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Correlation of core characteristics to outcrop upper Jackfork Group turbidites, DeGray Lake, Arkansas

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CORRELATION OF CORE CHARACTERISTICS TO OUTCROP, UPPER JACKFORK GROUP TURBIDITES, DEGRAY LAKE, ARKANSAS

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geology and Geophysics

by
Daniel James Golob
B. S., Ohio University, 1999
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ABSTRACT

Pennsylvanian age Jackfork Group cores from the DeGray Lake Dam and outcrop from the east wall of the DeGray Lake Spillway, Arkansas, provide an opportunity for a detailed study on the transport and depositional characteristics of a fine-grained, deep-water depositional system. Two phases of resedimentation processes are responsible for deposition of the sediments in the cores and the outcrop. Primary resedimentation processes transport terrigenous sediments from the shelf or basin edge into the middle fan environment, while secondary resedimentation alter the sediments after they are initially deposited in the environment. Debris flows, slurry flows, and high and low density turbidity currents are all of the primary flows that can be identified in the cores and outcrop. It is likely that most of these flows (termed sediment gravity flows) were derived from slides and slumps that originated up-slope. Slides, slumps, creep, and debris flows have occurred on localized slopes on the sea floor, creating a secondary phase of deposition. Each of these events is recorded in rather small-scale intervals in the cores and outcrops, but their accumulated influence is significant.

Core and outcrop can be placed into separate depositional packages based on changes in lithofacies characteristics. These packages are compared from core to outcrop, and those that are most similar are correlated. The cores and outcrop show bedding trends and other sedimentary characteristics that indicate they were deposited within the framework of a middle submarine fan. The middle fan is characteristic of thick-bedded channel axis sands, thick- to thin-bedded channel margin sands, thin-bedded levee/overbank sands and muds, and very thin-bedded distal overbank silty muds. In some cases, more than one subenvironment is suggested as an appropriate interpretation for a depositional package. This is due to the fact that the divisions between these subenvironments are gradual and many deposits may fall into a transitional realm.
Core and closely spaced outcrops studied together offer several benefits over studying each separately. The cores provide new data from the subsurface that is applied to a well known outcrop. Fresh core faces show more fine-scale details that are hard to see in the spillway, which has many heavily weathered and covered sections. The spillway east outcrop, although tilted, provides more spatial variation, which can be correlated back to the cores. Bedding trends and contacts are better exposed in outcrop due to artificial breaks in the cores caused by drilling and recovery.
CHAPTER 1: INTRODUCTION

Introduction

Cores taken by the United States Army Corps of Engineers (U.S.A.C.E) for the construction of the DeGray Lake Dam and Dike have been selected for a study of a fine-grained submarine fan complex. The cores are comprised of thin-bedded, fine-grained sandstones and mudstones as well as thick-bedded, fine- to medium-grained sandstones. Five of these cores nearest to the dam belong to the Pennsylvanian Jackfork Group. The remaining core is from the dike and belongs to the Mississippian Stanley Formation. Several authors (e.g., Morris, 1971; Moiola and Shanmugam, 1984; Breckton, 1988; DeVries, 1992; Al-Siyabi, 2000) have studied deposits from the DeGray Lake area and have reached different conclusions as to which part(s) of the submarine fan depositional subenvironments they belong. The majority of these studies have focused heavily on the outcrops along the DeGray Spillway walls. None of these previously mentioned studies included core as a major component, nor have they made any attempt at a stratigraphic correlation from core to outcrop. This study will achieve careful descriptions and interpretations of depositional characteristics recorded in the cores as well as attempt to correlate lithofacies utilizing an outcrop. The outcrop to be utilized is the east wall of the DeGray Spillway. This study does not attempt a direct lithologic correlation from core to core, or from core to outcrop because there is very little stratigraphic overlap in the tilted and faulted strata. The spacing of the cores and outcrop would have to be much closer when dealing with strata that dip 45° to 50° to the south. Therefore, the correlation will be achieved by developing depositional packages for the cores based on significant changes in lithofacies characteristics, and then correlating these packages to similar packages in outcrop.

The attention to fine-scale details this study provides will exceed all of the others from the DeGray Lake and Spillway areas because of the freshly cut core faces. One of the major advantages of the dam site cores is that they have not been exposed to
weathering effects that deteriorate outcrops, and therefore they will reveal more detailed characteristics. Also, the cores have been collected from areas covered by DeGray Lake, Dam and Dike structures so there are no direct outcrop analogs for their specific position within a submarine fan complex. These cores have the potential to offer new data and interpretations from an area that has not been interpreted before, unlike the outcrops at DeGray Lake.

Core and Outcrop Data

The first part of the data set for this study includes five complete 2-in diameter cores from the Pennsylvanian Jackfork Group and one complete 2-in diameter core from the Mississippian Stanley Formation. The cores were acquired from a collection in storage belonging to the Louisiana State University Geology and Geophysics Department. The six complete cores were preserved as uncut sections in 40 boxes. Each box contained approximately 4 m of core each. The cores were initially recovered from foundation borings taken by the United States Army Corps of Engineers during the construction of the DeGray Lake Dam and Dike (Figure 1.1) in the early 1960’s. Dam foundation and grouting plans show these cores were described in a general sense, mainly for the purposes of locating unknown faults and pressure testing of some mudstone sections. The cores have since remained unused until this study.

The five Jackfork Group cores are centrally located around the axis of the DeGray Lake Dam (Figure 1.2). The sixth Stanley core is located at the northern tip of the northern most dike embankment for DeGray Lake, 4.7 km to the north-northeast of the dam (Figure 1.1). Geologic field mapping by the Arkansas Geologic Commission indicates that this core was taken from strata of the Mississippian age Stanley Formation. The thickness of the core sections recovered and the actual stratigraphic thickness are not the same values. Strata near the dam dip 45°-50° to the south and strata near the dike embankment dip 50°-60° to the south, making it necessary to correct for stratigraphic
Figure 1.1: Map of study area showing the location of the dam, dike, and spillway at DeGray Lake. Inset of Arkansas with major cities and highways near DeGray Lake is provided in the upper right corner. The dashed area around the dam embankment indicates the approximate area covered in Figure 1.2. Core E-81’s location is shown on the north end of the dike at the top left corner of the map.
Figure 1.2: Partial trace map of Plate 3 of the United States Army Corps of Engineers dam foundation boring and grouting plan. The area shown includes the surface locations of the five Jackfork Group cores. The sixth core is from the Stanley Formation underneath the DeGray Dike, 4.7 km to the north (Figure 1.1).
thickness. Corrected stratigraphic thickness for each core, as well as actual thickness are listed in Table 1.1. Combined stratigraphic thickness for all six cores is 112 m.

The east wall of the DeGray Spillway is the outcrop used for correlation of the core packages. It is located approximately 1 km west-northwest of the dam (Figure 1.2). Strata in the spillway are also tilted and dip southward at 45°-50°. The spillway section includes 141 m of Pennsylvanian Jackfork Group strata.

Objectives

This study, utilizing both core and outcrop, attempts to accomplish several major objectives:

1. Identify the depositional characteristics of the Jackfork Group at DeGray Lake in both core and outcrop.
2. Correlate core and outcrop characteristics using depositional packages with similar lithofacies associations.
3. Conduct a literature review to assign depositional environments to each package.
4. Investigate sediment transport mechanisms based on some principal depositional features.
5. Demonstrate the value detailed core characterization adds to outcrop studies.

Methodology

DeVries (1992) showed that the east wall of the spillway could be separated into depositional units based on changes in lithofacies characteristics. This study advances that method by using changes in lithofacies characteristics to develop depositional packages, not only for the spillway, but also for the cores retrieved from the dam and dike area. Depositional packages are thus created for the cores and the spillway using sandstone bed thickness and net to gross (sandstone vs mudstone ratio) as the primary criteria.
Table 1.1: Calculated stratigraphic thickness for each core vs apparent thickness. * The dip angle used to calculate stratigraphic thickness for core E-81 is 55° compared to 45° for the other cores.

<table>
<thead>
<tr>
<th>CORE</th>
<th>APPARENT THICKNESS</th>
<th>STRATIGRAPHIC THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-14</td>
<td>20.9 m</td>
<td>14.7 m</td>
</tr>
<tr>
<td>T-31</td>
<td>24.5 m</td>
<td>17.5 m</td>
</tr>
<tr>
<td>T-39</td>
<td>42.0 m</td>
<td>31.2 m</td>
</tr>
<tr>
<td>G-109</td>
<td>25.5 m</td>
<td>17.8 m</td>
</tr>
<tr>
<td>G-121</td>
<td>22.6 m</td>
<td>15.9 m</td>
</tr>
<tr>
<td>E-81</td>
<td>24.4 m</td>
<td>14.0 m*</td>
</tr>
</tbody>
</table>
Interpretations for depositional environments follow those described by Walker (1978), Shanmugam and Moiola, (1984), DeVries (1992), Al-Siyabi (1998), Sullivan et al. (2000), and Bouma et al. (2002). DeVries used the association of thinner-bedded interchannel turbidites and thicker-bedded channelized turbidites to suggest a middle fan depositional environment for the spillway. Shanmugam and Moiola (1984) and Al-Siyabi (1998) also recognized channelized and interchannel turbidites from the Spillway. Walker (1978) suggested channelized middle fan areas are recognized by a finning- or (thinning-) upward facies succession. These studies provided the framework by which to make further interpretations of depositional subenvironments within a fine-grained middle submarine fan. Each of the depositional packages in the cores and outcrop are assigned a depositional subenvironment(s) based on the criteria outlined in Sullivan et al. (2000) and Bouma et al. (2002). A more thorough discussion of the specific subenvironments is developed in a review of depositional models in Chapter 2.

Depositional mechanisms have been tied to key lithofacies characteristics based on the discussions included in Hampton (1972), Middleton and Hampton (1976), Lowe (1982), Prior and Coleman (1984), Stow (1986), Kneller and Branney (1995), Lowe and Guy (2000), and Sullivan and Templett (2002). Several lithofacies that suggest one or more sediment transport mechanisms are presented in the context of a discussion in Chapter 4. Many photographs of fresh core faces are used to illustrate some of the more fine-scale depositional characteristics that are likely obscured in the weathered outcrop from the Spillway. These characteristics are linked to small-scale sediment transport mechanism that are deposited in 10 to 20 cm thick sections.

The depositional characteristics of core and outcrop were recorded using traditional field measurements and core descriptions. Gamma-ray logs, X-ray photographs and thin sections were also produced from the cores. An in depth account of these procedures is given in the following paragraphs.
Forty boxes containing the six cores were taken from the Department of Geology and Geophysics’ River Road storage facility to the Basin Research Institute’s Core Facility for processing. The cores were described in a general sense as whole sections. Descriptions of bedding patterns, composition, sedimentary structures, and visual estimates of grain size were recorded. To facilitate more detailed observations of sedimentary structures from fresh core faces, sand-rich portions of the cores were cut lengthwise in half with a 16” diamond blade masonry wet saw. Mud-rich portions of the cores were generally not cut, neither were quartzitic sandstones. Mud-rich portions would crumble, making descriptions more difficult than if they were left whole. Quartzitic sandstones were described as whole cores because they were extremely difficult to cut in long segments.

Apparent thickness of each bed was measured using a 5 m steel WEBCO tape. Stratigraphic (true vertical) thickness for each bed was calculated using the apparent bed thickness and dip angle (refer to Figure 1.3).

Half cores from core T-14 were cut lengthwise to produce 1/4” thick slabs for X-ray radiography to reveal depositional structures that are not visible on the surface of the core. Fine- to medium-grained sandstone slabs from 1.6 m of continuous section were arranged in 13 separate sections on 4 sheets of photographic paper. The slabs were exposed to X-ray radiation for a duration of 2.25 minutes using a Hewlett Packard Faxitron Series Cabinet X-Ray Machine. The core slices were saved for comparison with the negative images on the photographic paper.

