Seismic stratigraphic investigation of the Ukpokiti Field Channel complex, Oml 108, offshore Nigeria, northwestern Niger Delta

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SEISMIC STRATIGRAPHIC INVESTIGATION OF THE UKPOKITI FIELD
CHANNEL COMPLEX, OML 108, OFFSHORE NIGERIA,
NORTHWESTERN NIGER DELTA

A Thesis
Submitted to the Graduate Faculty of the
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Master of Science

in

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by
Toby Latwan Stewart
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“Father, I stretch my hand to thee. No other help I know. If thou withdraw thyself from me, tell me whither shall I go”.

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ABSTRACT

Detailed seismic stratigraphic analyses and mapping show that a well defined Ukpokiti Field Channel complex (late Miocene) found on the up-thrown side of a major back-to-back fault system in the West Niger delta inner-continental shelf probably formed during a single eustatic fall. The channel (>500 msec deep, 10 km wide) shows several tributaries entering the trunk axis from what was probably a surface of subaerial exposure. Slumping is prominent on the north flank of the trunk channel. No channel unconformity is evident in the down-thrown block. This investigation seeks to resolve the lack of down-dip correlative seismic expression across the major structural boundary and place the Ukpokiti Field channel complex within a sequence stratigraphic framework, thereby explaining the channel genesis.

Seismic sequence analysis was performed in the LSU Subsurface Laboratory with the Landmark Graphics© software suite using standard workstation interpretation procedures. Ukpokiti Field reservoir interval appraisals, preloaded digital well logs, poststack synthetic seismograms, and multiple horizon maps were interpreted during the course of the study.

Results show the down-thrown correlative channel base to be a depositional surface. Three internal channel fill seismic facies patterns (fluvial deposition, marine inundation, and deltaic progradation) are evident in both structural blocks.

On the basis of available biostratigraphic age control, the channel base probably represents an incised valley created at the 6.3 Ma sequence boundary. The internal seismic facies units probably represent a single shoreline regression interval. Shoreline and fluvio-marine deposition occurred after incision. Next, estuarine and pro-delta deposition occurred when the channel was flooded. Last, deltaic deposition filled the
valley. Observed slumping is probably a product of instability due to the rapid progradation of deltaic deposits in the final stage of channel evolution. The channel produces no resolvable lowstand basinfloor fan within the study area.
CHAPTER 1. INTRODUCTION

1.1 Investigation of Shelf to Slope Conduits

Seismic and well-log studies show that numerous canyon complexes exist at multiple stratigraphic levels within the Neogene Niger Delta (Petters, 1984; Damuth, 1994; Ibie, 1996). An example of such is the Opuama Canyon (Figure 1) for which Petters (1984) details the extent. Petters (1984) showed that the updip Opuama Canyon fill onlaps the lower Oligocene Agbada Formation and argues that the Opuama Canyon incision occurred during an early-middle Oligocene sea-level fall.

Figure 1. Opuama Canyon (yellow hachuring) is shown adjacent to study area (black box) modified from Petters (1984). Inset is a portion of the Cenozoic chronostratigraphic and eustatic cycle chart from Haq et al. (1988).
Initial cross shelf incision may be related to an ancestral Benin River (Petters, 1984). Petters suggests that narrowing of the 30 kilometer (km) wide canyon head into a restricted (~8 km) conduit results as updip tributaries converge into a single channel system. Petters (1984) describes the 1.3 km thick canyon fill as predominately marine shale (Opuama Shale Member). The base of canyon fill contains benthic foraminifera of late Oligocene/early Miocene age. Shallow water shelf benthonic foraminifera of latest-early Miocene age mark the top of the Opuama Shale Member and the subsequent filling of the Opuama Canyon (Petters, 1984).

On the western portion of the Nigeria inner continental shelf, seismic data over the Ukpokiti Field shows the existence of a large paleochannel feature. The head of the channel is found at the northeastern extent of the seismic data set. Preliminary seismic observations (Figure 2) show that the channel-fill thickness ranges between 200 and 550 milliseconds (msec) or 234 to 645 meters (m). The unconformable base can be traced 11 km down-dip, from the northeastern extent of seismic coverage to the juncture of a back-to-back fault system. The back-to-back fault system is a major structural feature that consists of a counter-regional (landward dip) and major down-to-the-basin growth fault (regional dip). Four kilometers before reaching the fault complex, the channel deepens to >500 msec (>645 m) and broadens to at least the total width of seismic survey (~11 km) (Figure 3a, b). Internal geometries within the channel fill and the related basal unconformity are distinguishable on the up-thrown fault block, but similar features are not discernible on the down-thrown (basinward) fault block (Figure 3a, b).

The Ukpokiti Field channel, and similar ancient canyon complexes identified in the western Neogene Niger Delta, may have formed by one or more of the following ways: 1) multiple fluvial incisions during successive eustatic falls (Ibie, 1996);
Figure 2. Uninterpreted seismic Line 180 (see Figure 1 for location) showing details of a hypothetical cross section of the same orientation. Positive amplitudes are displayed in red and negative amplitudes are blue. Modified after Merki (1972), Weber and Dankuru (1973), and Whiteman (1982).
Figure 3a. Uninterpreted dip-line, Line 180, oriented SW-NE within three-dimensional seismic volume. Amplitude display color bar is blue-white-brown (positive-zero-negative amplitude values, respectively). Vertical axis is two-way time (twt) in msec. Trace line (cross-line) intersections are annotated at the top of the line.
Figure 3b. Interpreted dip-line, Line 180, oriented SW-NE within three-dimensional seismic volume. Amplitude display color bar is blue-white-brown (positive-zero-negative amplitude values, respectively). Vertical axis is two-way time (twt) in msec. Trace line (cross-line) intersections are annotated at the top of the line.
2) aggradational stacking of shallow, incised channels within a single, deep episode of incision; or 3) a single, deep episode of incision representing one eustatic fall (Petters, 1984) (Figure 4).

Figures 4. (a) Multiple fluvial incisions of the shelf edge during succeeding eustatic falls; (b) Aggradational stacking of shallow incised channels within a single, deep episode of incision; (c) A single, deep episode of incision representing one eustatic fall. Based upon findings from Petters (1984), Ibie (1996), and this study.

1.2 Goal of the Research

The objective of this study is to evaluate the depositional evolution of the Ukpokiti Channel and its down-dip equivalent.

1.3 Thesis Organization

The seismic sequence analysis and well correlation were performed on a Sun Ultra™ 1 Workstation in the LSU Subsurface Laboratory. The geological background
of the region and study area are presented in Chapter 2. The methods used to interpret structure and seismic sequences on the interactive interpretation workstation are described in Chapter 3. Chapter 4 is focused on the results for this investigation. Chapter 5 covers interpretations and discussion while the conclusions reached as a result of this investigation are conveyed in Chapter 6.
CHAPTER 2. GEOLOGY BACKGROUND

2.1 Structural Evolution

The Niger Delta Basin occupies the Abakaliki Trough, which is the southern extent of the Benue-Abakaliki Trough; a rift basin trending NE-SW into the Gulf of Guinea (Figure 5). The Abakaliki Trough (commonly referred to as the lower Benue Trough), was initiated in Aptian—Albian times (Reijers et al., 1997). The trough is bound on the northwest by the Ilesha Spur (West African Massif), Benue Flank and Okitipupa High. The southwest-northeast trending edge of this feature separates the early Cretaceous Dahomey Basin from the Benue-Abakaliki Trough. The Abakaliki Trough is bound on the southeast by basement rocks of the Calabar Flank and Oban Massif. Centered in the lower Abakaliki Trough are the southwest-northeast trending Onitsha and Abakaliki highs, that have directed deposition through adjacent structural lows; the Anambra Basin, Onitsha Trough and Afikpo Syncline. The Ikang Trough trends northeast-southwest, parallel to the southwest facing Calabar Flank.

Proximal sediments of the Ilesha Spur cover a southeast facing Anambra Platform and form the Onitsha High which divides the Cretaceous Anambra Basin. Southwesterly winds forced longshore currents into the embayed coast, i.e., at the Abakaliki Trough (Reijers et al., 1997). The paleogeomorphology suggests that sedimentation during this time was influenced by storm waves, tides and fluviomarine processes (Reijers et al., 1997). By the Campanian, oceanic crustal subsidence and folding of Cretaceous sediment had converted the Abakaliki Trough into an anticline, i.e., the Abakaliki High and created the Afikpo Syncline, Onitsha and Ikang Troughs. Fluvial sediments were supplied to the Gulf of Guinea via the Afikpo Syncline and Ikang Trough (Figures 5) (Reijers et al., 1997). Prior to deformation, two transgressive-regressive
Figure 5. Cenozoic basement structures of the Tertiary Niger Delta Basin from Whiteman (1982).
Figure 6. Shown are the underlying basement structures of the study area. Line of section is highlighted and various locations are denoted with red squares on the location map inset. The figure is slightly modified from Whiteman, 1982.
parasequences were deposited in the Anambra Basin (Reijers et al., 1997). After deformation and uplift the new structural highs shed sediment that was directed into the Anambra Basin. The Anambra basin contained the proto-Niger and –Benue rivers which constructed Cenozoic deltas (Whiteman, 1982).

The convex outward shape of the modern Niger Delta strata (Cenozoic) is indicative of a high energy, constructive lobate-arcuate delta, for which the deposition of sediment has been greater than subsidence and physical reworking (Whiteman, 1982). During the Eocene prevailing winds approached from the southwest. Outbuilding, lobate deltas were influenced by four separate longshore current directions (Whiteman, 1982) depicted in Figure 7.

