>
<td>300.1</td>
</tr>
<tr>
<td>Wackestone (2.0)</td>
<td>87.1</td>
<td>15.8</td>
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<tr>
<td>Wackestone-Mud-Rich Packstone (2.5)</td>
<td>52.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Mud-Rich Packstone (3.0)</td>
<td>19.8</td>
<td>1.1</td>
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<tr>
<td>Mud-Rich-Mud-Lean Packstone (3.5)</td>
<td>3.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Mud-Rich Packstone (4.0)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Mud-Rich Packstone-Grainstone (4.5)</td>
<td>2.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Grainstone (5.0)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Lithofacies Comparison (%) for Cored Wells

Well A: 52.88% 55.22% 71.10% 76.55% 41.49% 61.25% 100.00% 57.05% 97.68% 65.46% 94.69% 100.00% 100.00%

Well B: 47.12% 44.78% 28.90% 23.15% 58.51% 38.75% 0.00% 42.95% 23.22% 34.54% 5.31% 0.00% 0.00%
APPENDIX F

UBSL Structure Map and Depth Profiles
APPENDIX G

Rock Evaluation Summary
<table>
<thead>
<tr>
<th>Facies Associations (Sedimentation Processes)</th>
<th>Lithofacies (Dunham (1962) classification)</th>
<th>Description (determined from whole core and thin-section data)</th>
<th>Internal Architecture (sedimentary structures, texture, fabric)</th>
<th>Bedding Geometry and Stratigraphic Cyclicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 - Pelagic and Hemipelagic Suspension Settling</td>
<td>1.1 - Argillaceous Mudstone - Spesiclitite Wackestone</td>
<td>Dark gray-black mudstone - wackestone composed of micrite, sponge spicules, radiolarians, and organic matter with minor peloids, fine silt-sized detrital quartz grains, and pyrite crystals; large nodular chert concretions are locally abundant.</td>
<td>Internal fabric is massive to thinly laminated (&lt;1 centimeter thick); beds are slightly tilted and plastically deformation around concretions; local contortions (&lt;1 centimeter thick) present, reworking of suspension deposits when concretions are present.</td>
<td>Deposits are variable in thickness (&lt;1 centimeter to &gt;30 feet) and occur throughout cored intervals at both well locations.</td>
</tr>
<tr>
<td>#2 - Bioturbation of Pelagic and Hemipelagic Suspension Sediment</td>
<td>1.2 - Siltstone - Carbonaceous Shale</td>
<td>Gray-tan-light brown siltstone - carbonaceous shale composed of micrite, organic matter, medium-fine silt-sized siliciclastic grains, and minor sponge spicules, peloids, radiolarians, and pyrite crystals; large nodular chert concretions are locally abundant.</td>
<td>Internal fabric is thinly laminated (laminae are &lt;1 centimeter thick); sedimentary structures include normal to inversely graded laminations, minor deformation of bedding laminations around concretions, and minor bottom-current re-working.</td>
<td>Deposits are thick (10-20&quot;) and exhibit no clear stacking pattern and are typically present when turbidite- and NTD frequency decreases.</td>
</tr>
<tr>
<td>#3 - Storm</td>
<td>2.1 - Bioturbated Argillaceous Mudstone - Spesiclitite Wackestone</td>
<td>Dark gray-black bioturbated argillaceous mudstone - wackestone composed of micrite, organic matter, sponge spicules, radiolarians, and minor peloids, pyrite crystals, and undifferentiated skeletal grains; significant burrowing and re-working of sediment differentiates this lithofacies from lithofacies 1.1.</td>
<td>Internal fabric is massively; sedimentary structures include small (&lt;1 centimeter long) sediment-filled burrows, and re-worked horizontal laminations.</td>
<td>Internal fabric exhibits folding and irregular contortion of bedding; deformation typically increases along basin boundaries; sedimentary structures include plastically deformed and folded (inclined and recumbent folds) laminated bedding layers, plastically deformed grains and clast (when present), grains and intraclasts exhibit chaotic orientation, sharp upper and lower bedding contacts, erosive base, and minor normal grading of folded beds.</td>
</tr>
<tr>
<td>#4 - Storm</td>
<td>3.1 - Mudstone - Spesiclitite Wackestone</td>
<td>Dark gray-black mudstone - wackestone composed of micrite, sponge spicules, peloids, radiolarians, and locally abundant skeletal fragments (echinoids, benthic foraminifers, bryozoa, and phylloid algae); grains are moderately well sorted, subangular-subrounded, medium-fine silt-size, with moderate-low sphericity.</td>
<td></td>
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<tr>
<td>Facies Associations (Sedimentation Processes)</td>
<td>Lithofacies (Dunham 1962 classification)</td>
<td>Description (determined from whole core and thin-section data)</td>
<td>Internal Architecture (sedimentary structures, texture, fabric)</td>
<td>Bedding Geometry and Stratigraphic Cyclicity</td>
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<td>---------------------------------------------------------------</td>