Synthetic gamma-ray logs of the cores were attempted using an EDA Instruments, Inc. GRS-500 hand held gamma-ray scintillometer, with the TC1 setting at one second. At this setting, the instrument records the total emission of energies above 80 KeV, over a period of one second. Twelve readings were taken at 10 cm intervals over the entire length of cores T-14 and T-31. The highest and lowest values were discarded and the remaining ten readings were averaged.
Figure 1.3: Method for calculating stratigraphic (true vertical) thickness from borehole cores. Thickness measurements taken from cores represent apparent thickness (X). The geometrical relationship used to calculate stratigraphic thickness (Y) is depicted in the figure (from Al-Siyabi, 1998).
A fine- to medium-grained sandstone sample and a fine-grained, mud-rich sandstone sample were taken from core T-14 along with a mudstone sample from core T-31 for further testing of gamma-ray activity using a more sensitive gamma spectrometer. The instrument used was an Intrinsic Geranium Type Gamma Spectrometer with 21% nominal relative efficiency (relative to conventional sodium iodide detectors). Each sample was enclosed individually in the lead encased spectrometer, which reduces background radiation by a factor of 10. Running time for each sample was approximately 72 hours. Total activity of the entire sample and for each separate nuclide was given in pCi/gm (p = 10^-12; 1 Ci = 3.7 \times 10^{10} \text{ decays/s}; \text{gm} = \text{gram}).

Thin sections were prepared from eight different sandstones from all five of the Jackfork Group cores. Each sample was cut, impregnated with epoxy, and ground to a thickness of 30 micrometers. Samples were analyzed for grain size, matrix percentage, and composition using an Olympus Vanox petrographic microscope.

Bed thickness measurements, bed contacts, bedding trends, composition, sedimentary structures, net to gross (sandstone vs mudstone ratio) and visual estimates of grain size were recorded from the east wall of DeGray Spillway. The base of the measured section begins to the immediate right (south) of the drainage culvert that cuts through the wall and continues until the outcrop runs into the subsurface at its southernmost end. Measurements were taken from north to south, oldest strata to the youngest. Stratigraphic thickness was measured at right angles to bedding using a Brunton compass, chalk, and a five meter steel WEBCO tape. Photographs were taken in sequence from north to south and then repeated from south to north to create a montage of the entire east wall. Individual photographs were also taken of prominent sedimentary and other depositional structures.
CHAPTER 2: PREVIOUS STUDIES

DeGray Lake, Arkansas

The outcrops at DeGray Lake, Arkansas, have been studied by several investigators. Morris (1971), Moiola and Shanmugam (1984), Breckon (1988), Al-Siyabi (1998; 2000), and references therein studied Jackfork Group rocks in a regional setting, while making the DeGray Spillway, because of its excellent exposures, a major component of their work. DeVries (1992) took a more concentrated approach by focusing on the DeGray Spillway and Intake only.

The objective of much of the work in the Jackfork Group in Arkansas was to place the deposits in an appropriate depositional model. Several researchers achieved this objective by using a variety of field techniques and methods. Morris (1971) was one of the first investigators to describe the Jackfork rocks as they appear in the field at DeGray Spillway, and to frame a depositional history. He used differences in bed thickness, mineral composition, and sand-shale ratios to construct a depositional model. Thicker-bedded proximal turbidites with high sand-shale ratios and thinner-bedded distal turbidites with low sand-shale ratios are the dominant deposits. These turbidites were interpreted to be associated with westward transport down the axis of the Ouachita Trough. Moiola and Shanmugam (1984) also conducted a regional study of the Jackfork rocks in which they described the depositional facies of the Jackfork Group to formulate a viable model for the depositional framework of the Ouachita flysch succession in general. Using the facies designations of Mutti and Ricci Lucchi (1972), they concluded that middle fan and interchannel turbidity current deposits occur at DeGray Lake. Later, Shanmugam and Moiola (1995) came to refute their own findings and reinterpret the rocks at DeGray Lake to be primarily of debris flow in origin.

DeVries (1992) and Al-Siyabi (1998) conducted studies that concentrated on the specific outcrop exposures at DeGray Lake, although each included smaller parts from
other areas. DeVries (1992) emphasized the importance of bedding associations and depositional cycles, which he labeled units, rather than facies associations, to make his interpretations. He also made use of the closeness of the outcrops by correlating bedding trends between the walls of the Spillway and then correlated these trends to an outcrop near the dam intake. All of this was done to assess the lateral variability in turbidite deposits. DeVries (1992) related these depositional units to several different subenvironments in a middle fan depositional environment. Al-Siyabi (1998) created a depositional model for the Upper Jackfork from closely spaced outcrop exposures coupled with general borehole descriptions found in the DeGray Lake Dam foundation plans. He used the facies designations of Mutti (1992) to link the Jackfork strata of DeGray Lake and surrounding areas into a facies continuum or facies tract. Analysis of facies distributions, vertical facies trends, and downcurrent relationships proved to be the most effective methods for interpreting depositional environments. Al-Siyabi’s proposed depositional model interprets the Upper Jackfork as a Type II (Mutti, 1985, 1992) depositional system. Type II depositional systems are characterized by channel fill and lobate sand sequences.

**Jackfork Group Location**

Pennsylvanian Jackfork strata are well exposed in numerous locations along two east-west trending fold belts in central Arkansas. These belts are the northerly Frontal Ouchitas, and the southerly Athens Plateau, which are separated by the Benton Uplift (Slatt et al., 2001) (Figure 2.1).

**Jackfork Group Nomenclature**

Deposits belonging to the Pennsylvanian Jackfork Group were the first recognized flysch deposits in North America (see in DeVries, 1992). Trace fossils of the Nereites facies, which are normally found at bathyl and abyssal depths, are commonly present and are the primary evidence for assigning a deep-water setting to the succession (Moiola and...
**Figure 2.1:** Index map showing physiographic provinces of Arkansas. Jackfork Group rocks are exposed in the frontal Ouachitas and Athens Plateau (modified from Morris, 1971).
Shanmugam, 1984). In the DeGray Spillway, the rocks have been identified as Upper Jackfork, equivalent to the Brushy Knob Formation in the frontal Ouachitas. White (1937; see in Jordan et al., 1991) was able to establish a post Mississippian age for the Jackfork. He documented the floral affinity of the Jackfork to the Morrowan Hale and Bloyd Formations of northwestern Arkansas. By synthesis of pertinent literature, Coleman et al. (1994; see in Shanmugam and Moiola, 1995) placed the Jackfork at the Mississippian-Pennsylvanian boundary, with an approximate age of 320-318 m.y. The Pennsylvanian Jackfork Group was deposited in the Ouachita Basin (trough) as part of a thick Carboniferous flysch sequence of synorogenic sedimentary rocks. This sequence in stratigraphic order is comprised of the Mississippian Stanley Formation, the Pennsylvanian Jackfork Group, and the Pennsylvanian Johns Valley and Atoka Formations (Figure 2.2).

**Tectonic History**

The tectonic evolution of the Ouachita Basin and the associated Ouachita Mountains is complex. Figure 2.3 shows several time slices (A-E) in cross section that illustrate the tectonic development of the southern margin of North America and the Ouachita orogenic belt. (A) In the late Precambrian to the earliest Paleozoic, the North American craton (Laurentia) rifted along a trend later followed by the Appalachian-Ouachita orogenic belt, and oceans opened along the newly formed continental margins (Viele and Thomas, 1989). Specifically, the Ouchita Ocean in the region which is now southern Arkansas. (B) Beginning in the late Cambrian through the earliest Mississippian, the Oachita Ocean was at its widest and deepest. The basin was dominated by hemipelagic and pelagic sedimentation (Al-Siyabi, 1998). Below the Stanley Formation in the Ouachita Mountains are the chert-like deposits from the Arkansas Novaculite Group, which records the final episodes of preorogenic deposition during the early Mississippian (see Figure 2.2). (C) In the early Mississippian, the shift
Figure 2.2: Geologic time scale showing the Carboniferous stratigraphy in Ouachita Mountains and the correlation of the Jackfork Group to the Hale and Bloyd Formations of the Ozark Region (modified from Ethington et al., 1989).
Figure 2.3: Diagrammatic cross sections showing the tectonic development of the southern margin of North America and the Ouchita orogenic belt, much shortened from north to south: (A) late Precambrian-earliest Paleozoic records the onset of extension. (B) During the late Cambrian-earliest Mississippian the Ouchita ocean is at its widest and deepest. (C) In early Mississippian-earliest Atokan times the Ouachita Basin is segmented by the development of an accretionary wedge, into a fore-arc basin to the south and a trench basin to the north. (D) During early to middle Atokan time, thrusting of the accretionary wedge onto the southern margin of North America occurred. (E) In the late Atokan-Desmoinesian, thrusting of the Ouachita orogen onto North America continued (from Viele and Thomas, 1989; Al-Siyabi, 1998).
from preorogenic deposition to synorogenic deposition occurred as the ocean basin along the southern margin of North America began to contract. The major plates (North America, South America, and Africa) began to converge at this time to ultimately form Pangea (Viele and Thomas, 1989). (D) During convergence, the synorogenic flysch deposits of the Ouachita basin were thrusted onto the North American continent to form the Ouachita Mountains. (E) Thrusting continued until the middle Pennsylvanian.

**Sediment Source Areas**

Three major source areas to the Ouachita Basin for the Jackfork Group have been proposed, the Illinois Basin to the Northeast, the Black Warrior Basin to the East, and the microcontinent Llanoria to the South (Morris, 1971; Danielson et al., 1988; Viele and Thomas, 1989). Sediments are likely to have bypassed the Illinois and Black Warrior Basins en route to the remnant ocean basin, the Ouachita Basin. Morris (1971) provided results from petrographic analysis of more than 200 thin sections to determine provenance. Remarkable similarities between the Chesterian-Lower Pennsylvanian sandstones of the Illinois Basin with Jackfork sandstones led him to conclude that some sediment may have bypassed the Illinois Basin to be deposited in the Ouachita Basin. Thin sections collected from the Athens Plateau had a higher feldspar and lithic content suggesting a different source area, such as the Black Warrior Basin to the East. A more southerly source for the Jackfork has been proposed by Danielson et al. (1988) and Viele and Thomas (1989), among others. During the Carboniferous subduction of the North American plate southward underneath a microcontinent, called Llanoria, created an elevated source-land that provided sediment to the basin. According to Danielson et al. (1988) a southern source is more pronounced in Upper Jackfork outcrops located in the southern Ouachitas because of the abundance of lithic fragments and conglomeratic sandstones in these rocks.
Turbidite Fan Models

Turbidite systems reflect a wide variability in morphology and in depositional processes in response to tectonic setting, climate, and eustacy. Two traditional end members are fine-grained, mud-rich and coarse-grained, sand-rich turbidite systems. While these end members confine the boundaries of most of the turbidite systems, it should be noted that there is a continuum that exists between them (Bouma, 1997, 2000). The parameters that influence the continuum are many. Fine-grained, mud-rich turbidite systems are characteristic of passive and active tectonic margins, extensive submarine deposits, efficient flow, and predominant fine sand-mud sediments. Coarse-grained, sand-rich turbidite systems are characteristic of active tectonic margins, less-extensive submarine deposits, non-efficient flow, and predominant sand-gravel sediments (Reading and Richards, 1994; Bouma, 1997, 2000). Since these systems do represent the end members, it is reasonable to assume that most modern submarine fans and ancient turbidite systems would fall somewhere in between. This concept makes it difficult for one all-encompassing model, which could be applied to every modern system and outcrop. It is the aim of this section to compare a variety of models and to investigate the depositional processes inherent to the models. This review is necessary to help characterize depositional subenvironments and transport processes for the cores and outcrop from DeGray Lake.

A number of different models have been developed to represent the geometry of turbidite systems. None of the models could have been created without regard for the depositional processes operating in turbidite systems. As Anderton (1985) is quoted in Coleman (1994) “a familiarity with published facies models is clearly essential for any practising sedimentologist, but this understanding is not nearly as important as how the model was constructed.” Therefore, to accurately interpret the characteristics of the models, it is necessary to consider sediment type, transport, and depositional processes.
Defining a Turbidite System

A turbidite system is considered to be the ancient equivalent of a modern submarine fan. It represents the second order in the hierarchical classification presented in Figure 2.4 (Bouma, 2000). Turbidite systems include depositional sequences that are several hundred meters thick with no significant breaks in sedimentation. A turbidite system (2nd order) is part of a very large (1st order) turbidite complex. As an analogy, the modern Mississippi submarine fan would be considered a turbidite system in the rock record, whereas the modern plus all of the underlying fans would be considered a turbidite complex in the rock record. This review focuses on the system scale of the classification scheme to provide a broad view of the active system. The cores and outcrop from DeGray Lake include only enough section to observe 4th order turbidite sub-stage (TSSG) deposits. A sub-stage is comprised of meter to decameter scale deposits that represent high-frequency changes in depositional and erosional processes. It should be noted that this classification scheme makes no distinction about grain size, but has been used in literature to classify fine-grained turbidites (i.e., Bouma, 2000).