Figure 7. Paleo-current conditions from Burke (1972).
Two longshore currents diverged from a large apex in the deltaic morphology. These longshore currents traveled north and east of the deltaic apex. To the north, the currents converged with east-directed longshore currents. The convergence forced water offshore through a canyon system (Mahin Canyon). At the base of the Mahin Canyon a large basin floor fan was constructed. A similar phenomena of converging currents being directed offshore occurred near Bioko Island.

Tectonic uplift of the Abakaliki High (and probably Onitsha High) in the Oligocene further routed sediment of the Niger Basin through the Onitsha Trough and Afikpo Syncline. After the early Miocene, the combined sediment input of the Niger-Benue and Afikpo drainage systems created a transgressive deltaic sedimentary wedge deformed by growth faults and active mud diapirs (Whiteman, 1982). The Niger Delta has prograded as much as 100 km from its basinward-most Miocene shoreline position to its Plio-Pleistocene shoreline position (Figure 5). The present highstand shoreline is located ~30 km landward of the Plio-Pleistocene shoreline shelfedge (i.e., lowstand shoreline).

2.1.1 Drainage Basin Geology

The Niger River drainage basin covers an area ~2.3 million km² and receives sediment flux from two sources, the Niger and Benue River sub-basins. Stream courses in the Niger River sub-basin collectively deliver Pleistocene sedimentary clasts, Paleozoic and Cretaceous metamorphic and igneous clasts to the coast. Of this sediment, 0.3 X 10⁶ m³/yr is medium to coarse sand bed load and 4.6 X 10⁶ m³/yr is suspended load (Ibe, 1996). Stream courses in the Benue River sub-basin collectively provide sediment from basement rocks, Cretaceous sedimentary rocks, and basic volcanics to the coast. Of this sediment, 0.6 X 10⁶ m³/yr is coarse sand bed load and 11 X 10⁶ m³/yr is suspended load (Ibe, 1996). Secondary sediment flux is delivered to the Nigeria coast by coastal
plain rivers. These include the Benin (1 \times 10^6 \text{ m}^3/\text{year}), Escravos, New Calabar, Bonny and Imo Rivers (Ibe, 1996).

2.1.2 Climate

The immense areal extent of the Niger Delta drainage basin (located between 5°N and 23°N of latitude, i.e., ~2000 km and 12°W and 17°E of longitude, i.e., ~3200 km, Figure 7) encompasses a variety of climates. In the west, the average temperature is 25.4°C and the average rainfall is 217.4 cm/yr. Near the Benue River headwaters, the average temperature is 28.0°C and the average rainfall is 99.3 cm/yr. In the north, the average temperature is 21.9°C and the average rainfall is 4.6 cm/yr. Centrally, the average temperature is 26.3°C and the average rainfall is 99.3 cm/yr. At Warri, Nigeria, the average temperature is 26.3°C and the average rainfall is 277.6 cm/yr (www.worldclimate.com).

The climate of the country varies from semi-arid in the north, to tropical in the central area, to equatorial in the offshore study area. Rainfall is the key climatic variable and there is a marked alternation of wet and dry seasons in most areas. Two air masses control rainfall--moist northward-moving maritime air coming from the Atlantic Ocean and dry continental air moving south from the saharan north Africa. In the coastal and southeastern portions of Nigeria, the rainy season usually begins in February or March as monsoons cross the country. The beginning of the rains is usually marked by the incidence of high winds and locally heavy squalls. The scattered quality of this storm rainfall is especially noticeable in the north in dry years, when rain may be abundant in some small areas while other contiguous places are completely dry. By April or early May, the rainy season is under way throughout most of the area south of the confluence.
Figure 8. Location map showing elevation detail (continental inset with drainage basin in red outline). Modified from the Global River Discharge Database (RivDIS v1.1, http://www.rivdis.sr.unh.edu). Purple box shows Study Area from Figure 1.
of the Niger and Benue River valleys. Farther north, heavy rains commence in June or July. The peak of the rainy season occurs through most of northern Nigeria in August, when moist Atlantic air masses cover the entire country. In southern regions, this period marks the August dip in precipitation. From September through November, northeast trade winds generally bring a season of clear skies, moderate temperatures, and lower humidity for most of the country. From December through February, however, strong northeast trade winds blow fine dust from the Sahara. These dust-laden winds, known locally as the ‘harmattan’, often appear as a dense fog and blanket the area with silt. The harmattan is more common in the north but affects the entire country except for a narrow strip along the southwest coast. An occasional strong ‘harmattan’, however, can sweep as far south as Lagos, providing relief from high humidity in the capital and pushing clouds of dust out to sea.

Temperatures throughout Nigeria are generally high; diurnal variations are more pronounced than seasonal ones. Highest temperatures occur during the dry season; rains and moderate afternoon highs occur during the wet season. Average highs and lows for Lagos are 31° C and 23° C in January and 28° C and 23° C in June. Although average temperatures vary little from coastal to inland areas, inland areas, especially in the northeast, have greater seasonal extremes. Temperatures reach as high as 44° C before the onset of rains and drop as low as 6° C during intrusions of cool air from the north from December to February.

2.1.3 Distributary Systems

The Niger River drainage basin has a high density of streams. The southernmost extent, the Niger Delta distributary system, forms a complex radiation of bifurcating distributaries (Figure 9, Table 1), of which ~ 20 form major river mouths at the coast.
Figure 9. Niger Delta distributary distribution and sediment types from Oyegun (1993a).
Sediment reaches the coast by way of two main distributaries; the Forcados and Nun rivers. To a lesser extent, sediment is also delivered to the coast, via the Orashi River, which parallels the Niger River (Figure 9). Due to dredging, the bulk of sediment flux has switched from the Forcados to the Nun River (Abam et al., 2000).

### 2.2 Niger Delta Stratigraphy within the Study Area

There are three diachronous formations that constitute a predominately regressive Cenozoic section of the Niger Delta (Figure 10). The formations are the Benin (nonmarine sand), Agbada (paralic sand and silt), and Akata (marine shale) formations (Figure 11). More than 12 km of section overlie igneous and metamorphic basement rocks of mainly Precambrian and Cretaceous age (Whiteman, 1982).

#### Akata Formation

The Akata Formation, basal most of the three, is an under-compacted marine shale (Whiteman, 1982) which represents the major source rock of the Niger Delta Oil Provenience (Tuttle et al., 1999). The Akata contains minor amounts of sand and silt that are attributed to density current and fan deposition. According to Reijers et al. (1997), these time-transgressive shales were deposited from shallow-marine shelf to bathyal environments from Paleocene to Recent. Thickness estimates range from 600-6100
Figure 10. Modern Niger Delta Basin with annotated Study Area (regional location map inset from RivDIS v1.1, http://www.rivdis.sr.unh.edu). Bathymetric contours are in meters.

**Agbada Formation**

The majority of the Agbada Formation is composed of interbedded sand and silt. The transition from the Akata to Agbada is gradational. The Agbada was deposited in environments ranging from lower delta plain to shallow marine shelf. Sands and silts of the Agbada Formation are the primary reservoirs in the Niger Delta Basin. The formation ranges in age from, at least Eocene to Present. Synsedimentary growth faulting and Akata Shale diapirism set up thicknesses ranging from 2900 m to 4300 m (Whiteman, 1982).

**Benin Formation**

The Benin Formation is composed of coarse continental, (e.g., fluvial) fluvio-marine sands. Maximum thickness of the Benin Formation is ~3 km. The maximum age of the Benin Formation is Oligocene, but these strata may have also been deposited during the Eocene (Reijers et al., 1997).

### 2.3 Present Coast in the Study Area

The study area (centered roughly at 5° 37’ 30” N latitude and 4° 52’ 30” E longitude) is on the inner-shelf of the Nigerian margin (Figure 9). The average water depth is ~25 m. The study area is 20 km from the coast at the Benin River estuary. The study area is south of a transgressive mud coast (Mahim) and 20 km west of the Farcados River beaches (Figure 9). Sediment accretion is documented at the beach near the Farcados River, but no beach ridges have been mapped at the beach near Mahim (Oyegun 1993a, b). Northwest directed longshore currents are the dominant erosive agent (Burke, 1972). Waves, induced by wind velocities that normally range between 2.5 and 5 m/s (Ibe, 1996), approach from the southwest at an average period of 12 seconds (Oyegun,
Figure 11. West Niger Delta chart of lithostratigraphy.
1995). Breaking waves, ranging in height from 45 to 250 cm, create 1 m/sec strong longshore currents with the ability to move sediment northwestward at quantities of 0.35 to 0.74 X 10^6 m³/y (Ibe, 1996). Sediment may also be transported up to 1.6 km perpendicular to the coast via rip currents moving at 0.5 m/sec (Ibe, 1996). The mean tidal range is 1.3 m and sediment discharge values of 1 X 10^6 m³/year have been reported at Benin River (Ibe, 1996). Beach ridges, levees and barrier islands are the only topography (i.e., features on this part of the Niger Delta) (Ibe, 1996). Slope of the shelf in the study area is 1:100.
CHAPTER 3. METHODS

3.1 Seismic Data (2D and 3D) Acquisition Parameters

In this study 2D and 3D seismic data were used to map the Ukpokiti Channel in the up-thrown block. Faults were mapped with the purpose of defining local structure. Key regional horizons above and below the channel were mapped to establish the best possible correlation of the Ukpokiti Channel. Well log data from were used to further constrain the seismic correlations. Detailed seismic facies analyses were performed to determine how the channel and its down-dip equivalents evolved.