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<td>-----------------------------------------------</td>
</tr>
<tr>
<td>#4 - Turbidity Current</td>
<td>4.1 - Mudstone - Spiculitic Wackestone</td>
<td>Light-dark gray wackestone composed of micrite, organic matter, sponge spicles, peloids, radiolarians, minor amounts of pyrite and fine silt-sized detrital quartz grains; grains are moderate-well sorted, subangular-subrounded, medium-fine silt-size, with low-moderate sphericity</td>
<td>Light-dark grey wackestone - mud-rich packstone composed of micrite, organic matter, and peloids; skeletal grains (present mainly as broken, or fragmented remnants) include crinoid ossicles, ostracods, brachiopods, phylloid algae, gastropods, bryozans, minor fusulinid tests, sponge spicles, radiolarians and undifferentiated skeletal grains; skeletal and non-skeletal grains are poorly-defined sorted, very angular-subrounded, medium sand-coarse silt-size, with low sphericity</td>
<td>Beds are relatively thin (&lt;1-2' thick) and may occur as isolated deposits, but are often cyclically stacked; intervals of cyclically stacked turbidites range from 1' - &gt;10' thick and may occur multiple times within 20-30' thick zones; these intervals typically exhibit decreasing turbidite thicknesses with increasing turbidite frequency up-section</td>
</tr>
<tr>
<td></td>
<td>4.2 - Skeletal Wackestone - mud-rich Packstone</td>
<td>Light grey wackestone - packstone composed of micrite, ooids, coated grains, peloids, organic matter and fine silt-sized detrital quartz grains; skeletal grains (present mainly as broken, or fragmented remnants) include crinoid ossicles, ostracods, bryozans, brachiopods, phylloid algae, gastropods, fusulinid tests, planktonic foraminifera, sponge spicles, radiolarians and undifferentiated skeletal grains; skeletal and non-skeletal grains are moderate-well sorted, subangular-subrounded (ooids are rounded-well rounded), very fine sand-coarse silt-size, with moderate-high sphericity</td>
<td>Light-grey wackestone - packstone composed of micrite, ooids, coated grains, peloids, organic matter and fine silt-sized detrital quartz grains; skeletal grains (present mainly as broken, or fragmented remnants) include crinoid ossicles, ostracods, bryozans, brachiopods, phylloid algae, gastropods, fusulinid tests, planktonic foraminifera, sponge spicles, radiolarians and undifferentiated skeletal grains; skeletal and non-skeletal grains are moderate-well sorted, subangular-subrounded (ooids are rounded-well rounded), very fine sand-coarse silt-size, with moderate-high sphericity</td>
<td>Internal fabric exhibits graded beds and bedsets separated by thinly (~1-2 centimeter thick) laminated argillaceous mudstones typical of Bonina Sequences; volume % of solid grains varies throughout due to grading within Bonina sequences but is typically &lt;10%-15%; sedimentary structures include partial and complete Bonina Sequences, sharp and slightly erosive basal contacts with gradational and non-erosive upper contacts, loadcasts at base, flume structures located at upper contacts (typical) and lower contacts (rare), fluidal deformation often present within upper half of flow deposit</td>
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<td>4.3 - Oolitic, Skeletal Wackestone - Packstone</td>
<td>Gray out-light brown siltsone-carbonaceous shale composed of micrite, organic matter, medium-fine silt-sized siliclastic grains (quartz, feldspars, and micas), and minor amounts of skeletal grains (crinoid ossicles, brachiopods, bryozans, and undifferentiated skeletal grains) locally present; siliclastic grains are moderate-well sorted, medium-fine silt-size, very angular-subrounded, with low sphericity</td>
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<td>#5 - Turbidity Current and/or Liquified Flow</td>
<td>5.1 - Mudstone - Specilific Wackestone</td>
<td>Light-gray wackestone composed of micrite, organic matter, sponge spicules, peloids, nodularites, and minor amounts of pyrite and fine silt-sized detrital quartz grains; grains are well sorted, subangular-subrounded, medium-fine silt-size, with moderate-lower sphericity.</td>
<td>Internal fabric is massive to slightly graded; volume % of solid grains falls within 10%-40% range for turbidity current and liquified flow classification; sedimentary structures include normal grading, sharp and moderately erosive basal contacts, gradational non-erosive upper contacts, horizontal lamination locally present, fluidal deformation and folding of bedding throughout, pressure solution seams locally present, basal and upper fluid escape structures, and local high-angled bedding.</td>
<td>Beds are typically 2-6&quot; thick and occur as stratigraphically isolated flow deposits or as underlying deposits to cyclically stacked turbidites; within Well A, deposits (2-3&quot; thick) are cyclically stacked over a 20-30&quot; thick cycle interval.</td>
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<td>#6 - Grain Flow</td>