The defining characteristics of the fine-grained end member of a turbidite system have previously been mentioned in this chapter. However, that definition neglected to include the actual depositional processes that form submarine fans (turbidite systems). Submarine fans can be loosely defined as the product of repeated accumulation and progradation of sediment gravity flows. Large laboratory basin modeling studies of turbidites (i.e., Simpson 1987; Ravenne et al., 1990; see both in Coleman, 1994) show that density currents emanating from a point source repeatedly produce fan-shaped deposits as long as the flow is not affected by the boundaries of the basin (Coleman, 1994). In fine-grained, mud-rich systems, turbidity currents comprise the majority of the flows, whereas debris flows are less common. It is commonly accepted that turbidity currents are developed from initial slumping of terrigenous sediments from the break of
Figure 2.4: Conceptual classification for turbidite system. (A) Hierarchy of units based on scale: decreasing in size to the right. (B) Classification in a time frame (from Mutti, 1992; Bouma, 2000). Turbidite systems are considered to be the ancient equivalents of modern submarine fans.
the continental shelf (Hampton, 1972; Middleton and Hampton, 1976; Prior and Coleman, 1984; Stow, 1986). The initial failure is most likely caused by overpressure in the sediments, causing instability, not seismic disturbances (Arnold Bouma, pers. comm., 2000). Overpressure is caused when excess fluid is trapped in the pore spaces of rapidly deposited sediments. Turbidity currents can also develop from the mouths of major rivers where high density water/sediment plumes (hyperpycnal flows) move downslope into deeper water (Prior and Coleman 1984; Stow, 1986).

The mechanism of how massive slump failures ultimately become turbidity currents has been documented (see in Chapter 4.). A slump failure is essentially a high-density gravity flow which exhibits plastic (non-Newtonian) flow rheology. In contrast, a turbidity current exhibits fluid (Newtonian) rheology (Shanmugam and Moiola, 1995). In order for a massive slump to organize itself into a turbidity current, a shift in flow rheology must occur. One hypothesis suggests that the flow enters a transitional stage at the base-of-slope where it encounters a sudden decrease in gradient (Hampton, 1972). At the base of slope, the flow loses some sediment and becomes water enriched, possibly entraining water as it flows.

Different fine-grained, mud-rich end members of turbidite systems should have geometric relationships that are ultimately the result of similar depositional processes. Many workers have developed models for fine-grained turbidite systems (i.e., Shanmugam and Moiola, 1991, 1995; Reading and Richards, 1994; Bouma et al., 1995, 2002; Sullivan et al., 2000). Others (Mutti, 1977, 1985, 1992; Walker, 1978; Sullivan et al., 2000) have developed models from more coarse-grained systems, but include depositional features that are applicable to both fine and coarse-grained systems. In the following paragraphs, the components of these models will be reviewed.

According to Coleman (1994), a successful model must act as an integrated basis for interpretation.
becomes a common body of knowledge. There are many models of turbidite systems. A detailed account of every model would require a very lengthy discussion, beyond the scope of this study. In the following review, the details of one well integrated model will be discussed and compared to other models.

The Bouma et al. (2002) model (Figure 2.5) is a composite based on studies from modern fans in the Gulf of Mexico, including the Mississippi Fan, and many outcrop studies on the Jackfork Group in Arkansas and the Tanqua Karoo Subbasin in South Africa. All of these locations are considered to be near the fine-grained end of the turbidite continuum. This model is large in scale. It considers the entire depositional system of a fine-grained submarine fan, from feeder canyon on the shelf to the distal fan lobes. In this model the turbidite system is divided into the upper fan, middle fan, and lower fan.

**Upper Fan**

The upper fan is located on the continental, or basin, slope and includes the upper fan canyon and the lower slope fan valley. Four types of sediment gravity flows originate in the upper fan: slides, slumps, debris flows, and turbidity currents. The slides and slumps that occur away from the main channel are ultimately thought to become debris flows. Turbidity currents are thought to be the result of initial slumping within the main canyon, or can originate from a dense sediment plume that enters the canyon directly from the mouth of a major river (Prior and Coleman, 1984; Stow, 1986).

Considering the upper fan, Reading and Richards (1994) have illustrated the need to consider turbidite systems with multiple sources (Figures 2.6 and 2.7). They contend that turbidite systems can have a point source (Figure 2.5), multiple source (Figure 2.6), or linear source (Figure 2.7). Interestingly, Reading and Richards (1994) point out that the turbidite complex for the Mississippi fans would look like a multiple source system in the rock record. This is due to the fact that over the last 3.5 m.y. the point source location
Figure 2.5: Fine-grained, mud-rich, point source turbidite system model (from Bouma et al., 2002). Note the presence of only one active channel at a given time in the middle fan. This channel originates in the upper fan, and no distributaries occur until the lower fan. Compare this model with Figures 2.6 and 2.7.
Figure 2.6: Depositional model for a multiple source, mud-rich turbidite system (from Reading and Richards, 1994). Reading and Richards differentiate between mud-rich and mud/sand rich turbidite systems. The mud-rich system has been chosen as the most analogous to the fine-grained, mud-rich end member.
Figure 2.7: Depositional model for a linear-source, mud-rich turbidite system (from Reading and Richards, 1994). Note the emphasis on debris flows vs turbidity currents. This model is appropriate for the interpretations made by Shanmugam and Moiola (1995) for the Jackfork rocks at DeGray Lake.
has moved at least 17 different times (Weimer, 1990). Therefore, it may be more appropriate to use the term multiple point source system when describing the entire complex.

Middle Fan

The middle fan contains two types (types 1&2) of channel deposits, levee-overbank deposits, and crevasse splay deposits (Kirschner and Bouma, 2000). Both type 1 and 2 channel deposits result from turbidity currents that are confined to the channel, however type 2 channels have a lower aspect ratio (width/thickness ratio of channel fills). Typical aspect ratios for type 1 channels are less than 50, whereas the minimum aspect ratio for type 2 channels is 150-200. Both types 1 and 2 channel deposits are characterized by massive sand deposits overlain by plane parallel laminated sands. The levee-overbank deposits are laid down when turbidity currents overtop the levees and deposit sediment away from the channel. Thin-bedded sandstones and shales comprise all of the levee-overbank deposits and can be distinguished from the main channel deposits based on the lesser vertical thickness of the sandstone beds. The crevasse deposits occur when a levee is breached by a turbidity current. These deposits have different paleocurrent directions and an overall coarsening-upward trend that will distinguish them from the channel sands.

Mutti (1977) has recognized the depositional facies of Bouma et al. (1995, 2002) but included them in the inner fan of his model (Figure 2.8). Figure 2.9 details the equivalence of some of the facies. An additional depositional facies, not included in the Bouma model, is the channel mouth bar (Figure 2.8). Channel mouth bars are thought to be deposited when turbidity currents abruptly change from confined to unconfined flow conditions as well as when the slope decreases. They can be distinguished from other deposits within the inner fan by paleocurrents and by large scale cross-banding that is typically absent in this part of the fan.
Figure 2.8: Depositional model for the Eocene Hecho Group (South-central Pyrenees, Spain) turbidite system as inferred from observed facies and facies relationships (from Mutti, 1977). The inner fan is characteristically similar to the middle fan from Bouma (1995). The major deviations from the Bouma (1995) model are the presence of the channel mouth bar (CMB) and the presence of multiple active channels.
Figure 2.9: Relationships and terminology of channel and interchannel turbidite facies observed in the inner fan deposits of the Hecho Group system (from Mutti, 1977). *Some characteristically similar Bouma (1995) facies are: inter-channel facies = overbank deposits, broadly channelized inter-channel sandstone beds = crevasse splays, channel axis facies = types 1&2 channel deposits.
Lower Fan

The lower fan is comprised of distributary channels and numerous compensationally stacked sheet sands (depositional lobes). The distributary channels form by avulsing turbidity currents. Massive and parallel laminated sands are dominant in these channels. The sheet sand lobes are formed when the turbidity current is no longer confined by the channel. These deposits are characteristically massive and can be laterally extensive in sand-rich fans (according to Mutti, 1977). Depending on the frequency of turbidity currents, the sheet sands will have either amalgamated contacts, be separated by thin hemipelagic muds, or both over restricted distances. These sheet sands, although distal, are the result of very efficient turbidity currents and therefore exhibit very high net-to-gross ratios (% sandstone vs % shale).

Walker (1978) and Mutti (1985) both considered the lower part of the fan to include non-channelized depositional lobes. Mutti (1985) identified Type I turbidite systems in the lower fan. Type I turbidite systems contain the bulk of sandstone deposition in non-channelized and elongate bodies or lobes in the outer reaches of the system. Walker (1978) divided the fan into three parts: upper, middle, and lower. He distinguished the upper fan and the upper reaches of the middle fan from the lower reaches of the middle fan and lower fan by channelization and facies succession. Channelized areas (upper fan and the upper reaches of the middle fan) are recognized by a fining- (or thinning-) upward pattern, whereas the non-channelized (or lobe) areas (lower middle to outer lower fan) are characterized by a coarsening- (or thickening-) upward sequence. The terms coarsening upward and fining upward are successfully used when considering coarse-grained fan progradation.

Integrated Industrial Fan Model

Depositional models of turbidite systems are of great importance to the petroleum industry because they can provide the framework to exploit large hydrocarbon
accumulations that turbidites are known to contain. Industrial models are built from subsurface data that would not be recovered if economic hydrocarbons could not ultimately be exploited. A depositional model that incorporates this subsurface data with outcrop studies is examined in the following paragraphs.

Sullivan et al. (2000) have developed a depositional model for the Diana Subbasin in the western Gulf of Mexico that is well integrated with seismic, well log, and core data from the modern basin, as well as outcrop studies from the Permian Skoorsteenberg Formation in the Tanqua Karoo Basin, South Africa, and the Lower Carboniferous Ross Formation in the Claire Basin, western Ireland. Based on a detailed characterization of channel aspect ratio, net to gross, erosional vs non-erosional contacts, and sandstone continuity, Sullivan et al. (2000) divided the outcrops into (i) proximal, (ii) transition from proximal to medial, and (iii) medial fan settings (Figure 2.10). The most proximal settings are characterized by erosionally confined, channelized sandbodies. These areas have low aspect ratio channels, high net to gross (approx. 90%), erosional channel contacts, and excellent vertical and low lateral continuity of sand bodies. Very broad, compensationally stacked channel complexes dominate the transition from proximal to medial fan settings. The medial fan setting is comprised of extremely broad channels to sheets. The medial fan has high aspect ratio channels, moderate net to gross (approx. 65% to 80%), non-erosional contacts, and moderate vertical and high lateral continuity of sand bodies. Distal fan deposits are also present, but were not a major focus of Sullivan et al. (2000) due to their limited reservoir potential and relative poor exposure. These areas have moderate to low net to gross (approx. 40% to 60%), non-erosional contacts, and moderate lateral continuity of sand bodies.

To better assess pre-drilling predictions in the Diana Subbasin, Sullivan et al. (2000) attempted to identify the architectural characteristics of the Skoorsteenberg and Ross Formations that were imbedded in the seismic responses. Depth models were
Figure 2.10: The deep-water deposits of the Skoorsteenberg Formation in Tanqua Karoo Basin, South Africa can be subdivided into proximal, medial and distal fan settings each with their own key characteristics (from Sullivan et al., 2000).
created by applying subsurface rock properties (density and velocity) for outcrops from the Ross and Skoorsteenberg Formations. Forward seismic models were then generated from these depth models. The higher frequency (45-60 Hz) forward seismic models showed the most detail of the outcrops. Figure 2.11 illustrates the three step method of creating forward seismic models from raw outcrop data.

**Summary of Depositional Criteria**

As outlined in the methodology in Chapter 1, the middle submarine fan environment provides the framework to make depositional interpretations. The previous review established that the middle fan includes several subenvironments characteristic of channelized interchannel deposits. The criteria for distinguishing between these environments is developed below, primarily to aid in understanding the interpretations made in Chapter 3.