Seismic data used in this study were provided by Conoco Inc. A grid of both industry standard resolution two dimensional (2-D) and 3-D seismic lines represent the primary data evaluated in this study. For each survey, the acquisition grid was oriented to capture the strike and dip of the present day shelf edge. Two companies, Seismograph Service Ltd. and GECO Geophysical Company Inc., acquired the 2-D data in October and June of 1991, respectively. The 3-D seismic volume was acquired by CGG in June 1993 to provide higher resolution for exploration targets.

Seismograph Service Ltd. utilized a 9000 cubic inch (in$^3$) water gun at 2000 pounds per square inch (psi) as the source. A 2986 m Prakla-Seismos GMGH streamer, at 7-9 m water depth, transmitted data to a Sercel SN358 DMX recorder for SEG-D formatting. There were 180 receiver groups on the streamer. Group intervals were spaced at 16.6 m and the near group distance was 144.3 m. Recording was done over 9 seconds (secs) at a 2 msec sample rate. The field frequency filter was set from 3.5 Hertz (Hz) to 154 Hz.

During acquisition, GECO Geophysical Company Inc. used a 6324 in$^3$ air gun operated at 2000 psi as the source. The 2 X DFS5/GDR-1000 acquisition system recorded the data in SEG-D format via a 4775 m multiple channel cable streamer at 9 m
(±1 m) depth below the sea surface. The group interval was 25 m and the near group
distance was 82 m; in total there were 192 groups. Frequencies from 3.5-128 Hz were
sampled every 2 msec over 8 secs. Approximately 152 square kilometers (km²) of
coverage is provided by the 3-D survey. Traces are oriented NW-SE at 12.05 m apart
while the lines are oriented SW-NE at 25.03 m spacing. There were 162 groups with a
group interval of 25 m and a shot interval of 50 m. The maximum offset is 4189 m and
the minimum offset is 164 m. The fold is 40. Eighteen 2-D lines of various folds, also
oriented NW-SE and SW-NE, were also used.

A 1996 well log post drilling appraisal report was provided courtesy of Conoco to
aid this investigation. In conjunction with the suite of digital well curves (Table-2), this
report provides the foundation for basic inferences about seismic signal, age estimates,
and reservoir characteristics within the study area. All well trajectories, curve
information and time-depth tables for the 8 wells contained in the 3-D seismic volume
were preloaded digitally into a Landmark Open Works® project environment and then
transferred on digital tapes. Table-3 shows only the wells and respective log curves used
in the generation of synthetic seismograms. Shared log suites consist of Spontaneous
Potential (SP), Laterolog Deep-resistivity borehole Corrected (LLDC), Delta Transit
Time-Sonic (DT), bulk density (RHOB) and Gamma Ray (GR) logs. A graphical
lithology log from Well 1 was used in latter part of the study. Electric and induction logs
exist over production intervals but were not employed for this investigation. Seismic data
was interpreted in the LSU Subsurface Laboratory on a SUN Ultra™ 1 170E dual-screen
workstations using the Landmark Graphics© Release 1998.1 software suite including:
SeisWorks®, ZAP!®, SeisCube™, PostStack™ ESP™ (Event Similarity Prediction) and
PAL™ (PostStack Attribute Library), and SynTool™. Work- station procedures outlined
Table 2. Summary of wells available in the study area.

<table>
<thead>
<tr>
<th>WELL</th>
<th>TD (True Vertical Depth) meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3048</td>
</tr>
<tr>
<td>2</td>
<td>2016</td>
</tr>
<tr>
<td>3</td>
<td>2432</td>
</tr>
<tr>
<td>4</td>
<td>2445</td>
</tr>
<tr>
<td>5</td>
<td>2517</td>
</tr>
<tr>
<td>6</td>
<td>2545</td>
</tr>
<tr>
<td>7</td>
<td>3544</td>
</tr>
<tr>
<td>8</td>
<td>3932</td>
</tr>
</tbody>
</table>

Table 3. Summary of well log curves used in synthetic wavelet generation.

<table>
<thead>
<tr>
<th>WELL</th>
<th>SP Begin</th>
<th>SP End</th>
<th>GR Begin</th>
<th>GR End</th>
<th>LLDC Begin</th>
<th>LLDC End</th>
<th>RHOB Begin</th>
<th>RHOB End</th>
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<td>3352</td>
<td>518</td>
<td>3352</td>
<td>1524</td>
<td>3055</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>1604</td>
<td>2323</td>
<td>not used</td>
<td>not used</td>
<td>1604</td>
<td>2321</td>
</tr>
<tr>
<td>3</td>
<td>NA</td>
<td>NA</td>
<td>448</td>
<td>2918</td>
<td>not used</td>
<td>not used</td>
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<td>2918</td>
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<tr>
<td>4</td>
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<td>2668</td>
<td>1401</td>
<td>8754</td>
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<td>not used</td>
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<td>2668</td>
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<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>396</td>
<td>2950</td>
<td>396</td>
<td>2950</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
by A. Brown (1999) in Interpretation of Three-Dimensional Seismic Data served as the fundamental guide for interactive interpretation.

3.2 Fault Mapping to Define Local Structures

A link between stratigraphy and the general structural evolution of the Niger Delta has been established by the previous work (Evamy et al., 1978; Weber et al., 1978; Damuth, 1994; Rouby and Cobbold, 1996; Cohen and McClay, 1996; and Onuoha, 1999). Faults were mapped to establish timing of the development of structures as well as to document the influence of these structures on depositional architecture. Seismic correlations of faults from seismic reflections to well logs were used to establish stratigraphic control.

Major faults were picked on every twentieth dip line within the 3-D survey. On second pass, every fourth inline was interpreted to map minor faults and major fault splays. After completion of the dip-oriented fault mapping, strike-oriented fault correlation was done on every fifth cross-line (trace). Fault mapping on every inline and crossline was performed in areas of high interest or structural complexity. Time and horizon slices were used to confirm vertical section fault picks in horizontal sections.

Fault nomenclature is based on proximity to producing fields, similar to unpublished seismic studies in the region (Ibie, 1996). For example, major faults identified in the southern half of the 3-D coverage are recognized by all upper case letters, such as “KUNZA1” or “KUNZA4”, while minor faults are recognized by “K1” or “K4”. Splays of either major or minor faults are documented by an upper case alphabet suffix, such as “KUNZ1C” and “K4B”. When applicable, an “a” or “s” denotes an antithetic or synthetic fault, respectively. Fault picking was performed while seismic sections were displayed in a black-white color bar to enhance the seismic-stratal discontinuity. Fault
surfaces were generated in Seisworks® using the interpreted fault segments.

Nomenclature used to describe the location and structural relationship of faults mapped this study was based on Figure 12 (Evamy et al., 1990).

Figure 12. Syndepositional fault type classification scheme (Evamy et al., 1978).

3.3 Generation of Synthetic Seismic Traces at Well Log Locations

As a quality control check for the seismic data, the Landmark® SynTool™ program was used to generate a synthetic seismic trace from the product of the velocity and density curves for each well. Down-hole differences in acoustic impedance were used to calculate a reflection coefficient trace. Negative and positive reflection coefficient spikes
represent negative and positive changes in acoustic impedance. A seismic wavelet extracted from seismic data was then convolved with the reflection coefficient spikes to form a composite synthetic seismic trace. The synthetic seismic trace was then compared with actual seismic trace data from the well location.

For the purpose of this investigation, the Reflection Coefficient Sonic Indirectly (RC Sonic Indirectly) was selected as the depth-to-time source for the time-depth relationship. This procedure permitted a smooth application of checkshot corrections and preserved more well geology (SynTool™ User Guide, 1996). Sonic logs (DTs) were the RC Sonic source from which the reflection coefficients were calculated. In absence of a DT, a Faust transform was applied to a resistivity curve. The transform converted ohm-m to velocity to calculate reflection coefficients. Impedance curves were generated from the multiplication of the RC Sonic and RC Density. A density curve having the units grams per cubic centimeter (g/cc) was chosen as the RC Density source. Time-depth tables corresponding to each well were added to the process list. A summary process list of synthetic generation using SynTool™ is provided (Figure 13). SynTool™ was further used to extract and fit wavelets, and measure seismogram to seismic trace similarity. Synthetic seismograms were primarily used as quality control for seismic correlation ties. A digital time-depth table was the primary technique used to post the graphic lithology log to the vertical seismic profiles.

3.4 Horizon Mapping

Seismic reflections having the greatest lateral continuity and reflection strength throughout the 3-D volume were chosen to be reference horizons above and below the Ukpokiti Channel. Landmark© ZAP!® was used to auto pick these horizons after a coarse grid of line and cross-line seed points was manually picked. First, a minimum
Figure 13. Landmark® SynTool™ process flow from Landmark Graphics (1996).
user-specified score was chosen to determine how similar a prospective pick must be to the seed point. Second, a maximum jump value was specified to determine the maximum time window between the prospective and seed point can be compared vertically. The amplitudes of the traces surrounding each seed point were cross-checked in a loop to match the similarity score by using ZAP!®. These same constraints were used in the manual auto-picking mode. Final parameter options allowed for ‘blocking’ of ZAP!® auto-picking at fault surfaces and deletion of miss-interpreted horizons appearing inside bound fault surfaces called fault gaps. Horizons shown exclusively as reference horizons or those manipulated for attribute extraction were all ZAP!® horizons smoothed with a filter adequate to correct for interpretation miss-ties. Adhering to the practice put forth by Mitchum et al. (1977a), select horizons were designated as seismic sequence boundaries based on an angular relationship to other reflection terminations or deposition related seismic concordance.