<td>5.2 - Skeletal Wackestone - mud-rich Packstone</td>
<td>Light-gray wackestone-packstone composed of micrite, skeletal grains, organic matter, and minor amounts of silt-sized detrital quartz grains; skeletal grains include sponge spicules, radiolarians, crinoids, brachiopods, byssus, oysters, gastropods, fusulinids, planktonic foraminifers, and undifferentiated skeletal grains; skeletal grains are poorly sorted, very angular-subrounded, fine sand-fine silt-size, with low sphericity.</td>
<td>Internal fabric is massive; volume % of solid grains is significantly greater than 25% but does not exceed 90% (estimated ~75% solid grains for clast-dominated grain flows); sedimentary structures include normal and reverse grading, sharp and lower contacts, erosive base, load casts at base, random grain orientation, skeletal and non-skeletal grains are typically grain supported (and supported when deposits exhibit normal grading), and elongate mudstone intraclasts (&lt;1 centimeter thick) present along erosive basal contacts.</td>
<td>Beds occur as relatively thick (&gt;2&quot; thick) individual deposits often associated with slumped strata or as cyclically stacked deposits (&lt;1&quot; thick).</td>
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<td>6.1 - Skeletal Wackestone - mud-rich Packstone</td>
<td>Light-gray wackestone-packstone composed of ooids, coated grains, micrite, skeletal grains, peloids, organic matter, and minor amounts of silt-sized detrital quartz grains; skeletal grains are poorly sorted, very angular-subrounded, coarse-sand fine sand size, with low sphericity; allochems (ooids and coated grains) are moderately sorted, spherical-subospherical, medium-coarse sand (250μm - 750μm), with moderate-high sphericity.</td>
<td>Internal fabric is massive; volume % of solid grains is significantly greater than 25% but does not exceed 90% (estimated ~75% solid grains for clast-dominated grain flows); sedimentary structures include normal and reverse grading, sharp and lower contacts, erosive base, load casts at base, random grain orientation, skeletal and non-skeletal grains are typically grain supported (and supported when deposits exhibit normal grading), and elongate mudstone intraclasts (&lt;1 centimeter thick) present along erosive basal contacts.</td>
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<td>6.2 - Oolitic Wackestone - Packstone</td>
<td>Light-gray wackestone-packstone composed of ooids, coated grains, micrite, skeletal grains, peloids, organic matter, and minor amounts of silt-sized detrital quartz grains; skeletal grains are poorly sorted, very angular-subrounded, coarse-sand fine sand size, with low sphericity; allochems (ooids and coated grains) are moderately sorted, spherical-subospherical, medium-coarse sand (250μm - 750μm), with moderate-high sphericity.</td>
<td>Internal fabric is massive; volume % of solid grains is significantly greater than 25% but does not exceed 90% (estimated ~75% solid grains for clast-dominated grain flows); sedimentary structures include normal and reverse grading, sharp and lower contacts, erosive base, load casts at base, random grain orientation, skeletal and non-skeletal grains are typically grain supported (and supported when deposits exhibit normal grading), and elongate mudstone intraclasts (&lt;1 centimeter thick) present along erosive basal contacts.</td>
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<td>#7 - Debris Flow</td>
<td>7.1 - Intralastic, Skeletal Wackestone - Packstone</td>
<td>Dark gray-black intralastic, skeletal wackestone-packstone; matrix is composed of micrite, abundant skeletal grains, and minor amounts of silt-sized detrital quartz grains (skeletal grains are more abundant within Type #2 debris flow matrix than in debris flow Type #1 matrix); composition of intralastics is often similar to matrix composition but with increased amounts of skeletal grains present; intralastics exhibit variable geometries (very angular-subrounded, and elongate stringer-like shapes), and range in size from &gt;1 to &lt;5 mm in diameter.</td>
<td>Internal fabric is massive with chaotic arrangement of intralastics and skeletal grains; volume % of solid grains is estimated between 80%-60% from thin-section analysis; sedimentary structures include abundant irregularly shaped intralastics composed of basin and shoal-water fauna, intralastics protrusion into underlying strata, no preferential grain orientation, intralastics are matrix- and intralast-supported (varies within individual deposits), plastically deformed intralastics, and normal and inverse grading locally present.</td>
<td>Present only in the Well A core; debris flows occur as thick (7'-14' thick) isolated deposits often overlain by slumps or cyclically stacked turbidites; between depths 9626' - 9686'; debris flows occur as stacked deposits separated by 9'-15' thick intervals of cyclically stacked turbidites.</td>
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