Deep water sediments transported to the middle submarine fan can end up as either channel fill deposits or interchannel deposits, or the sediments can bypass the system entirely in route to the outer fan. Channel fill deposits can be distinguished by having the highest sandstone/mudstone ratio in the system, numerous thick-bedded sandstones with amalgamated contacts, and are generally massive (T_a) with some minor parallel laminations (T_b). They also exhibit a fining- and thinning- upward facies succession in contrast to depositional lobes which are progradational and coarsen- and thicken-upward (Walker, 1978). Individual channel fill successions can be further subdivided into channel-axis, channel-off-axis, and channel-margin associations (Sullivan and Templet, 2002). The difference between the channel fill subdivisions is gradual, and not easily recognized, unless the entire channel fill is exposed in outcrop. Basically, as the sediment is deposited further from the channel, it becomes more mud-rich, thinner-bedded, and contains more parallel laminated and rippled sandstones (T_c). Interchannel deposits are characteristically more mud-rich, thinner-bedded, and show more T_{bc} current
Figure 2.11: Forward seismic model for the proximal to medial fan transition channels of the Ross Formation. (A) Outcrop photo from compensationally stacked channel complexes. (B) Depth model for this outcrop by applying subsurface rock properties. (C) Forward seismic models for 45 and 30 Hz are shown. Individual channel complexes are best resolved on the higher resolution (45 Hz) seismic model (from Sullivan et al., 2000).
structured sandstones than their channelized counterparts. Interchannel deposits include levee/overbank and crevasse splay deposits (Bouma, 2002). Crevasse splay deposits are recognized by coarsening- and thickening- upward successions and deviations in paleocurrent up to 90° from the main channel flow direction. Again, it can be difficult to distinguish between channel margin deposits and interchannel deposits unless you have the complete boundary exposed in outcrop, as did Kirschner in the Tanqua Karoo (Kirschner and Bouma, 2000).
CHAPTER 3: CORE AND OUTCROP CHARACTERISTICS RELATED TO DEPOSITIONAL PROCESSES IN DEEP SEA FANS

Introduction

It is known that most submarine fan sediments have been recycled through many phases of deposition and erosion. In most cases, fine-grained depositional systems, such as the Jackfork Group at DeGray Lake, are the end products of terrigenous sediments that have passed through continental fluvial systems, coastal plain fluvial systems, and shelf margin deltaic systems on their way to the deep sea. Upon reaching the outer continental shelf, the sediments are once again remobilized by various resedimentation processes that ultimately determine the following principal depositional features: grain size and textural attributes, sand/mud ratio, bed thickness and geometry, internal organization of beds, fabric, composition, and sedimentary structures (Stow, 1986). In the ideal case, the cores and outcrop in this study could be divided into separate zones, each characteristic of one resedimentation process. However, the morphological and sedimentological end result of a particular resedimentation process do not always show the principal features characteristic of that process (Prior and Coleman, 1984). In spite of this, the following sections attempt to use key characteristics of both outcrop and core to identify the primary resedimentation processes involved in bringing the sediments into the deep-water system as well as identify any secondary resedimentation processes that have altered the deposits after initial deposition.

There are numerous resedimentation processes that affect deep sea sediments once they reach the edge of the continental shelf (Hampton, 1972; Middleton and Hampton, 1976; Prior and Coleman, 1984; Stow, 1986). Stow (1986) defines resedimentation processes as those processes that move sediment downslope over the sea floor from shallower to deeper water and are driven by gravitational forces. Stow includes the following list of resedimentation processes: rock fall (synonymous to submarine fall), sediment creep, slide, slump, debris flow, grain flow, fluidized flow,
liquefied flow, high-density turbidity current, and low density turbidity current. In addition to these, slurry flow (Lowe and Guy, 2000) is also considered to be an important resedimentation process.

Most fine-grained deep-water systems receive sediment from resedimentation events initiated on the edge of the continental shelf. During relative lowstands of sea level, narrow continental shelves allow large volumes of sediment to quickly reach the shelf edge (Mullenbach and Nittrouer, 2000). This was the case for the Mississippi Fan, when during the late Wisconsinan glaciation sea levels were lower, allowing fluvial systems to prograde out to the shelf break and build shelf edge deltas (Suter and Berryhill, 1985). Here sediments are deposited rapidly, contributing to oversteepening and overpressured sediments which result in instability and ultimately failure (Prior and Coleman, 1984). Catastrophic failures along the shelf edge scour submarine canyons which can be important conduits of terrigenous sediment from shelf environments to the deep sea (Mullenbach and Nittrouer, 2000). Many resedimentation processes will be initiated at this point, the head of the canyon.

The following sections attempt to discuss the flow mechanics and resultant deposits of each of the resedimentation processes listed earlier. Special emphasis will be placed on examples from core and outcrop.

**Resedimentation Processes**

**Submarine Falls**

Submarine falls are the free fall of rock, mud or sand sized particles (Prior and Coleman, 1984). These are relatively rare at sea because most slopes are too gentle (Stow, 1986). However, they have been known to occur along the walls or at the heads of deeply incised submarine canyons (Prior and Coleman, 1984; Stow, 1986). Submarine fall deposits can be easily identified by the presence of large displaced clasts, known as, olistoliths. Submarine falls most likely loose momentum rather quickly once they encounter shallower slopes, prohibiting them from traveling long distances. If this is the
case, one should expect to find these within the slope or at the base of slope in a
submarine fan. In this study, submarine fall deposits could not be identified from either
core or outcrop.

Slides

Sliding involves downslope movement of a semi-consolidated or cohesive
sediment mass down a basal shear plane while retaining most of its internal (bedding)
coherence (Stow, 1986). Massive slides can occur off the edge of continental shelves
when huge blocks of sediment slide down the slope en masse, as was the case for
Pinnacle Mountain, west-northwest of Little Rock, Arkansas. It is clear that most slides
become slumps and ultimately flows with continued downslope movement as the
sedimentary layers progressively disintegrate (Prior and Coleman, 1986). While there is
no record of major slide deposits from the continental slope at DeGray Lake, slides have
played a major role in influencing the sediments in two ways. First, many of the
sediment gravity flows were probably initiated as slides (Hampton, 1972; Middleton and
Hampton, 1976, Prior and Coleman, 1984; Stow, 1986); second, both core and outcrop
reveal sliding has played a role in altering the deposits on the sea floor. In fact, Prior and
Coleman (1984) indicate that offshore surveys are showing that sea-floor instability can
occur in extremely small low angle slopes (<1°). Based on this information, it is not
unreasonable to expect that sliding would occur down localized slopes on the sea floor.

Figure 3.1 shows a good example of secondary sliding in very thin-bedded strata from
Package O in the east wall of the spillway. The wavy character of these beds indicates
some deformation has taken place, but was not severe enough to obscure the original
bedding. The entire depositional Package M above the massive debris flow appears to
have been altered by either erosion, or resedimentation, or likely a combination of both.

Figure 3.2 is a core photograph showing how thin muddy laminae in a fine-grained
sandstone have been distorted, possibly due to sliding. Distorted laminae, such as in
Figure 3.1: Outcrop photograph of package O from the east wall of the spillway, showing wavy bedding in very thin-bedded units consistent with deformation due to sliding (see arrow). The entire depositional package shows deformation likely due to erosion and also resedimentation.
Figure 3.2: Photograph of core section from core T-31. The muddy laminae in this sandstone are slightly distorted from either sliding or sediment creep. Laminae at the top of the photograph are almost horizontal, in contrast to the lower laminae which dip slightly to the right. Both laminae are out of phase with bedding dip angles for core T-31, which range from 45°-50°.
Figure 3.2 are very common from the core sections, indicating secondary resedimentation is a significant factor in these deposits.

**Slumps**

Slumping occurs by the same process as sliding, where sediment moves downslope along a basal shear plane (Stow, 1986). The major difference between the two is the degree of internal (bedding) deformation. Prior and Coleman (1984) suggest that the term slump is often misused and that slide and slump deposits are often confused. For the purposes of this study, slump deposits will be distinguished from slide deposits by their greater degree of internal deformation. Large slump deposits are absent from DeGray Lake, just as are large slide deposits. However, their importance to the sediments is by secondary resedimentation, much the same as slides. Slumps can also deteriorate into sediment gravity flows with continued downslope movement (Hampton, 1972; Middleton and Hampton, 1976, Prior and Coleman, 1984; Stow, 1986); or occur on the sea floor. Several core sections show intensely deformed layers of silt and mud that were probably the result of small localized slumps on the sea floor. Figure 3.3 A shows a core section where thin siltstone and mudstone beds have been tilted and folded over. In the case of Figure 3.3 B, more severe slumping has almost wiped out any trace of original bedding.

**Sediment Creep**

Sediment creep is a process of slow strain due to constant load induced stress that may extend over periods ranging from hours to thousands of years (Stow, 1986). Sediment creep is not often attributed to the deep sea, but is probably widespread (Stow, 1986). Sediment creep most likely occurs on localized slopes in the deep sea, just like slides. One of the problems this flow presents is how to distinguish deposits altered by creep from those altered by slides. The flow speeds are quite different, but the internal deformation of the beds is limited in both cases. For this reason, it is difficult to distinguish between the two in core and outcrop. Likely both have played a significant
Figure 3.3: Photographs from core G-121 top and core T-39 bottom. Figure 3.3 A shows very pronounced internal deformation of mud and silt layers due to slumping. Deformation in Figure 3.3 B is much more severe. Only faint remnants of initial layering remain. This is a good example of a flow deposited in the transitional phase between slump and debris flow.
role in the deposits at DeGray Lake. Figure 3.2 and at least the upper beds in Figure 3.1 could well be from sediment creep instead of sliding.

**Sediment Gravity Flows**

The remaining resedimentation processes to be covered are most often referred to as sediment gravity flows in the literature (Hampton, 1972; Middleton and Hampton, 1976; Prior and Coleman, 1984). Sediment gravity flows consist of sediment moving downslope under the action of gravity (Middleton and Hampton, 1976). They are distinguished from slides and slumps on the basis of complete internal deformation (Middleton and Hampton, 1976). In fact, many sediment gravity flows are the result of slides and slumps disintegrating as they continue to move downslope. Several authors (Hampton, 1972; Middleton and Hampton, 1976; Prior and Coleman, 1984) list four main sediment gravity flows: debris flows, grain flows, fluidized flows, and turbidity currents. Stow (1986) lists liquefied flows in addition to these. More recently, Lowe and Guy (2000) have emphasized the importance of slurry flows in deep-water systems. Each of these flows can be characterized by having a different sediment support mechanism.

Middleton and Hampton (1976) acknowledged that categories of flows consist of conceptual end members, whereas real flows exist throughout a continuum between these end members. In most real sediment gravity flows, more than one grain support mechanism will be important. This fact makes distinguishing between flows in the sedimentary record difficult.

**Debris Flows**

Debris flows are flows in which the larger grains are supported by a “matrix” that is, by a mixture of interstitial fluid and fine sediment, which has a finite yield strength and displays plastic flow behavior (Middleton and Hampton, 1976; Prior and Coleman, 1984; Stow, 1986). Most debris flows are thought to originate from slides and slumps that progressively disintegrate as they move downslope. Hampton (1972) states that a debris flow can be expected to develop from a landslide or a slump if there is sufficient
agitation of the slide mass and a supply of water. Examples from the cores suggest that this process can operate at a small scale as a secondary resedimentation process on the sea floor. One of the lithofacies commonly found in the cores consisted of angular siltstone clasts supported by a mudstone matrix. These are generally found in thin sections (10-20 cm). Close inspection of these sections and comparison with slump deposits show that they are possibly related by the previously discussed slumping to debris flow transition. In fact, if one compares Figures 3.3 A, 3.3 B and 3.4, a progressive slump to debris flow transition can be separated into three stages: slumping with moderate deformation where layers remain in tact (3.3 A), slumping associated with severe deformation where layers are barely discernible (3.3 B), and debris flow associated with complete disintegration of layering (3.4). Thick sections of large-scale debris flows, considered primary resedimentation processes, are not found in the cores, but do occur in several outcrop sections. Figure 3.5 shows a thick debris flow deposit from the Spillway. The large boulders and cobbles randomly oriented in this section illustrate how debris flows deposit sediment “en masse” by cohesive freezing.

Turbidity Currents

Turbidity currents involve the downslope transport of sediment which is supported by the upward component of fluid turbulence. It is argued that turbidity flow can be sustained for great distances (4000 - 5000 km) in the form of autosuspension (Stow, 1986). These great distances can be covered because with autosuspension all that is needed to keep the system going is that the energy loss caused by friction should be compensated by the input of gravitational (potential) energy as the current moves downslope (Middleton and Hampton, 1976). Turbidity currents are believed to occur off the mouths of major rivers where high density water/sediment plumes move downslope into deeper water (Prior and Coleman 1984; Stow, 1986). They can also occur in association with submarine slides and debris flows (Hampton, 1972). Hampton (1972) provides a comprehensive discussion about how debris flows can become turbidity
Figure 3.4: Photograph of core fragment from core G-109. Angular pebble sized clasts of siltstone are supported by a mud matrix in this debris flow deposit. The clasts are fragments of initially horizontal siltstone beds that were disintegrated during transport within a debris flow. Compare this photograph to those in Figures 3.3 A and 3.3 B to see deposits that represent stages in the transition from slump to debris flow.
Figure 3.5: Outcrop photograph of a 6.5 m thick section of the debris flow deposit from depositional package N from the east wall of DeGray Spillway. Large floating cobble- to boulder-sized clasts show the characteristic “en mass” deposition by cohesive freezing.
currents by mixing and incorporating water. Two different types of turbidity currents are separated into high-density (50-250 g/l) and low density (0.025-2.5 g/l) (Stow, 1986), based on sediment concentrations within the flow.