3.5 Seismic Stratigraphic Analysis of Ukpokiti Channel and Subject Strata

This investigation uses the procedure outlined in Mitchum et al. (1977b) to conduct a seismic stratigraphic study; seismic sequence and seismic facies analysis. Identification of the sequence boundaries in this investigation is based on the seismic reflection terminations of truncation, toplap, onlap, downlap, and concordance, designated in Mitchum et al. (1977a). Figure 14 shows the seismic reflection termination surfaces used in this investigation. The seismic sequence was then analyzed on the basis of reflection pattern, geometry, continuity, and amplitude in the seismic facies analysis (Figure 15).

To establish the chronostratigraphic significance of a sequence/sequence boundaries, I used the foram-based age model derived from well log cuttings by Geochem Group Limited. Truncation surfaces indicate strata removal from the outermost
Figure 14. Shown is a diagrammatic representation of the classification used for reflection terminations. Red circles highlight the ends of the stratal (clinoform) shape. Modified from Mitchum et al. (1977a, b).
Figure 15. Diagrammatic representations of the seismic parameters used to interpret seismic sequences and seismic facies. From Mitchum et al. (1977) and Sangree and Widmier, (1977).
limits of deposition and may be either erosional or structural in nature. Toplap represents a surface of where stratal deposition changes between horizontal to inclined and characterizes bypass of sediment, with possible erosion. Both truncation and toplap surfaces refer to the upper boundary relationship of strata within a sequence. Onlap surfaces are the updip limit changes of depositional position (e.g., coastal onlap) against older strata. Downlap surfaces represent the downdip limits of inclined strata (e.g., prodelta bottomsets) against older, horizontal or inclined strata. Onlap and toplap surfaces are collectively called baselap surfaces and refer to the lower boundary relationship of strata within sequences. Truncation, toplap, and baselap surfaces are readily recognized by discordance, the angular incidence of reflections to each other, for which an unconformity is inferred (Mitchum et al., 1977a). When discordance is not recognizable due to seismic resolution limits (Sheriff, 1977; Mitchum et al., 1977a, b), the relationship is apparent and a sequence boundary exists. A concordant surface refers to both upper and lower sequence boundary relationships. Concordant surfaces occur where there is no stratal reflection angle of incidence and create a conformable sequence boundary (Mitchum et al., 1977a). Seismic reflection parameters observed during the seismic facies analysis help to define concordant sequence boundaries.

3.5.1 Seismic Facies Analysis

A seismic facies unit is “a mappable three-dimensional seismic unit composed of groups of reflections whose [seismic] parameters…differ from those of adjacent units (Mitchum, 1977). In the seismic facies analysis, the external shape of the sequence and the internal reflection configuration are both considered to interpret sedimentary processes, environmental setting, depositional energy, and lithologic potential (Mitchum et al., 1977b; Sangree and Widmier, 1977). Description of external geometry or shape is a
seismic parameter that includes, but is not limited to sheets, wedges, lenses and mounds. Internal seismic reflection configuration is a seismic parameter that includes, but is not limited to parallel, divergent, chaotic, reflection-free, and, various shapes of prograding clinoforms. Modifiers added to configuration terms, such as, uniform, even, wavy, hummocky, disrupted and contorted further qualify the seismic facies configurations (Mitchum et al., 1977b). An additional seismic parameter is reflection continuity and depositional processes (Mitchum et al., 1977b; Sangree and Widmier, 1977). In this study, the seismic parameter of reflection amplitude was used to infer bed spacing and velocity density contrast (Mitchum et al., 1977b, Sangree and Widmier, 1977). Interval velocity was the seismic parameter used in this study to infer lithology estimates (Mitchum et al., 1977b). The juxtaposition of seismic facies units and areal extent provides an inference for geologic setting and sediment source (Mitchum et al., 1977b).

3.5.2 Depositional Environments from Seismic Facies Analysis

Reflection amplitude, continuity, and lateral gradation are used in the characterization of seismic facies grouped into two principal environments specific to this study area; shelf, and, shelf-margin and prograded slope (Sangree and Widmier, 1977).

Shelf seismic facies include marine and non-marine deposition such as shelf deltaics, marshes, and fluvial clastics (Sangree and Widmier, 1977). Seismic facies associated with shelf deltaics exhibit oblique and shingled reflection configurations (Mitchum et al., 1977b) of high amplitude and continuity (Sangree and Widmier, 1977). The uppermost boundary is interpreted as a shallow water erosional surface that preserves the most distal portions of clinoform advancement (Mitchum et al., 1977b). Marsh and fluvial deposition exhibit parallel reflection configurations that are variable in amplitude and continuity (Sangree and Widmier, 1977). Low, discontinuous amplitude reflections
infer uniform deposition of one to the other (Sangree and Widmier, 1977). Fluvial processes create abrupt lateral changes in lithology that will produce discontinuous, low amplitude responses (Stuart and Caughey, 1977). Amplitude reflection width of fluvial deposition is usually narrow, but uniform deposition will produce large, high amplitude reflections (Sangree and Widmier, 1977). However, beach and shoreface deposits have been shown to produce high continuity and high amplitude reflections (Sangree and Widmier, 1977). Tabular, basinward thickening wedges of parallel reflections may also indicate widespread, shelf aggradation produced by relative subsidence (Brown and Fisher, 1977; Stuart and Caughey, 1977). Sheet and wedge shaped units containing downdip divergent reflections that exhibit apparent internal convergence in the updip direction indicate lateral differences in deposition (Mitchum et al., 1977b). Shingled reflection configurations contain low angle, parallel oblique reflections that are interpreted as prograded deposition into shallow water (Mitchum et al., 1977b).

Shelf margin and prograded slope facies include deltaic sediments, and density current deposits. Shelf margin and prograded slope facies exhibit oblique, sigmoid, shingled, and hummocky clinoform prograding reflection configurations of variable amplitude and continuity due to the water depth range of deposition (Sangree and Widmier, 1977). The difference between low angle reflections (<1°) found in sigmoid configurations and high angle reflections (up to 10°) found in oblique configurations is attributed to a decrease in accommodation. Low accommodation, or sediment bypass, is inferred by the lack of topset development in oblique configurations, while more pronounced topset development in sigmoid configurations suggests greater accommodation, or aggradation (Mitchum et al., 1977b). Oblique configurations suggest conditions of high sediment input, and relatively low basin subsidence, which is in
contrast to lower sediment input and/or higher levels of subsidence inferred by sigmoid configuration (Mitchum et al., 1977b). Hummocky clinoform reflection configurations are segmented and discontinuous, reflections that are usually sub-parallel (Mitchum et al., 1977b). These configurations represent either fingered interdeltaic sediments or prodelta bottomsets (Mitchum et al., 1977b).

Chaotic reflection configurations may be found in either shelf, or shelf margin and prograding slope environments. The configuration is characterized by discontinuous contorted reflections that may fill or mound a topographic low. Mass-transport and density current deposits are depositional products inferred from the configuration (Sangree and Widmier, 1977).
CHAPTER 4. RESULTS

4.1 Mapping Results

In the study area (Figure 16), the major fault complex consists of two northwest trending down to the basin faults. The northern-most of these faults, Fault A, defines the southern boundary of the up-thrown block 9 (Figure 17 a-d). Numerous (~20) smaller faults (i.e., in terms of stratigraphic offset and regional extent) are found within the up-thrown and down-thrown blocks. In most cases, these faults have a northwest trend and are down-to-the-basin but generally do not extend across the width of the study area. Antithetic faults are associated with minor graben/horst structures within the up-thrown and down-thrown faults but generally do not influence interval thickness across the faults in the section above canyon, i.e., shallower than ~1000 msec.

Immediately to the northeast of the Fault A, several relatively low-angle major counter-regional faults offset section below the Ukpokiti Channel unconformity (Figures 17 c-d). These faults are concave to the northeast in plan view (Figures 18 a-f). Reflections at depth are hard to correlate due to poor resolution, but there is an increase of interval thickness toward the counter-regional faults. The overlying strata (i.e., the interval of interest) have a basinward tilt, i.e., strata dip toward the Fault A. In the down-thrown block, the main structural feature is a faulted anticline (from at least 300 to 2000 msec), the northeast flank of which dips into the major fault complex. The following sections concern, first, the correlation and map characteristics of the Ukpokiti Channel unconformity and its general stratal relationships with the underlying and overlying section in the up-thrown block; second, correlation of these seismic-based observations to paleoenvironmental
Figure 16. Basemap of 3-D seismic coverage showing well locations and areas of no data (white). Lines labeled ‘L’ are dip-lines, and lines labeled ‘T’ are cross-lines.
Figure 17a. Interpreted dip-line, Line 25. Horizontal seismic sections are displayed at two-way time (msec) intersections. Faults are interpreted in black. Bold lines are the major structural faults.
Figure 17b. Interpreted dip-line, Line 165. Horizontal seismic sections are displayed at two-way time (msec) intersections. Faults are interpreted in black. Bold lines are the major structural faults.
Figure 17c. Interpreted dip-line, Line 230. Horizontal seismic sections are displayed at two-way time (msec) intersections. Faults are interpreted in black. Bold lines are the major structural faults.
Figure 17d. Interpreted dip-line, Line 290. Horizontal seismic sections are displayed at two-way time (msec) intersections. Faults are interpreted in black. Bold lines are the major structural faults.
Figure 17e. Interpreted dip-line, Line 325. Horizontal seismic sections are displayed at two-way time (msec) intersections. Faults are interpreted in black. Bold lines are the major structural faults.
Figure 18a. Interpreted horizontal section at 252 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, bold lines are the major structure building faults and dashed lines represent approximate location.
Figure 18b. Interpreted horizontal section at 700 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, bold lines are the major structure building faults and dashed lines represent approximate location.
Figure 18c. Interpreted horizontal section at 252 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, bold lines are the major structure building faults and dashed lines represent approximate location.
Figure 18d. Interpreted horizontal section at 1600 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, the bold lines are the major structure building faults and dashed lines represent approximate location.
Figure 18e. Interpreted horizontal section at 2000 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, bold lines are the major structure building faults and dashed lines represent approximate location.
Figure 18f. Interpreted horizontal section at 2500 msec, twt. Red lines are faults located in the up-thrown block. Black lines are faults in the down-thrown block. Tick marks show the fault dip direction, bold lines are the major structure building faults and dashed lines represent approximate location.
summaries based upon separate micropaleontological, nannofossil, palynological and lithological analyses of drill cuttings from Wells 1 and 2 as reported to Conoco Inc. by Geochem Group Limited; and third, a detailed evaluation of stratigraphic relationships from the correlative section in the down-thrown block.