**Low Density Turbidity Currents**

Low density turbidity currents are made up largely of clay- to medium sand- sized particles (Lowe, 1982). These small particles can easily be suspended by flow turbulence. Lowe (1982) suggests that low density turbidity currents typically show an initial period of traction sedimentation, forming Bouma $T_b$ and $T_c$ divisions, followed by one of mixed traction and suspension ($T_d$), and a terminal period of fine-grained suspension sedimentation ($T_e$). The majority of the grain sizes at DeGray Lake are in the clay- to medium sand- size range, suggesting a significant influence from low density turbidity currents. The only exceptions are some larger pebble sized quartzite clasts, occasionally found in ($T_d$) massive sand bodies. Figure 3.6 shows the lower half ($T_{bc}$) of a typical sequence of a low density turbidity current as described by Lowe (1982). Notice in the figure that the basal massive sandstone ($T_a$) from the classic Bouma Sequence (Bouma, 1962) is absent. Lowe argues that the $T_a$ division does not belong in the sequence of structures deposited by low-density turbidity currents, but is the final stage of suspension sedimentation in high-density turbidity currents.

**High Density Turbidity Currents**

The sediment loads of high-density turbidity currents can include grains ranging from clay- to cobble size (Lowe, 1982). Since virtually all of the sediments at DeGray Lake are smaller than medium sand size, this section focuses the discussion on high-density turbidity currents that include grains in that size range. One consequence of separating the $T_a$ division from the $T_{bc}$ divisions is that two separate flow types are necessary to form the complete Bouma Sequence. Lowe (1982) suggests that high-density turbidity currents are deposited first in three stages ($S_1$, $S_2$, $S_3$) and then the same flow becomes low-density and $T_{bc}$ strata are deposited. As a result, often it is the case that
Figure 3.6: Photograph of a parallel laminated (Tₚ) sandstone that grades into current ripple laminated (Tᵣ) sandstone from package G in the east wall of the DeGray Spillway (quarter for scale). These two traction structures are typical of low-density turbidity currents.
the $T_a$ division is attributed to deposition by high-density turbidity currents (Lowe, 1982; Stow, 1986; Kneller and Branney, 1995).

One of the more interesting questions about the Jackfork strata at DeGray Lake and about fine-grained deep-water systems in general is what flow mechanism(s) are responsible for creating thick massive sands with little or no traction structures? This question is of considerable importance to this study because fine- to medium grained massive sands ($T_a$) comprise the majority of the deposits in both core and outcrop. Middleton and Hampton (1976) do not invoke the need for $T_a$ sandstones to be deposited by high-density turbidity currents. They suggest that massive sands are deposited rapidly, burying the sediment before an extended phase of traction can develop. Lowe (1992) invokes deposition by direct suspension sedimentation during the waning stages of high density flow, where sediment is deposited at a significantly higher rate. The problem with trying to apply this idea to the Jackfork at DeGray Lake is twofold. First, Lowe suggests high-density flows have a traction phase before suspension sedimentation, similar to low-density flows. The problem with that is no traction structures are observable at the base of thick, massive sands. Second, the complete high-density model ($S_1, S_2, S_3$) for deposition is based on coarse-grained deposits, which are absent at DeGray Lake. Kneller and Branney (1995) add that massive sand divisions appear to be the products of discrete depositional events from one or more gravity currents. They question the notion that massive sands are deposited by rapid dumping due to flow unsteadiness, and suggest that deposition occurs by gradual aggradation from a sustained, quasi-steady high-density current.

In high-density turbidity currents sediment concentrations are high enough to suggest more than one grain support mechanism is active within the flow. Shanmugam and Moiola (1995) have used Lowe’s (1982) ideas for hindered settling, matrix buoyant lift, and dispersive pressure as being part of a high-density turbidity current and alternatively suggested these are all properties of debris flows. This information, along
with a high average matrix content (10-25%) and lack of graded bedding in sandstone deposits from the Jackfork have led them to suggest deposition by sandy debris flows instead of high-density turbidity currents.

It appears that the answer to the question: How are thick massive sands with no traction structures deposited?; is still not completely clear. There seems to be somewhat of a consensus that Ta sandstones are deposited from higher-density flows than the Tb-e divisions. If this is the case, it is likely that flow turbulence is aided by grain to grain collisions, hindered settling, and possibly matrix buoyant lift in the highest concentration flows. Multiple grain support mechanisms should not be surprising because nature doesn’t always follow the standards man sets by defining its processes.

**Slurry Flows**

Slurry flows are muddy, sand-rich sediment flows that exhibit both turbulent and cohesive sediment support. They are transitional between end-member turbidity currents and debris flows (Lowe and Guy, 2000). Typically, slurry flow deposits have 10-35% mud matrix, fluid escape structures, and floating or aligned mudclasts (Lowe and Guy, 2000). Sullivan and Templet (2002) have noticed core sections from the Diana Subbasin in the western Gulf of Mexico as being similar to the slurry flow deposits described by Lowe and Guy (2000). The abundance of unaligned, floating shale clasts, pipes and dish structures, and irregular internal banding all suggest these sandstones are sandy debrites deposited by non-turbulent suspension. However, Sullivan and Templet (2002) suggest that some of the more cohesive deposits, thought to be deposited by turbidity currents, may in fact be the result of slurry flows. Again it seems there remains some uncertainty about the flow processes that created these muddy sandstones. Slurry flows are an important process to consider because muddy sandstone deposits resembling slurry flows or sandy debrites are found in distinct units in all but one (T-39) of the borehole cores (Figure 3.7).
Figure 3.7: Photographs from core T-14 top and core T-31 bottom. Both core sections are comprised of muddy sandstone with vertical to sub-vertical fluid escape structures. Figure 3.7 A is more sandy and appears to have a lower percentage of mud matrix than Figure 3.7 B, and so more closely resembles a slurry flow deposit. Petrographic analysis of a thin-section taken from Figure 3.7 B reveals a matrix content of approximately 40%, which supports a sandy debris flow origin.
Grain Flows

Grain flows are quasi-visco-elastic flows characterized by grain-to-grain collisions that result in a dispersive pressure sediment support mechanism (Stow, 1986). They require steep slopes (>18°) and so are probably very localized processes in the deep sea. Grain flows have been observed from the heads of submarine canyons (Prior and Coleman, 1984). Because they are so localized, grain flows have probably not played much of a role in the deposits at DeGray Lake.

Liquefied and Fluidized Flows

Liquefied and fluidized flows are related processes in which grain support is provided by upward-moving pore fluids (Stow, 1986). These flows rarely occur alone as a separate process in the deep sea, but commonly take place during the final stages of a high-density turbidity current (Stow, 1986; Kneller and Branney, 1995). Kneller and Branney (1995) suggest that fluidization during the final stages of a high-density may be responsible for obliterating any traction sedimentation structures, resulting in massive sand (Tₙ) deposits.
CHAPTER 4: X-RAY RADIOGRAPHY AND GAMMA-RAY PROFILING OF CORE SECTIONS

X-Ray Radiography

Thick massive sands are volumetrically very important in fine-grained turbidite systems. Fine- to medium-grained massive sandstone (Tₙ) is the most commonly occurring lithofacies in this study. Kneller and Branney (1995) have suggested that thick massive sands accumulate from a succession of different high-density turbidity currents. Several other hypotheses about the depositional mechanisms that created these sands are presented in Chapter 3. This section addresses this topic by using X-ray radiography to identify any flow boundaries that may be present, but not visible to the naked eye.

The results from the X-ray negatives showed that no flow boundaries could be positively identified (Figure 4.1). The negatives did, however, show significant contrast due to color bands created by iron staining. Pore fluids likely encountered areas in the core with higher iron contents. The iron was then oxidized in these areas, revealing light bands in the X-rays and dark red bands in the cores. Fluids encountered areas in the massive sandstone that were slightly different iron content. These bands alone do not provide enough evidence to support that these compositional variations correspond to separate depositional events.

Gamma-Ray Profiles

Gamma-ray profiles were attempted for cores T-14 and T-31. These were to be compared to the lithologies in the core and to gamma-ray profiles from outcrop. The hand-held scintillometer consistently produced readings between 90 to 115 counts per second (cps) for both cores. Background radiation in the core processing produced readings in that range. Compared to other outcrop studies that used the same instrument, the readings were dramatically lower. Rehmer (2000) and Wyble (2001) reported readings from deepwater turbidites in the Tanqua Karoo Subbasin, South Africa, in the 200 to 400 cps range. Based on the considerably higher values from those studies as well
Figure 4.1: X-ray image of core sections 11-13 from the upper meter of core T-14. The massive sandstones do not show any discrete boundaries related to separate flow events. Contrasting bands, parallel to bedding in section 13, precisely match iron stained bands from the original cores. The iron staining is probably due to permeability variations and not necessarily depositional events. The bright, elongate structures near the top of section 13 are aligned mud rip-up clasts.
as the CPS values for background radiation, the gamma-ray profile data can not be relied upon to draw any significant conclusions for correlation purposes.

Three samples from cores T-31 and T-14, along with the gamma-ray scintillometer, were taken to the Radiation Safety Office at Louisiana State University for a more thorough gamma-radiation analysis and also to check the accuracy of the instrument. The scintillometer was tested against another and proved to be functional.

Each of the core samples showed a detectable level of nuclide gamma-ray activity. The mudstone had the highest level (52.1 pCi/gm), followed by the matrix-poor sandstone (11.1 pCi/gm), and the muddy sandstone had the lowest level (10.3 pCi/gm). The activity of the mudstone was five times greater than the other samples primarily due to a high nuclide activity of K-40 (31.2 pCi/gm). A summary of the nuclide activity from the major elements is given in Table 4.1. Although significant differences in gamma-ray activity could be detected by the more sensitive spectrometer, the total activity from each sample is still too low for accurate readings from a hand-held field scintillometer. This suggests that the area sampled from 2-in borehole cores is not large enough to provide reliable data. Thus, a hand-held scintillometer is not an appropriate tool for making gamma-ray profiles of 2-in cores.
Table 4.1: Total nuclide activity (pCi/gm) and nuclide activity of K-40, TH-231, and U-234 for the three core samples. The nuclide activity of the mudstone is five times higher than the others due to an increased K-40 content. The sandstone sample shows the lowest abundance of K-40, possibly due to low mud content. The symbols for nuclide activity indicate the following: p =10^{-12}; Ci = 3.7 x 10^{10} decays /second; gm = gram.

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<th>SAMPLE</th>
<th>NUCLIDE</th>
<th>ACTIVITY</th>
<th>NUCLIDE</th>
<th>ACTIVITY</th>
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CHAPTER 5: CORE AND OUTCROP DESCRIPTIONS

Core Descriptions and Interpretations

In this section general descriptions are given first for each core, followed by depositional interpretations. Lithologic columns for each core have been included to follow the written descriptions and interpretations. An explanation of the lithologic symbols used in the columns is provided in Figure 5.1.

Core T-14

General Description

Core T-14 includes 14.7 m of strata taken from underneath the present day location of the DeGray Dam Powerhouse (Figure 1.2). Core T-14 has the highest net to gross of all cores, consisting of nearly 100% sandstone (Figure 5.2).

Massive, fine- to medium-grained sandstone (T_a from the Bouma Sequence) is the dominant lithofacies in core T-14. Stacked, fine- to medium-grained massive sandstone beds comprise almost the entire 14.7 m. Most beds are separated by amalgamated contacts. Thin layers (< 1 cm) of (T_e) mudstone and silty mudstone (T_d) can be present between the contacts. The massive sandstone beds are internally structureless and no grading is apparent. Occasionally iron stains occur in layers or concentric patterns as evident in Figure 5.3. Post depositional features include joints, fractures, quartz veins, and abundant iron staining.

Massive, fine-grained muddy sandstone (S_f) is interbedded with the dominant lithofacies in two different sections of core T-14. From 5.8-6.2 m the core is comprised of massive, fine-grained, gray muddy sandstone with light-gray fluid escape structures. From 11.5-12.9 m the core is comprised of fine-grained, gray muddy sandstone with light-gray fluid escape structures and floating, elongate mud clasts.

Mud-rich, fine-grained sandstone is discrete and distinguishable from the dominant lithofacies, having a sharp depositional contact with the dominant massive sandstone facies. There is no apparent grading from matrix poor to matrix rich.
<table>
<thead>
<tr>
<th>SYMBOL</th>
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<tr>
<td></td>
<td>Parallel lamination</td>
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<td>Wavy lamination</td>
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<td>Convolute lamination</td>
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<td>Current ripple lamination</td>
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<td>Loading structure</td>
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<td>Fluid escape structure</td>
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<td>Mud clast</td>
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**Figure 5.1:** Key to the descriptive symbols used in all of the lithologic columns.
Figure 5.2: Lithologic column of core T-14. Most of this core is comprised of fine- to medium-grained massive sandstone. Close inspection reveals that several sections are slightly muddy and have vertical fluid escape structures, characteristic of slurry flow deposits. The entire core is comprised of channel axis deposits, similar to those found in Package N from the DeGray Spillway.
Figure 5.3: Photograph of a section of fine-grained massive sandstone from the upper 2 m of core T-14. The concentric pattern and darker layering are the result of iron-staining.
sandstone. A general analysis of composition from a thin section at 6 m showed approximately 30%-40% mud matrix. Upon first inspection, this lithofacies could be incorrectly described as a sandy or silty mudstone, but the thin section revealed that the quartz sand clasts are self supported and comprise better than 60% of the sample.

Parallel laminated, fine-grained sandstone (Tb) is common and found in several sections of the core. Laminated sections are generally less than 14 cm thick, with one exception. At 9.5 m a laminated section is quite thick and continues until 10.3 m. Laminations at the top of this section grade from parallel- to wavy- to slightly convoluted. In most cases the laminations have minor amounts of mud that make them distinguishable.

Mudstone is absent from core T-14, except for one 7 cm thick section, which separates two massive sandstones. In this small section, the mudstone is dark in color and has very fine-grained sand- to silt laminae.

**Interpretation**

The massive sandstone deposits of core T-14 are interpreted as high concentration turbidity currents, analogous to the Bouma Ta division, indicating rapid and turbulent deposition from suspension. A gradual decrease in velocity and sediment concentration can be deduced when the massive sandstones grade into parallel laminated (Tb) fine-grained sandstones. Notably absent from the core is rippled and cross-laminated (Tc) sandstone, which reflect a further decrease in flow energy and sediment concentration. However, in some cases Tb sandstone does reveal a slight undulatory character in response to waning flow.

The prevalence of Ta sandstone facies with amalgamated contacts and the thick-bedded nature of the depositional units suggests that core T-14 was taken entirely from a channelized depositional environment. More specifically in or near the axis of a major submarine channel. Channel axis deposits characteristically lack a high proportion of thin-bedded sandstones and mudstones that are common in other subenvironments of a
fine-grained submarine fan. Thin-bedded sandstones and mudstones can occur within the confines of a submarine channel in the margins or in or near the axis when the associated turbidity current is too small to fill the entire channel. The thin, 7 cm section of silty shale in core T-14 provides the only evidence of a turbidity current that did not fill the entire channel. Mud-rich, fine-grained massive sandstone with fluid escape structures and floating mud clasts suggest turbidity currents were not the only sediment gravity flow operating in the channelized environment. This lithofacies is characteristic of slurry flows, after Lowe and Guy (2000), or from sandy debris flows, after Sullivan and Templet (2002).

Core T-31

General Description

Core T-31 includes 17.5 m of strata taken from a location just north of the DeGray Dam Intake Control Structure (Figure 1.2). Net to gross for the entire core is approximately 80%. Core T-31 sediments are thinner-bedded overall than T-14, and represent more variability in lithofacies (Figure 5.4).

Massive, fine- to medium-grained sandstone is the most abundant lithofacies in core T-31. Amalgamated contacts are present, but depositional boundaries are usually with lithofacies other than sandstone. Post depositional features include joints, fractures, quartz veins and some minor iron staining. In a few sections of the core, the massive sandstones are very hard and dense, but not quite quartzitic.

Fine-grained, muddy sandstone is present in core T-31 in 5 different sections, the thickest measuring 1.6 m and the thinnest measuring 25 cm. Fluid escape structures, mud layers, and mud rip-up clasts are common. The thickest section, starting at 1.9 m and continuing to 0.4 m contains several distinct fluid escape structures that are more sand-rich.

Parallel- to wavy- to convolute-laminated sandstone occurs frequently in core T-31. The thickness of the laminated sections ranges from 7-21 cm. Commonly this
Figure 5.4: Lithologic column of core T-31. Channel margin deposits thin- and fine- upward into interchannel deposits in two separate sequences. Slurry flow/sandy debris flow deposits that were present in the channel axis deposits of T-14 are also found in the interchannel deposits of this core.
lithofacies occurs directly above a massive sandstone. Compared to Borehole T-14 the laminations in this lithofacies are much more convoluted (Figure 5.5). In most of the laminations, minor amounts of mudstone are present that make them distinguishable.

Core T-31 is comprised of approximately 20% silt-rich, thin-bedded mudstone separated into several sections. The thickest of the sections totaling 1.4 m and the thinnest 8 cm. Mudstone lithofacies are very blocky and micaceous and most always have very thin interbedded layers of very fine sandstone or siltstone. One 15 cm thick section of this lithofacies had enough organic material to form thin lenses of coal. The sandy and silty layers are mostly parallel to bedding, but can be wavy- to convoluted. Commonly these coarser layers in the mudstone are very thin, on the order of 1-2 cm. Small ripples and climbing ripples are also common in the sandy and silty layers.

**Interpretation**

The basal layer of core T-31 is a massive sandstone that has been recovered in an incomplete section and, therefore, is part of an undetermined depositional package. Positioned stratigraphically above this sandstone is a 1.1 m thick section of silty mudstone, interpreted to be part of the interchannel turbidite facies. Thicker sections of the same facies, without any interbedded sandstone, would be classified as distal overbank, but any interpretation other than interchannel would be based upon incomplete data. The interchannel silty mudstone has an abrupt contact with a 3.8 m thick-bedded and highly amalgamated section of massive- to parallel-laminated channelized sandstone above. This channelized section is not as thick as the succession of deposits in core T-14 and the thin 1-2 cm shale layers occur near the top suggest deposition in a more broadly channelized area, or away from the main channel axis. The thinning-upward channelized sandstone section into several alternating beds of silty mudstone and mud-rich, makes the massive sandstone similar to the slurry flow/sandy debris flow deposits in core T-14. This type of bedding association with cleaner, turbiditic sandstones would be interpreted as levee/overbank facies after Bouma (2000), but the slurry flow/sandy debris flow
**Figure 5.5:** This figure shows typical convoluted layering of thin muddy laminae in a section of fine-grained sandstone at 12.5 m in core T-31.
deposits were not included in this environment and therefore the deposits are given an interchannel designation.

At 8.8 m a sharp contact between silty mudstone and massive sandstone indicates a change in depositional subenvironment. Stacked, massive-to parallel laminated, sandstones in both thick and thin-bedded intervals, which indicate the channel margin subenvironment after Sullivan et al. (2002), occur for 3.5 m. The numerous wavy- to convolute thin mud laminae between sand contacts and laminated sandstones that occur in this interval are a common feature to the channel margin subenvironment. Although this section has a very high net to gross (approx. 95%), the mixture of both thick-bedding and thin-bedding with the abundance of thin muddy layers and current structures preclude this section from being a channel axis deposit. Channel margin deposits are contiguous with the channel axis deposits, but they thin laterally, have more silty mudstone layers and contain more current structures. Above the channel margin deposit at 5 m starts a coarsening- and thickening- upward sequence that suggests deposition by a crevasse splay after DeVries (1992). Crevasse splay deposits are recognized as one of the few progradational features in the middle-fan depositional environment. At 1.8 m the crevasse splay deposit is overlain by channelized slurry flow and massive sandstone beds. This package is incomplete, and so is generalized as a channelized package.

**Core T-39**

**General Description**

Core T-39 includes 31.2 meters of strata taken from and area located just south of the main road over the DeGray Dam and 61 m west of the Caddo River bank (Figure 1.2). Net to gross for the entire core is approximately 85% (Figures 5.6 and 5.7).

Core T-39 includes one fining- and thinning-upward sequence. The rest of the core is comprised of thick-bedded and thin-bedded sandstones and shows no definite trends in bed thickness. At the base of the sequence are several thick beds of massive- to parallel laminated- to rippled sandstone. The sequence grades upward into alternating
**Figure 5.6:** Lithologic column of the upper 18 m of core T-39. Thin-bedded interchannel deposits are overlain by a thick section of stacked fine-grained $T_{a-c}$ channelized sandstones.
Figure 5.7: Lithologic column of the lower 13 m of core T-39. The basal section is characterized by channelized sandstones which fine- and thin-upward into levee/overbank deposits. Parallel- to wavy laminations and ripples become more common in the levee/overbank subenvironment.
thin beds of fine-grained sandstone and mudstone as well as very thin bedded silty mudstone. Ripples and climbing ripples are common in the sandy portions. The thin-bedded mudstones are black in color with thin siltstone layers.

Fine- to medium-grained massive sandstone is the dominant lithofacies in Core T-39. Individual sections range from 0.4 m to several meters thick. Amalgamated contacts are common, especially in the thicker sections. The color of the fresh surface of these sandstones ranges from gray to light gray. Fractures and joints are common. The lighter colored sections are very hard and dense, quartzitic in some sections. The upper 14.8 m of this core is very sand-rich, slightly resembling the entire core section taken from core T-14.

Laminated sandstone occurs frequently in core T-39, generally in intervals of thickness between 7-14 cm. Most laminae are parallel to bedding but sub-parallel- to convolute laminations do occur. Minor amounts of mudstone are present in the laminated layers. Laminae in some sections are near vertical.

Finer-grained and thinner-bedded lithofacies include alternating beds of parallel laminated- to rippled sandstone and sandy to silty laminated mudstone. The mudstone is dark in color with many rippled silty layers.

At 22.1 m and 12.2 m, two sections, less than 21 cm thick are characterized by a mudstone that has extremely distorted and fragmented fine-grained sand and silt layers. Layers initially deposited parallel to bedding have been turned up almost vertical if not slumped over. In several other sections of the core, mudstone with very angular pebble-sized clasts occur. The pebble-sized clasts appear to be broken off from fine-grained sand and silt layers.

**Interpretation**

The thick-bedded nature and the dominance of massive sandstone suggests the lower 8.9 m of core T-39 was taken from a channelized deposit. The abundance of current structures and mud laminae further suggest a channel margin depositional
environment. Mudstone with angular sandstone clasts in this section may have been caused by slumping of initial layered deposits which ultimately became a debris flow. The thick-bedded channel deposits gradually thin upward into thin- to very thin-bedded silty mudstone and interbedded fine-grained sandstone indicating waning channelized flow. These deposits are characteristic of levee/overbank after Bouma (2002). Wavy lamination and climbing ripples that are characteristic of the levee/overbank are the dominant traction structure (Tc) in this section.

From 15.3 m to the surface, core T-39 is similar in character to the channel margin deposits in the lower part of the core. This entire 15.3 m section includes channel margin deposits that grade upward into a channel axis deposit. The upper 2 m is entirely comprised of fine- to medium-grained massive sand, much like the channel axis sands of core T-14.

**Core G-109**

**General Description**

Core G-109 includes 17.8 m of strata taken from the north side of the present day axis of the dam and to the east of the old Caddo River channel (Figure 1.1). Core G-109 is the most mud-rich of the Jackfork cores used in this study, with sandy and silty mudstone comprising approximately 50% (net to gross) of the total core (Figure 5.8).

Massive, fine- to medium-grained sandstone lithofacies is found in several sections of the core. Bed thickness ranges from 13 cm to 3 m. Amalgamated contacts, joints, fractures, and quartz veins are common. The massive sands in core G-109 are characteristically hard to quartzitic, more so than any of the other cores.

Parallel laminated sandstones are characteristically less abundant when compared to the other Jackfork Group cores. Only one 11 cm thick section shows parallel laminations.