4.1.1 Stratigraphy in the Up-thrown Ukpokiti Field Structural Block

At any one strike-oriented cross section, the Ukpokiti Channel is a single major angular unconformity well defined by 1) the abrupt termination of the highly-continuous strata underlying basinward dipping strata along channel flanks and base, and 2) markedly discontinuous nature of the overlying seismic facies immediately above the channel. These stratal-terminations and seismic-facies relations are observed essentially across the entire up-thrown block (Figure 19 a-d). The channel can be traced from the northern end of the survey to Fault A, i.e., the southern end of the up-thrown block. The thalweg is in the central portion of the 3D grid throughout the up-thrown block. The average dip of the channel flanks range from 4° to 13° but locally, the channel flanks are considerably higher. The channel geometry is highly variable within the up-thrown block. In some cross sections, channel flanks contain at least one terrace. For example on Trace 1300 (Figure 19a), there is a 1 km-wide terrace at 950 msec. On Trace 950, there is a 1.5 km-wide terrace at 1250 msec. In general, terraces occur on the southwest flank of the channel but some cross sections contain no terrace-like feature (e.g., Trace 1200, Figure 19b). The overall pattern of channel-flank dip is variable. At Trace 1300 (Figure 19a), the channel flanks dip at roughly the same angle towards the thalweg. However, about 1.25 km basinward (at Trace 1200, Figure 19b), northwest flank dips gently towards the thalweg, whereas the southeast flank is steep. At Trace 950 (Figure 19c), the southeast flank has a
Figure 19a. Interpreted cross-line, Trace 1300 with amplitude scale bar shown at left. Horizontal seismic sections are displayed at two-way time (msec) intersections. The red line denotes the Ukpokiti unconformity.
Figure 19b. Interpreted cross-line, Trace 1200. Horizontal seismic sections are displayed at two-way time (msec) intersections. Prominent faults are interpreted in black. The red line denotes the Ukpokiti unconformity.
Figure 19c. Interpreted cross-line, Trace 950. Horizontal seismic sections are displayed at two-way time (msec) intersections. Prominent faults are interpreted in black. The red line denotes the Ukpokiti unconformity.
Figure 19d. Interpreted cross-line, Trace 850. Horizontal seismic sections are displayed at two-way time (msec) intersections. Prominent faults are interpreted in black. The red line denotes the Ukpokiti unconformity.
more gentle average dip towards the thalweg whereas the northwest flank is relatively steep. The width of the thalweg is approximately 1 to 2 km but the overall channel width ranges from 4 to 7 km, i.e., the channel occupies nearly the entire trace width of the 3-D survey such that only a small part of the unconformity (that forms the channel) is observed beyond the channel axis. At the north end of the channel (e.g., Trace 1300), the aspect ratio (width/depth) of the thalweg is ~11 and the cross-sectional area is ~2.3 X 10^5 m^2. Close to the down-thrown fault block (e.g., Trace 950), the aspect ratio of the thalweg is ~27 and the cross-sectional area is ~3.2 X 10^5 m^2. In the area beyond the channel axis and flanks, the unconformity is sub-horizontal, i.e., the surface generally parallels the underlying strata. The maximum depth of the channel is 350 m (e.g., Figure 19c) but in some places the channel thalweg is significantly shallower (i.e., 100 m).

Beyond the channel axis, several smaller scale incisions (i.e., less deep and less wide) into the underlying section are observed. For example, two small channels are observed to the southwest of the main channel (Figure 20). These relatively small channels have a maximum width of 2 km and depths of 100 to 120 m.

On dip-oriented profiles, the Ukpokiti channel unconformity is characterized by low-angle truncation of the underlying strata that generally dip offshore at a slightly shallower angle than does the unconformity (Figure 21 and Figure 22). In a basinward direction, the unconformity can be traced to within 500 m to Fault A as within this zone the seismic reflections are generally washed-out. Regional seismic correlation of the Ukpokiti channel unconformity demonstrates that this horizon can be traced as a single surface within the channel and laterally beyond the channel flanks throughout the up-thrown block. For example, on Line 165 (Figure 23), at least three progradational packages are noted and the offlap break (transition between the topset and foreset)
Figure 20. Dip-line, Line 400 across the up-thrown Ukpokiti block. Shown is the southeastern flank of the Ukpokiti channel with smaller channels that run to the main canyon axis. The base of Seismic Unit 1 is a very localized unconformity.
Figure 21. Dip-line, Line 180 across the up-thrown Ukpokiti block. Contrasted are the seismic reflection patterns directly above the channel base (red line), center (blue dashed line) and directly below the top of channel (green line).
Figure 22. Dip-line, Line 425 across the up-thrown Ukpokiti block. Black arrows indicate stratal terminations. Note the similar angle of dip between the Seismic Units and the adjacent strata.
Figure 23. Dip-line, Line 165 across the up-thrown Ukpokiti block. Black arrows indicate direction of topset termination. Shown are the prominent progradational clinoform packages and the underlying sub-horizontal reflections.
Figure 24a. Two-way-time structure map of the top of the Ukpokiti channel surface (Seismic Unit 2-3 Boundary). Fault heaves are shown in red. The major structure building faults of the down-thrown block, center of map, are depicted as the summation of the two heaves.
Figure 24b. Two-way-time structure map of the Ukpokiti channel unconformity surface (Seismic Sequence 1-2 Boundary). Dashed lines indicate tributary feeders to the main axis. Fault heaves are shown in red. The major structure building faults of both the down-thrown and up-thrown blocks (center map) are each depicted as the summation of the two heaves. The opposite fault dip directions create the back-to-back fault structure not observed at the top of channel (Figure 24a).
decreases from 900 msec, to 1050 msec, then to 1150 msec. There is no significant channelized incision associated with either the topsets or forests. Up-section (Figures 24 a-b), there is a transition to parallel stratification which is roughly coincident with the top of channel fill, i.e., no channel incisions and/or regressive packages are noted within the section overlying the Ukpokiti Channel.

In plan view, the Ukpokiti Channel extends from the northeastern end of the survey a distance of 11 km basinward toward Fault A (Figures 24b and 25). A more or less sinuous channel can be delineated and the overall trend is northeast-southwest. The Ukpokiti Channel widens and deepens to the southwest but deep areas and isolated highs are also observed in the updip part of the channel (Figure 24b). The deep area immediately to the west of the location where the Ukpokiti Channel meets Fault A may correspond to a second large sinuous channel at this stratigraphic level.

A network of smaller channels converge towards the main Ukpokiti Channel at ~30° to 60° angle from the northeast (on the southeast flank of the channel) and from the northwest (on the northwest flank of the channel). These small channels exhibit a low sinuosity and generally speaking, these channels die out in an updip direction, i.e., they cannot be traced as distinct channels to the boundaries of the study area. Only the terrace feature noted on the southwest Ukpokiti Channel flank (strike-oriented profiles Figures 19a and 19c) is a subtle map feature.

4.2 Correlation of Seismic-based Observations to Paleoenvironment Summaries at Wells 1 and 2

On the basis of the seismic observations noted in the above description of the strike- and dip-oriented profiles, three seismic units can be defined and correlated to the down-thrown Ukpokiti block (Figures 26-29b). The lowest seismic unit, Unit 1, is the basinward dipping section truncated below the Ukpokiti channel. The second unit,
Figure 25. Horizontal section at 1340 msec, twt. The slice captures the deeper portions of the up-dip section of the channel. Sediment pathways are shown in dashed outline. Major structural faults are shown in black.
Figure 26. Interpreted dip-line, Line 180 showing Seismic Units 1-3 correlation across the major structural boundary separating the Ukpokiti unconformity. Bold lines indicate the major structure building faults.
Figure 27. Dip-line, Line 180 across the down-thrown Ukpokiti block. Highlighted are differences in the reflection patterns.
Figure 28a. Dip-line, Line 133 across the down-thrown Ukpokiti block. Shown is the correlation of Seismic Units 1-3 to the down-thrown Ukpokiti block immediately down-dip from Well 2.
Figure 28b. Strike-line, Trace 507 across the down-thrown Ukpokiti block. Red arrows indicate direction of fault movement. Shown is the correlation of Seismic Units 1-3 to the down-thrown Ukpokiti block at Well 2 (vertical green line).
Unit 2, is the section corresponding to the channel fill. This unit can be subdivided into a lower part, Unit 2a, which is the 100 m-thick section that exhibits sub-parallel stratification, and an upper part, Unit 2b, which contains the thick offlapping sequences. Unit 3, the upper-most unit, is the parallel-stratified section above the channel fill.