Sandy and silty mudstone is common in several thick sections of core G-109. Four different sections that range from 1.3-1.8 m in length along with six thinner sections
Figure 5.8: Lithologic column of core G-109. Most of this core shows the thin-bedded $T_{bc}$ sandstones and silty mudstones that are characteristic of interchannel deposits. This section has a sandstone/mudstone ratio closer to that found in the majority of the depositional packages in the Spillway.
comprise 50% of the total core. Individual sandy and silty layers are thin (1-2 cm) and have small climbing ripples. Several thin sections of mudstone without any silty laminations are also present.

Two thin, less than 7 cm thick sections of core contain mudstone with angular sandstone fragments and quartz crystal overgrowths. This lithofacies is similar to that described in core T-39 with the exception of the quartz crystal overgrowths.

Interpretation

From 17.8-14.5 m core G-109 contains thin-bedded, fine-grained massive sandstones interbedded with very thin-bedded sandstones and silty mudstones that are found in the levee/overbank subenvironment. These deposits are more thin-bedded and mud-rich than channel margin facies. Sandstones are highly consolidated; almost quartzitic, which could explain the lack of current structures that are characteristic of levee/overbank deposits. Above the levee/overbank deposits is a thick-bedded section of channel margin deposits that are 5.2 m in total length.

Core G-109 is characterized by the thickest section of distal overbank deposits of all the cores studies. The dominant lithofacies includes interbedded silt/fine-sand with mudstone (T_d), which are thought to be deposited by low velocity turbidity currents in the waning stages of flow, whereas blocky mudstones (T_e), with no larger grain size fraction, are hemipelagic or very dilute turbidity current deposits. Evidence that some larger flows did reach this distal region is provided by two thin beds (<10 cm) of fine-grained massive sandstone and one 18 cm thick slurry flow/sandy debris flow deposit. At 4.5 m a sharp change in lithofacies from mud-rich distal overbank deposits to sand-rich deposits indicates a change in subenvironment. Above 4.5 m, thin-bedded and fine-grained T_{a-c} sandstones indicate a shift to levee/overbank deposits, which may shift back to distal overbank at 1.8 m.
Core G-121

General Description

Core G-121 includes 15.9 m of strata from a location directly underneath the axis of the dam, on the far west bank of the Caddo River (Figure 1.1). The core covers 15.9 m of section when corrected for stratigraphic thickness. Net to gross for the entire core is approximately 90% (Figure 5.9).

Massive, fine- to medium-grained sandstone is the dominant lithofacies in core G-121. In the upper 1.1 m of the core, the sandstone is relatively matrix-poor and light gray in color. Throughout the rest of the core most of the massive sandstones are brown to dark gray, reflecting a higher mud content in the matrix.

Laminated sandstone is very common in core G-121. Most laminations are sub-parallel- to highly convolute with noticeable amounts of mud. The laminated sections range in length from 4-14 cm.

Massive sandstone with incorporated mudclasts is found in small sections throughout the core. Most mudclasts appear to be floating and are isolated, lacking any orientation with bedding planes.

Three different types of mudstone lithofacies are present in core G-121. Sandy and silty layered mudstone occur as described in previous cores. Blocky mudstone without sandstone or silt layers also occur. Mudstone with angular sandstone and siltstone pebble sized class is present, as well.

Core G-121 is characterized by numerous thin- to thick-bedded sandstone deposits similar to those found in core T-39. At 15.9 m an incomplete thick-bedded fine-to medium-grained sandstone with $T_{av}$ current divisions grades upward into thinner-bedded silty mudstones and parallel- to wavy laminated sandstones. Above the thinning- and fining- upward section just described, the remaining strata (above 12.8 m) consists of two separate sequences that fine and thin upward overall, although smaller coarsening- and thickening- upward sections do occur within finning- and thinning- upward
**Figure 5.9:** Lithologic column of core G-121. This core contains many amalgamated $T_{ac}$ sandstones with little sandy mudstone characteristic of channelized deposits, off the axis or near the margin.
sequences of channelized deposits. $T_a$ through $T_c$ sandstone occurs in many thick to thin amalgamated sections. Very thin silty mudstone layers occur throughout the length of the core and show evidence of sliding and major slumping. Floating to aligned mudclasts are also common.

**Interpretation**

The lower fining upward sequence described between 15.8 and 12.8 m represents a channelized deposit that is capped by a waning channel deposit or levee/overbank deposit. The predominance of channelized deposits in the rest of the core suggests that this thinner-bedded unit may have also been deposited within a channel. Although the net to gross of the core is rather high (approx. 90%) , the abundance of $T_{hc}$ current structures and thin sandy mudstone layers preclude this core from a channel axis interpretation. Channel margin environment may be more appropriate.

**Core E-81**

**General Description**

Core E-81 consists of 14 m of Mississippian Stanley Formation strata from the DeGray Lake Dike Embankment (Figure 1.1). Net to gross is much lower than any of the Jackfork Group cores, with a value around 10% (Figure 5.10).

Most of the core is black, organic-rich mudstone interbedded with a few thin layers of sandstone or siltstone. In the upper 3 m of the core, the mudstone has been oxidized and has a tannish to reddish tint. Thin sandstone layers are definitely less common than in the Jackfork, and overall the mudstone has less fine-grained sand and silt layers.

Fine-grained, massive sandstone with mud clasts, mud diapirs, and loading structures are present in several thin beds. Loading structures are triangular in shape and become detached downward into the underlying shale. All, except one of the sections, are less than 20 cm in total thickness. The thickest section of sandstone is 90 cm.
**Figure 5.10:** Lithologic column of core E-81. This core consists primarily of distal or lateral submarine fan deposits.
Interpretation

Core E-81 consists entirely of distal or lateral submarine fan deposits. Silty mudstone lithofacies represent the most distal influence of terrigenous sediment gravity flows. The rest of the core consists of hemipelagic mudstone lithofacies. The sandstone deposits are the result of only the largest flows that could reach the distal ends of the environment. Clearly, in this location, the system was not channelized as it was during Jackfork deposition at the DeGray Spillway.

DeGray Spillway

A photo-montage of the east wall of the DeGray Spillway shows the identification of 16 different depositional packages based on significant changes in lithofacies characteristics (Figures 5.11 and 5.12). Brief descriptions and interpretations of each of these packages are provided in the following sections.

Package A

General Description

Similar to the facies association found in the upper part of core T-31, two distinct thickening- and coarsening-upward sequences occur in succession at the base of the measured section, directly over several massive, amalgamated channel (C1) sandstones, which due to the drainage culvert and terrain were impossible to measure closely. The fine-grained sandstone beds in these sequences are thin and have parallel- to wavy laminations. Rippled sandstone and mudstone also occurs. Loadcasts occur in the thickest sandstone, which measures 57 cm in total. Silty mudstone is present in roughly equal abundance with the sandstone beds. The total thickness of both sequences is 4.4 m, with the first occupying 3.0 m of that total. Above the thickening- and coarsening-upward sequences, the beds begin to thin- and fine-upward into very thin-bedded massive- to parallel laminated fine-grained sandstone interbedded with silty mudstone.
Figure 5.11: Photo-montage of depositional packages A-K from the east wall of the DeGray Spillway. Abbreviation C1 indicates channelized deposits that were not measured for this study. The upper and lower sections of the montage overlap at package F.
Figure 5.12: Photo-montage of depositional packages K-P from the east wall of the DeGray Spillway. This section overlaps at package K with the lower section of Figure 5.11.
Interpretation

The thin-bedded nature and the abundance of $T_{bc}$ traction structures suggest all of package A should be included in an interchannel environment. Coarsening-upward sequences in the Spillway have been identified as crevasse splay deposits by DeVries (1992), but no paleocurrents have been noticed from this section that record a shift in transport direction from the predominant flow direction, which was one of the key criteria DeVries (1992) used to identify these deposits.

Package B

General Description

Package B reveals a transition to more thicker-bedded sandstone units compared to package A. Massive, fine- to medium grained sandstone is the dominant lithofacies, with parallel laminated sandstone also being common. There are no pronounced thinning- or thickening-upward trends as there were in package A. Silty mudstone also occurs and is interbedded with the sandstones but are much less common than in package A.

Interpretation

The thick-bedded nature of the sandstone beds and $T_{bc}$ traction structures suggest a channel margin subenvironment for package B. However, most of the previously interpreted channel margin deposits were characteristic of thick-bedded sand on sand contacts which are absent here. Therefore, it is probably more appropriate to place package B within the channel margin or the levee/proximal overbank.

Package C

General Description

Package C reveals a thinning- and fining-upward trend when compared to package B. The entire package is comprised of a 3.2 m thick section of very thin-bedded sandstones interbedded with silty shale. The surface is highly weathered, but most of the
mudstone likely contains the wavy and rippled silt laminae as they did so often in the cores.

**Interpretation**

The very thin-bedded nature and fine grain size suggest package C was deposited in a low energy environment in the waning stages of a turbidite flow. The most appropriate location within the middle fan that fits the low flow energy criteria is the distal overbank.

**Package D**

**General Description**

Package D is characteristic of fine- to medium grained, massive, thin-bedded sandstone that show \( T_{ab} \) current structures interbedded with silty mudstone. Sandstone bed thickness reaches 35 cm for a maximum, and most are between 1 to 15 cm. This entire package thins and fines upward and shows a gradual shift into being very thin-bedded.

**Interpretation**

Package D contains the thin-bedded deposits that are characteristic of the levee/overbank subenvironment. One fact of note is the rarity of \( T_{bc} \) sandstone, which is uncharacteristic of this environment.

**Package E**

**General Description**

Package E is a relatively thick (11.4 m) sequence of very thin-bedded sandstone interbedded with silty mudstone, similar to the lithofacies of package C.

**Interpretation**

The thickness of these distal overbank deposits that make up package E suggests the main channel was distal from this location for an extended time period.
**Package F**

**General Description**

Above the very thin-bedded distal overbank of package E lies a 3.9 m thick chaotic section. Muddy sediments in this deposit do not show any definite bedding surfaces. Sandstone clasts and boulders are common up to 50 cm in diameter.

**Interpretation**

All of the above characteristics can be used to classify package F as a debris flow deposit.

**Package G**

**General Description**

Package G is a very thick succession of alternating thick and thin-bedded T\textsubscript{a-c} sandstone interbedded with silty mudstone (Figure 5.13). Although T\textsubscript{a} sandstone is most common, T\textsubscript{b-c} sandstone lithofacies do occur. Loadcasts, groove casts, and amalgamated contacts are common in the sandstone beds.

**Interpretation**

Sandstone bed thickness, the presence of many silty mudstones, and the recognition of several T\textsubscript{b-c} current structures all support a levee/overbank subenvironment for package G.

**Package H**

**General Description**

Package H begins with a thick, massive sandstone bed and then thins- and fines-upward into thin-bedded massive sandstone alternating with silty mudstone. Thick-bedded T\textsubscript{a-b} amalgamated sandstone with interbedded silty mudstone continue above the fining- and thinning-upward sequence until the end of the package.

**Interpretation**

The high sandstone content and bed the prevalence of thick beds suggests that package H is from a channelized subenvironment, possibly channel margin (Figure 5.14).
Figure 5.13: Alternating thick- and thin-bedded sandstones interbedded with silty mudstones, characteristic of the **levee/overbank** subenvironment. This photo shows only a partial section of 14.5 m thick package G.
Figure 5.14: Nine meter thick section of package H included between the thick black lines. Package H has been interpreted to be representative of the channel margin subenvironment. The fining- and thinning- upward trend in the lower third of this package is well illustrated by this photograph.
Package I

General Description

Package I consists of very thin-bedded silty mudstone interbedded with very fine-grained sandstone (Figure 5.15). Seven fine-grained sandstones are present that range from 3-5 cm in thickness.

Interpretation

The very thin-bedded and fine-grained nature of all of package I suggests that deposition occurred in the distal overbank subenvironment.

Package J

General Description

The basal unit for package J is a 31 cm thick, fine-grained, parallel laminated sandstone that thins- and fines- upward into alternating beds of thin (6-8 cm) fine-grained sandstone and silty mudstone. The fining- and thinning- upward trend is broken by a 1.4 m thick fine- to medium-grained massive sandstone. Above this sandstone are several thinner-bedded sandstones, separated by amalgamated contacts, that grade into very thin-bedded sandstone and silty mudstone. Capping the package are thick beds of T_a sandstone that have a very pronounced contact with very thin-bedded T_a sandstone and silty mudstone above (Figure 5.14).

Interpretation

Except, for the 1.4 m thick sandstone, package J consists of primarily thin bedded sandstone and silty mudstone with T_{ac} current divisions that are characteristic of levee/overbank. The thick T_a sandstone bed could alternatively suggest channel margin.