4.3 Well Log Biostratigraphic and Lithostratigraphic Results

Presented in this section are paleoenvironment summaries based upon separate micropaleontological, nannofossil, palynological and lithological analyses of ditch cuttings from Wells 1 and 2; as reported to Conoco Inc. by Geochem Group Limited. Microfacies and palynological zonation are primarily based on Geochem Group Limited internal schemes, which gives consideration to published literature and industry schemes. At Well 1, Seismic Unit 1 ranges in depth from ~1445 m to 1183 m. Seismic Unit 2 ranges in depth from 1183 m to 823 m. Seismic Unit 3 ranges in depth from 823 m to 704 m.

Well 1 penetrates the Ukpokiti Channel in the up-thrown block and Well 2 penetrates an anticline structure which encompasses the correlative section in the down-thrown block. At Well 1, the three seismic units (Units 1-3) correspond to depositional sequences which represent an overall regression of sediments assigned to the Akata and Agbada Formations. At this location, the Akata and Agbada Formations are dated at late Miocene. The youngest age for these formations at Well 1 is limited to the early Pliocene. A summary of the key points presented in the reports from both wells follow starting below the channel unconformity (Seismic Unit 1), moving up-section to the channel fill (Seismic Unit 2), and ending with section overlying the channel fill (Seismic Unit 3). Due to structure at Well 2 (Figure 28b),
reported interval thickness is an approximation based primarily on time to depth postings.

4.3.1 Seismic Unit 1 Lithofacies and Paleoenvironment at Well 1

According to lithographic log interpretation, Seismic Unit 1 (Figures 29a-b and 30a-b) is predominately a thick sequence of claystones including minor sandstones. The section comprises a thick sequence of medium dark grey to medium grey claystones with minor fine-grained sandstone horizons. Seismic Unit 1 (from 1445 m to 1183 m) contains hemipelagic claystones interbedded with poorly sorted sandstones in a marine, middle to outer neritic setting. Above 1439 m, Geochem Group Limited characterizes the strata as a depositional sequence of inter-beded sandstone and claystone of the Agbada Formation. Coarse-grained, dirty inter-beded sandstones and claystones start to appear at 1228 m and increase in frequency and thickness up-hole. Geochem reports this interval to be representative of a regressive series of interbedded hemipelagic claystones deposited in a marine, outer-to middle-neritic paleoenvironmnet subject to frequent influxes of coarse, poorly sorted sandstones, perhaps deposited by density driven currents. Microforamineral analysis by Geochem Group Limited indicates uphole-decreasing paleodepths and episodically increased run off and fluvio-marine influence. Decreased paleodepths are also indicated by the uphole-decrease in the frequency of microforaminiferal test linings and dinocysts. Further, there is an uphole-increase of abundance in charred Gramineae cuticle and reworked Pediastrum sp., which is also indicative of fluvio-estuarine influence. The highest occurrence of Globorotalia merotumida is found within Unit 1 (1317 m) and is used in conjunction with regional comparisons and stratigraphic position by Geochem Group Limited, to date the section no younger
Figure 29a. Dip-line, Line 107 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation below the channel, and rotational feature on the northwestern channel flank. Gamma-ray log is highlighted.
Figure 29b. Strike-line, Trace 1089 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation below the channel, and rotational feature on the northwestern channel flank.
Figure 30a. Dip-line, Line 107 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation at the channel base, and rotational feature on the northwestern channel flank.
Figure 30b. Strike-line, Trace 1089 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation below the channel, and rotational feature on the northwestern channel flank.
than late Miocene in age, N17 Zone. At the Well 1 location, incision of Seismic Unit 1 by the Ukpokiti unconformity has been noted in seismic section and is considered while investigating the thickness of the unit.

4.3.2 Seismic Unit 2 Lithofacies and Paleoenvironment at Well 1

Unit 2 (from 1183 m to 823 m), the channel fill, is a sequence of poorly sorted, coarse grained sandstones. Immediately above 1189 m, there are several three-meter-thick packages of sands containing rare, lithic clasts of argillaceous, dolomitic sandstones. The sands correlate with a distinct response in gamma ray log signature (Figures 30 a-b, 31a-b and 32 a-b). A change in the up-hole pattern of gamma-ray log response is noted at a positive spike at 1128 m. The log response pattern is inverted until reaching a negative spike at 1018 m. Very sparse calcareous benthonic and planktonic foraminifera are recorded, much of which may represent caving from the diverse microfaunas of the overlying section. Microfaunas in the upper part (951 m to 823 m) of the sequence, if in-situ, indicate a marine, inner- to middle-neritic paleoenvironment with strong deltaic/estuarine influences. Typical taxa of at least middle neritic depths, such as, *Cibicidoides* gr. *Dutemplei*, *Lenticulina cultrate* and *Marginulina costata* are associated with taxa typical of inner neritic (*Amphistegina gibbosa*) and inner neritic to fluvio-marine environments (*Ammonia beccarii* var. *tepida*). Geochem reports the age for this interval as early Pliocene and classifies the section as Agbada Formation.

4.3.3 Seismic Unit 3 Lithofacies and Paleoenvironment at Well 1

Unit 3 (from 823 m to 704 m), is a regressive sequence of poorly sorted, fine to very coarse, sandstones with minor interbedded claystones (Figures 32 a-b). Geochem reports this interval as being formed by marine, inner to middle neritic
Figure 31a. Dip-line, Line 107 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation at the channel top, and rotational feature on the northwestern channel flank.
Figure 31b. Strike-line, Trace 1089 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation below the channel top, and rotational feature on the northwestern channel flank.
Figure 32a. Dip-line, Line 107 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation above the channel top, and rotational feature on the northwestern channel flank.
Figure 32b. Strike-line, Trace 1089 across the up-thrown Ukpokiti block. Shown are the seismic facies designation, Well 1 lithology log correlation below the channel top, and rotational feature on the northwestern channel flank.
deposition with strong fluvio-marine influences. There is an up-hole-increase in the abundance of the fresh/brackish water algae *Botryococcus*. Shallow marine ostracods, gastropods and scaphopods are common to this interval. The depositional unit from 823 m to 704 m is a regressive sequence of sandstones with minor claystones. Geochem reports an early Pliocene age and classifies the section as Agbada Formation. This sequence is considered to represent a regressive series of coastal and deltaic sand deposition with limited, minor hemipelagic claystones.

### 4.3.4 Well 2 Biostratigraphic and Lithostratigraphic Results

At Well 2, Seismic Units 1 to 3 (~1690 m to ~1265 m) are difficult to precisely define because sampling was widely spaced. Geochem reports the microfacies found at this depth suggests a neritic setting with within a prodelta environment. Benthonic faunas within Unit 1 represent inner neritic and proximal fluvo-marine assemblages. Analysis presented by Geochem shows that the upper-most portion of Seismic Units 1 through 3 were deposited in an outer- to inner-neritic setting also with coastal fluvo-marine influences. The variability in facies is reported to be associated with the onset of true paralic/deltaic influences. The overall age of Seismic Units 1 to 3 is reported by Geochem Group Limited to be early Pliocene and is classified as Agbada Formation.
CHAPTER 5. DISCUSSION

5.1 Interpreted Channel Evolution

Discussion of results obtained from this analysis will demonstrate the evolution of the Ukpokiti Field Channel across the entire study area and present a hypothesis for the lack of a pronounced unconformity down-dip. Interpretation of the data led to the creation of a six stage conceptual model which depicts correlative stratigraphy as the relative sea-level position fluctuated. The discussion is partitioned into the stages of the model as it relates to the structural interpretation. Emphasis is given to the interpretation of seismic facies Units 2a and 2b.

5.1.1 Stage 1: Paleogeographic Shelf Reconstruction Before Incision

The paleogeographic location of the shelf edge is in the study and includes the stratigraphic section incised by the Ukpokiti Channel unconformity. This location is predicted from the conceptual model based on paleoenvironment extrapolation between well locations and observed paleoshoreline profiles. It is speculated that the precise location of the shelf break is coincident with the current back-to-back fault structure.

Chrono-biostratigraphic and lithologic well correlation show that Unit 1 represents the distal portions of an overall regressive Upper-Miocene cycle (Figure 33). Specifically, Unit 1 was deposited from a mid-shelf to upper-slope position, the northeastern to southwestern extent of the study area, respectively. Microfaunas immediately underlying the Ukpokiti Channel unconformity in Well 1 are interpreted to represent an outer- to middle-neritic environment. At Well 1, there were increasing episodes of run-off and fluvio-estuarine influence which is thought to have deposited the coarser sands in the basinward-thinning, Unit 1 section. The conceptual model predicts turbidite deposition in the down-thrown block (Well 2), below the channel base. These deposits are below
Figure 33. Stage 1 diagrammatic representation of initial conditions before relative sea-level fall. Vertical is not to scale.
seismic resolution, but are depicted in the diagrammatic representation of Stage 1. Well and seismic studies from Oso Field (Armentrout et al., 1999), on the southeastern continental margin, also show that an alluvial plain to upper bathyal profile are found over a distance of 18 km. The onlap observed in mappable reflections of Unit 1 represent the up-dip portion of a shelf-margin system (Posamentier and Vail, 1988; Posamentier et al., 1988). Basinward expansion into the counter-regional fault is also depicted in the diagrammatic representation. Onlap observed in the upper section of Unit 1 may be the direct indication of a previous instance for which fluctuation in relative sea-level substantially moved the position of shoreline/coastal deposition, without shelf incision (Posamentier, 2001).

5.1.2 Stage 2: Fluvial Shelf Incision

The Ukopokiti Channel unconformity is interpreted to be a fluvially incised valley (Figure 34) (based on the lack of submarine slope-depositional architecture, geomorphology, paleo-environment interpretation and well lithology). Submarine canyon erosion on the slope usually results in a basinward bottleneck of the erosional surface due to down-dip tributary confluence to a single channel (Pratson and Coakley, 1996; Armentrout et al., 2000). Also characteristic of submarine slope canyons are gull-shaped channel-levee systems observed in strike view containing related seismic facies units of one or more episodes of erosion (Wonham et al., 2000). There are often convex-up depositional lobes at the end or just down-dip from the submarine slope canyon mouth (Gregersen, 1998; Armentrout et al., 2000). These observations are not resolved at the Ukpokiti Field Channel. In addition, there is no detectable, classic slope-fill geometry (Posamentier and Vail, 1988) at the channel mouth. Moreover, there is a flaring of the V-shaped channel in the down-dip direction, similar to how the Hudson Valley system
Figure 34. Stage 2 diagrammatic representation of conditions at time of relative sea-level fall. Vertical is not to scale.
flares out at the shelf edge and the morphology of New Jersey continental margin incisions (Fulthorpe et al., 2000); all of which are believed to be related to eustaticly-induced fluvial incision of the shelf. Though there is no direct correlation between the process of channel formation (subaerial versus submarine erosion) and channel morphology (V- or U-shaped), V-shaped channels presumably are associated with high levels of erosion (Posamentier and Vail, 1988; Yu and Lee, 1998).

No specific paleo-environment is reported for the section immediately above the unconformity in Well 1. A sharp contact between shallow water environments overlying deeper water environments at the unconformity seen at both wells would support an incised valley interpretation (Posamentier and Vail, 1988). Whether the channel fill immediately above the channel unconformity was deposited fluvially or by density driven currents is not determined by biostratigraphic data. However, both the interpretation of lithology overlying the channel unconformity at Well 1 (see Stage 3) and the seismic parameters favor fluvial incision into an outer-shelf position.

A drop in the position of relative sea-level and the associated basinward shift in the fluvial system profile is interpreted to be the cause of the channel unconformity. The result is an incised valley across the outer shelf. In the latest-Miocene, there were two instances of eustatic fluctuation corresponding to the 3.2 and 3.3 third order cycles (Haq et al., 1988). One of these fluctuations is thought to be related to the relative fall in sea-level that created the incised valley at Ukpokiti. Chrono-biostratigraphic data constraints reveal that channel fill formation predates the 3.3/3.4 third order boundary. The seismic to well tie for the 3.3/3.4 boundary is stratigraphically above the top of channel. The shift of coastal onlap at the 8.2 Ma sequence boundary appears to be of sufficient magnitude to develop the prominent unconformity observed in this study. However, the
high frequency fluctuation of eustatic sea-level at 6.3 Ma is favored to be directly related to the Ukpokiti unconformity. The preceding shelf margin and highstand of the 3.2 cycle would have moved the relative depositional shoreline location basinward and created a broader shelf (Posamentier et al., 1988). Up-dip portions of the study area show that the top and base of channel coalesce into a stratigraphically thin interval. No absolute age boundaries for the late-Miocene or direct measure of the time hiatus are available, nevertheless the channel base age is stratigraphically positioned close to the 3.3/3.4 cycle boundary; latest-Miocene. The prominent slope-fill facies observed in the down-thrown block is stratigraphically above the 3.3/3.4 boundary and is thought to be related to the lowstand deposits of the 3.4 cycle. The stratigraphic position of the incised valley fill at Ukpokiti Field is then interpreted to be correlated to the 3.3 third order cycle of the Haq et al. (1988), eustatic curve. In summary, it is speculated that the prograded position of depositional shoreline in the late-Miocene in conjunction with the close proximity of fluvial feeders led to the creation of an incised valley during a rapid eustatic fall, circa 6.6 Ma.

Coarse-grained sands found immediately above the channel base are interpreted to be the remnants of fluvial channels that were actively incising the shelf during the fall and lowstand of relative sea-level. It is presumed that the eroded section from the up-thrown block was transported basinward of the study area during the relative sea-level fall. However, deposition within the proximal valley or at the valley mouth may have been cannibalized during continued shoreline translation. During the fall of sea-level, it is also possible that the valley may have been accompanied by line sourced sediment bypass of the shelf surface and shelf-edge positions. Small-scale incisions on the flanks of the channel walls are believed to have been cross-shelf feeders to the incised valley.
system. Support for an interpreted rapid rate of relative sea-level fall is found in the
subsidence augmented, basin-scaled flume modeling of Heller et al. (2002). The deep,
narrow incision achieved during rapid base-level fall over a prograded highstand system
is similar to that observed at the Ukpokiti Field Channel unconformity. The smaller scale
channels observed at the shallow flanks of the Ukpokiti unconformity are thought to be
analogous to the terracing created during the Heller et al. (2002) flume experiment.
These channels probably delivered sediment as by-pass feeders to the main valley.
Significant changes in the morphology of the eroded paleo-shelf surface and the small
cross-shelf channels may have occurred during the evolution of the valley fill.

Also noted are the similarity in channel mouth morphology between this study and
the flume investigation. The Heller et al. (2002) interpretation of the morphology is shelf
edge failure at the channel mouth during lowered sea-level. Results from this
investigation cannot support that interpretation for this data set, because the timing of
minor faulting observed at the Ukpokiti channel mouth is thought to post-date channel fill
deposition. Initially, this slumping and faulting, best observed in channel strike view,
was interpreted as the base of the unconformity creating a geomorphology of two discrete
episodes of channeling. Detailed inspection of horizontal sections showed that the extent
of erosion (i.e., the Ukpokiti unconformity) was stratigraphically above the slump and
fault surfaces. Seismic reflection ties to well lithology later confirmed this reasoning.
The tendency to map the unconformity at the base of the slump and fault surfaces were
due to issues of seismic resolution related to “seismic healing” of the slip surface. The
distinction between disrupted and faulted section juxtaposed to (a) contiguous
undisturbed section, and (b) the basal channel fill that at times appears sub-horizontal in
strike view, verifies that there is was only one instance of a third order magnitude
fluctuation in sea level and only one cycle of channel incision and fill (Figure 4). It is also highly probable that the immense size of the Ukpokiti channel is due to continued subariel channel mouth degradation during relative sea level fall.

5.1.3 Stage 3: Shoreline Regression

Stage 3 (Figure 35) depicts the deposition of U- and D-Units 1 which are interpreted to be a shelf-edge delta; lower delta plain to prodelta facies, respectively. Stage 3 deposition is distinct because of the explanation offered for the seismic reflection character of the correlative down-dip conformity to the up-dip unconformity. The reason for the conformable seismic reflection is due to the deposition of sediment, as opposed to, the erosion of sediment across that surface (i.e., incision). To explain deposition on a surface that is thought to be at an upper-slope to outer-shelf position during relative sea-level fall, the model of deposition offered is that of shelf edge shoreline regression (Figure 61) reported recently by Posamentier et al. (1992), Poulsen et al. (1998), Winn et al. (1998), Armentrout et al. (1999), Edwards (2000), Heller et al. (2000), Bjorklund et al., (2001), and Hiscott (2001), often referred to as “forced regression” (Posamentier et al., 1992).

It is the interpretation of this author that the fluvial systems that incised the Ukpokiti Channel were connected to the shoreline during the relative fall of sea-level, which created alternating episodes of sediment by-pass, erosion, and deposition. The conditions favoring deposition of Unit 2a in the up-thrown block, include up-dip erosion leading to down-dip sediment by-pass with minor preserved deposition at the fluvial system end, which was the depositional shoreline. The previously mentioned basal lag of coarse grained sandstones is included in the up-thrown section of Unit 2a deposition. During relative sea-level fall and at lowstand, shoreline deposition represented by the down-
Figure 35. Stage 3 diagrammatic representation of conditions during relative sea-level fall to lowstand. Vertical is not to scale.
Figure 36. Model of shoreline regression during relative fall of sea-level, from Back et al., 2001.
thrown extent of Unit 2a, was able to prograde farther onto the upper slope (Figure 36). The author interprets the most basal fill of the Ukpokiti Channel as a shallow water depositional environment prone to fluvial and fluvio-marine influence. The obliquity of these seismic reflections to the channel unconformity seen in this interval, strengthens (but does not unequivocally concede) the argument for post-incision fill as opposed to contemporaneous sediment flux (remobilized stratigraphic section). Although not observed at the same scale, the interpretation of the down-thrown section of Unit 2a is envisioned at a production scale (4th and 5th order cycles) to be similar to the observations made in Bjorklund et al. (2001) and at Oso Field, Nigeria by Armentrout et al. (1999). Using the outcrop data of a shelf edge to base of slope profile, Bjorklund et al. (2001) were able to detail facies distribution within shelf edge deltaic systems. D-Unit 1, found in this study, is surmised to be analogous to the Hogsnyta Type 2 clinoforms (Figure 37) reported in Bjorklund et al. (2001). The observed similarities are slope accretion without fan development and hetero-lithic deposition (Figure 38). Hetero-lithology in Unit 2a in the down-thrown block is interpreted from the Well 2 gamma-ray curve and the chaotic, slightly discontinuous, and low to moderate amplitude response of the seismic reflections (Armentrout et al., 1999). Basinward thinning and updip thickening is not resolved in this study.

Still, it is possible that continued sediment supply via the fluvial systems during incision is preserved in depositional unit 2a in the down-thrown block, which then would also include more proximal sediments, such as, the lower delta plain. Outer-shelf to upper-slope deposition of sediments connected fluvial systems can be explained in terms of density driven flow dynamics as they relate to the basin (Bjorklund et al., 2001).