Package K

General Description

Package K lithofacies, for the most part include very thin-bedded silty mudstone interbedded with thin-bedded, fine-grained sandstone. In the upper section a few pronounced sandstone beds occur.
Figure 5.15: Seven meter thick section of very thin-bedded, mud-rich, distal overbank deposits included in package I. Notice the contrast in bed thickness compared to package H below and package J above.
Interpretation

These very thin-bedded lithofacies suggest most of the package was deposited in the distal overbank subenvironment. The pronounced sandstone beds indicate that the submarine channel may have been closer when they were deposited in a more proximal overbank environment.

Package L

General Description

Package L starts with a thick (3.2 m) fine- to medium-grained massive sandstone, that is the largest single unit outside of the massive channel axis deposits at the end of the outcrop. Internal amalgamations are most likely present, but cannot be distinguished in this bed. Stacked on top of this bed are several thick amalgamated beds of T₂₅ fine- to medium-grained massive sandstone and one 40 cm thick covered section that has been interpreted to be a debris flow by DeVries (1992).

Interpretation

The predominance of thick T₂₅ sandstone and relative absence of silty mudstone that occurs in package L is characteristic of deposition in a channelized environment, possibly near the channel axis.

Package M

General Description

Package M has similar lithofacies to package L, although the beds are thinner on average. Parallel- to wavy laminated and rippled sandstone is also more abundant.

Interpretation

Package L is probably most appropriately placed in the channel margin subenvironment, more so than package L, which could be placed more proximal to the channel axis.
Package N

General Description

Above package M is the largest chaotic deposit in this study at 6.5 m in length. It is mainly comprised of silty mudstone which supports floating pebble- to cobble- to boulder sized rock fragments. The largest rocks appear to have originated from sandstone beds.

Interpretation

The chaotic nature of this package N suggests deposition by a debris flow.

Package O

General Description

At the top of the debris flow deposit rests a deformed 2.2 m thick section of sandstone and silty mudstone that pinches out on both ends.

Interpretation

The predominance of thin-bedded sandstone and very thin-bedded silty mudstone in package O indicates deposition within the levee/overbank. Deformation of the entire unit is attributed to weathering of the underlying debris flow and possibly sliding and slumping on the sea floor.

Package P

General Description

Package P is a very thick (24 m) succession of thick-bedded, massive, fine-to medium-grained sandstone (Figure 5.16). Silty mudstone is present in a few very thin layers between the massive stacked sandstone sections. Parallel laminated and pebbly sandstone is present in minor abundance.

Interpretation

Based on its very thick-bedded nature and high sandstone content, package P was deposited in the channel axis subenvironment.
Figure 5.16: Partial section of very-thick bedded channel axis sandstones included in package P. Three separate thinning-upward sequences are separated by thin layers of silty mudstone. Amalgamated contacts that are characteristic in channelized deposits are well illustrated in this photograph.
CHAPTER 6: DISCUSSION AND CONCLUSIONS

Correlation of Core to Outcrop

One of the major objectives of this study was to correlate the depositional packages in the cores to those found in the spillway outcrop. In the introduction it was suggested that because of the dip angle (45° to 50°) and the 1 km of separation, it would be impossible to accomplish a direct bed to bed correlation. It is also questionable weather or not there is any stratigraphic overlap between any of the cores and the spillway. The strike of the strata at DeGray Dam and Spillway maintain a consistent due east-west orientation, and the beds dip southward at 45° to 50°. These two pieces of information can be used to establish the relative stratigraphic position of the dam cores and the spillway. Figure 1.2 shows that most if not all of the spillway is north of the axis of the dam, making it stratigraphically older. The most northward of the dam cores is T-31 (Figure 1.2) and the most southward spillway strata is the thick channelized deposits of package P. Based on these positions, these two would have the best chance at being correlative. No key beds or other key markers could be identified to correlate them.

Alternatively, instead of a direct bed to bed correlation, depositional packages can be correlated based on similar depositional characteristics. The correlation is achieved by grouping packages with similarities in bed thickness, net to gross, and sedimentary structures. For example, depositional package C is a 3.5 m thick section of very thin-bedded fine-grained sandstone and mudstone and is correlated to the same lithofacies association in core G-109 at 9.3 to 4.4 m. Both of these stratigraphic sections are indicative of distal overbank deposits. One of the best correlations is achieved between core T-14 and package P. Both are entirely comprised of very thick-bedded channel axis sandstones and very little silty mudstone. Core T-14 is likely part of a very thick channel axis succession that is stratigraphically younger that package P. Two depositional packages have no correlative section in the cores. Packages N and F are large-scale (3.9-
6.5 m) chaotic debris flows that do not exist at that scale in the cores. Table 6.1 lists all of the depositional packages from outcrop correlated to the most similar core section.

**Value of Detailed Core Characterization**

This study was attempted with the intent to show how detailed core characterization could aid outcrop studies. Specifically, what do cores provide that outcrop does not. The results indicate that both core and outcrop have advantages.

The main advantage the cores offered is best illustrated in the discussion of secondary resedimentation processes in Chapter 4. Most of these processes including creep, slides, slumps, and debris flows are observed in small scale (10-20 cm) intervals in the core. The fresh core surfaces offer the best medium for investigating details at this scale. In contrast, the spillway is not the ideal because it is heavily weathered and many sections are obscured by vegetation.

The spillway outcrop allows for the observation of several depositional characteristics that are impossible or more difficult to see in the cores. Sandstone bed thickness was one of the criteria used to separate depositional packages and make depositional interpretations of both core and outcrop. Some of the core sections were damaged in the drilling and recovery process, creating broken and fragmented sections that obscured bed contacts. So actual bed thickness for these sections is not known. Except for the covered sections, bed thickness could always be determined from the spillway. An inherent limitation of cores is that they do not offer much in the way of lateral observations. Beds and bed contacts can be traced out to a much greater extent along the outcrop, although the tilting restricts this advantage when compared to horizontal outcrops.

**Limitations to Determining Depositional Subenvironments**

Cores and most outcrops offer a difficult challenge to pinpointing subenvironments of deposition because they do not provide the luxury of complete lateral associations, as can be found in horizontally oriented outcrops, such as Big Rock Quarry.
Table 6.1: Complete list of spillway depositional packages correlated to the most similar core section. The package and core sections have been correlated based on similarities in bed thickness, net to gross, and sedimentary structures. These characteristics have also been used to suggest a depositional subenvironment, listed in the last column.

<table>
<thead>
<tr>
<th>DEPOSITIONAL PACKAGE</th>
<th>THICKNESS (m)</th>
<th>COMPARATIVE CORE SECTION</th>
<th>ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package A</td>
<td>6.6</td>
<td>Core G-109; 14.5-17.8 m</td>
<td>Interchannel</td>
</tr>
<tr>
<td>Package B</td>
<td>5.6</td>
<td>Core G-109; 9.3-14.5 m</td>
<td>Channel margin</td>
</tr>
<tr>
<td>Package C</td>
<td>3.5</td>
<td>Core G-109; 4.4-9.3 m</td>
<td>Distal overbank</td>
</tr>
<tr>
<td>Package D</td>
<td>9.1</td>
<td>Core G-109; 14.5-17.8 m</td>
<td>Levee/overbank</td>
</tr>
<tr>
<td>Package E</td>
<td>11.4</td>
<td>Core G-109; 4.4-9.3 m</td>
<td>Distal overbank</td>
</tr>
<tr>
<td>Package F</td>
<td>3.9</td>
<td>None</td>
<td>Debris Flow</td>
</tr>
<tr>
<td>Package G</td>
<td>14.7</td>
<td>Core G-109; 14.5-17.8 m</td>
<td>Levee/overbank</td>
</tr>
<tr>
<td>Package H</td>
<td>9.3</td>
<td>Core G-121; entire core</td>
<td>Channel margin</td>
</tr>
<tr>
<td>Package I</td>
<td>7.4</td>
<td>Core G-109; 4.4-9.3 m</td>
<td>Distal overbank</td>
</tr>
<tr>
<td>Package J</td>
<td>6.6</td>
<td>Core T-31; 5.1-9.1 m</td>
<td>Channel margin</td>
</tr>
<tr>
<td>Package K</td>
<td>10.3</td>
<td>Core G-109; 4.4-9.3 m</td>
<td>Distal overbank</td>
</tr>
<tr>
<td>Package L</td>
<td>12.5</td>
<td>Core T-39; 15.4-31 m</td>
<td>Channelized</td>
</tr>
<tr>
<td>Package M</td>
<td>9.6</td>
<td>Core T-31; 8.8-16.2</td>
<td>Channel margin</td>
</tr>
<tr>
<td>Package N</td>
<td>6.5</td>
<td>None</td>
<td>Debris Flow</td>
</tr>
<tr>
<td>Package O</td>
<td>2.2</td>
<td>Core G-109; 14.5-17.8 m</td>
<td>Levee/overbank</td>
</tr>
<tr>
<td>Package P</td>
<td>2.4</td>
<td>Core T-14; entire core</td>
<td>Channel axis</td>
</tr>
</tbody>
</table>
near Little Rock, Arkansas. Deep-water strata are rarely uplifted and exposed without significant tilting due to deformational mechanisms associated with tectonics. In some cases they have been, such as the Ross Formation in Ireland and the Skoorsteenberg Formation in South Africa. Studies from these turbidite systems (Kirschner and Bouma, 2000; Sullivan and Templet, 2002) have described the characteristics of the middle fan subenvironments which can be applied to tilted outcrops and cores. Some core studies have also been conducted to ground truth modern submarine fans (Stelting et al., 1985) as well as subsurface systems (Sullivan et al., 2000). Only by utilizing the finding of these studies, as well as other key studies of turbidite systems (Morris, 1971; Mutti, 1977; Walker, 1978; Moiola and Shanmugam, 1984; DeVries, 1992; Al-Siyabi, 1998), could depositional subenvironments be suggested for the core and outcrop packages.

**Conclusions**

Several conclusions can be reached from the investigation of core and outcrop characteristics at DeGray Lake, Arkansas.

- Core to outcrop correlation is best achieved by using depositional packages from each that contain similar lithofacies characteristics. A more direct bed to bed correlation is prohibited because the cores and spillway are not in the same stratigraphic position.
- Depositional packages can be placed into several unique subenvironments of deposition within a channelized middle submarine fan: channel axis, channel margin, and levee/overbank (proximal and distal).
- The differences between these subenvironments is gradual, and as a result there are many borderline or transitional deposits. In some cases two transitional subenvironments are suggested, or the terms channelized or interchannel deposit are more appropriate.
• Other studies of laterally extensive outcrops are necessary to make interpretations about environments of deposition for cores and tilted outcrops that lack complete lateral associations.

• Primary and secondary resedimentation processes are responsible for the variety of lithofacies found in both the cores and outcrop. Primary resedimentation processes transport sediments into the middle fan area and then secondary resedimentation processes act to remobilize and finally deposit those sediments.

• Creep, slides, slumps, debris flows, slurry flows, and high and low density turbidity currents are all identified as gravity driven processes that transported and deposited sediments in the cores and spillway east outcrop at DeGray Lake.

• Core and closely spaced outcrops studied together offer several benefits over studying each separately. Fresh core faces show some details that are covered by weathered outcrops. Core samples provide new sub-surface data to DeGray Lake, an area that has received extensive attention to its outcrops. The spillway outcrop, although tilted, provides some spatial observations which can be correlated to similar core sections. Bedding trends and contacts are best observed in outcrop due to artificial breaks in the cores that were caused by drilling and recovery.
REFERENCES


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VITA

Daniel James Golob is the first of two children born to Dale Brian Golob and Theresa Golob on May 26, 1977, in Cleveland, Ohio. He attended high school in Cleveland at Villa Angela-Saint Joseph. Growing up, Daniel excelled in athletics and enjoyed fishing, the outdoors, and science. Daniel worked throughout high school and college as a glazier for his father’s commercial glazing business.

Daniel received his Bachelor of Science Degree in geology from Ohio University. He first became interested in the subject through an introductory environmental geology course. He initially chose environmental geology as his major, but later switched to major in geology. Upon the recommendation of several professors at Ohio University, Daniel decided to continue his studies in geology. He enrolled at Louisiana State University in the fall of 2000 to pursue a Master of Science Degree in geology.

Daniel has interned with Cabot Oil and Gas Company in Houston, Texas, and will pursue a career in the oil and gas industry upon completion of his master’s degree.