Conclusions from the Spitsbergen, Central Basin investigation report hyperpycnal flows
Figure 37. Dip view of slope wedges and related architecture from Bjorklund et al., 2001.

Figure 38. A) Regressive and B) retrogradational phases of deposition over a shelf-edge to lower slope profile from Bjorklund et al., 2001.
deposited (as opposed entraining or by-passing) sediment on a steep upper-slope (ca. 4 degrees) (Bjorklund et al., 2001). Unlike the biostratigraphic data available to Armentrout et al. (1999), Ukpokiti biofacies data is low resolution due to sampling rates over the section of interest. Contemporaneous adjustment to the stream profile up-dip produced Unit 2a in the up-thrown block and marked the beginning of deposition in the proximal valley. The coarse to very coarse siltstones and claystones from the channel base to ~1128 m are thought to represent the lower most channel sequence. The irregular shape at the flanks of valley mouth may indicate slump features that contributed sediment input during this time or just prior (Stage 2). In summary, the up- and down-thrown sections of Unit 2a represent up-dip erosion, bypass, and accretion, and down-dip by-pass and deposition of sediments along an unconformable and correlative conformable channel base, respectively.

### 5.1.4 Stage 4: Channel Flooding

The interpretation that a rapid relative sea-level rise occurs after depositional unit 2a (down- and up-thrown) drives the Stage 4 model (Figure 39). The transgression of shoreline occurs first in the down-dip location of Unit 2a, and as the sea-level migrates shore-ward, sediment is reworked into a thin transgressive interval which is depicted by a single toplap reflection above the down-thrown portion of Unit 2a (Posamentier et al., 1992; Armentrout et al., 1999; Bjorklund et al., 2001). Complete flooding of the valley to the most landward extent occurs during this stage (Posamentier et al., 1992; Armentrout et al., 1999). In the proximal valley (up-thrown block) onlapping reflections appear to back-step over the lower sections in Unit 2a. Perhaps, due to the seismic character of the underlying facies or the nature of the flooding event, the onlapping reflections rest disconformably over Unit 2a (Posamentier et al., 1992; Bjorklund et al.,
Figure 39. Stage 4 diagrammatic representation conditions at time of rapid relative sea-level rise. Vertical is not to scale.
The intersection of the lithology log with a subtle seismic reflection, correlated as
the flooding event, reveals a minor claystone containing pebbles and bioclastic fragments.
The claystone also marks a spike in the gamma ray curve and a change in grain size from
intermittently very coarse below, to medium and fine grained above which possibly
indicates a decrease in energy regime related to marine incursion (Armentrout et al.,
1999; Hiscott, 2001). The interpretation of erosive processes acting during this flooding
event is preferred due to the correlation of a prominent down-dip toplap surface to the
lithology log, and the limited extent of the back-stepping onlapping reflections. Whereas
there is an up-dip limit to back-stepping reflections, it is possible that rapid flooding may
have also created significant sediment input distally, through the process of mass wasting
in the landward part of the valley.

5.1.5 Stage 5: Deltaic Progradation

Stage 5 (Figure 40) is interpreted as a return to shoreline regression which is
exhibited in the prograding clinoform package of Unit 2b. In the most landward portions
of the flooded valley, clinoform reflection angles are steepest and topset preservation is
minor. Presumably, this indicates rapid progradation into the incised valley. Rotated
blocks in the basal Unit 2a bolster this line of reasoning. The underlying section
probably rotated to accommodate the overlying clinoform packages (Back et al., 2001).
There is no observed divergence of reflections at the top of the rotated blocks which
would suggest syndepositional faulting, so load accommodation follows as a mechanism
for glide plane rotation (Whitebread et al., 2000). These rotations are only observed in
the basal unit along the flanks of the valley. Slumping occurs along the basinward flanks
of the valley, near the mouth and may be related to the counter-regional extension of the
underlying fault (Cohen and McKlay, 1996; Whitebread et al., 2000). Slumping in this
Figure 40. Stage 5 diagrammatic representation of conditions during time of relative sea-level rise to highstand. Vertical is not to scale.
area is interpreted to post date valley incision but whether these slumps contributed to the sediment input (Edwards, 2000) after shelf incision is indiscernible, though plausible. The down-dip clinoform angles become shallow due to increased accommodation as the progradational package approached the relict shelf edge within an increasingly deeper valley and lower energy regime (Mitchum et al., 1977). Furthermore, slumping at the valley mouth as the prograding clinoform package was deposited could also create accommodation (Edwards, 2000), thereby lessening the foreset angle. But this idea is only offered as conjecture because no sufficient evidence for the timing of slump activity is available. Minor slumping, detected at the toes of the proximal clinoforms and just above the Unit 2b downlap surface, may have contributed to a progradational platform on the upper slope (Hiscott, 2001); represented in the down-thrown block by the Unit 2b downlap surface.

Down-thrown, Unit 2b represents the distal clinoform toes of the prograding package (Armentrout et al., 1999). The seismic reflection tie to the Well 2 gamma-ray curve offers a vague interpretation of the nature Unit 2b, in the up-thrown block, which is taken to be aggradational (Armentrout et al., 1999; Hiscott, 2001; Hodgetts et al., 2001). Nonetheless, the seismic parameters of the shallow water, low angle, shingled clinoform unit is interpreted to be an upward coarsening, distal interval of deltaic progradation (Vail et al., 1977; Mitchum et al., 1977; Todd and Mitchum, 1977; Sangree and Widmier, 1977; Armentrout et al., 1999).

Correlated across the back-to-back fault system, Unit 2b represents shelf margin regression which completely fills the incised valley and onlaps the initial erosive shelf unconformity. During this last stage of valley infill, the small scale channels noted on the flanks of the valley are filled. The in-lap (confined to the channel) and off-lap
relationship of Unit 2b in the up-thrown block, to the upper-most stratigraphic level of valley fill is the basis for the interpretation of this depositional stage (Hiscott, 2001). This in-lap relationship also confirms the interpretation of the Ukpokiti valley as the product of a single incision. The sub-parallel reflections that constitute Unit 2b are not aggraded channels or multiple incisions, but are interpreted as toplap surfaces in dip-view on the basis the in-lap and off-lap relationship to the Ukpokiti unconformity. Subsequent to the deposition of Unit 2b which indicates complete valley fill, it is expected that there is a shift in depositional processes.

5.1.6 Stage 6: Depocenter Relocation

Stage 6 depicts a lower floodplain environment as the depositional model for Unit 3 (Figure 41). Well lithology to seismic ties show that the section above the valley fill (Unit 3) contains lignite intervals and sands with abundant gastropods and bioclasts. The conditions of relative sea-level probably range from late highstand to stillstand for this section (Armentrout et al., 1999; Hodgetts et al., 2001). The most important observation to note is that there is no other recognized unconformity within Unit 3 and below the 3.3/3.4 boundary tie. This fact is considered when deriving a correlation to 3\textsuperscript{rd} order cycles. Unit 3 and Unit 2 are interpreted to be the upper-most section of the highstand systems tract within the 3.3 third order cycle (Haq et al., 1988).

5.2 Structural Interpretation

The major structural boundary in the study area is a growth fault that creates a roll-over anticline in the downthrown block. Counter regional faulting creates a small scale crestal collapse structure in the up-thrown block. Seismic data indicate extensional faulting may be soled at great depth. The majority of faults in the study area are through-going to the surface. Although seismic tremors observed in western Nigeria during the
Figure 41. Stage 6 diagrammatic representation of conditions during highstand to stillstand of relative sea-level and after complete fill of valley. Vertical is not to scale.
The study area is composed of a back-to-back fault system consisting of a major regional and counter-regional fault. This fault system is a major structural boundary (Evamy et al., 1978) that is used to separate the study area into predominately down-thrown and up-thrown blocks. Against the regional fault is a striking rollover anticline that dominates the down-thrown block. Steep, parallel crestal faults cut the rollover anticline associated with the major growth fault in the southern half of the study area, while additional crestal faults cut into an under developed crestal collapse structure in the northern half and help to create hydrocarbon traps. Half of a crestal collapse feature (Evamy et al., 1978) is observed to the northeastern most extent of the study area in the up-thrown block. Findings from the published work of Evamy et al. (1978), Weber et al. (1978), Damuth (1994) and Cohen and McKlay (1996), greatly contributed to the understanding of regional and local structural evolution. As observed in the cross-cutting relationship between the counter-regional fault and the Ukpokiti unconformity, the fault may have been active until at least shelf incision. Understanding the structural setting of the Ukpokiti study area from literature allowed me to predict expansion of section within the up-thrown block, at the major counter-regional fault, though my interpretative work proved inconclusive.

In addition, it is evident from a cross-cutting relationship that the regional fault was active in the uppermost stratigraphic column, after the counter-regional. Cohen and McKlay (1996) and Damuth (1994) have shown that the evolution of shale diapir-bound,
graben depocenters starts with an active counter-regional fault that accommodates the overlying sediment input through subsidence, up to a point. The point at which the counter-regional fault can no longer accommodate deposition, marks a basinward shift in depocenters and the subsequent initiation of regional extensional. No regional fault is present in any of the schematic models because the valley incision is thought to be the instance of shelf margin (depocenter) shift across the counter-regional fault. Expansion of section above both, the down-thrown and up-thrown channel fill and the proximal change in depositional environment clearly denote a change in depocenter location to down-dip of where the prominent deltaic clinoforms are found.

The author’s early thoughts to explain the lack of down-dip incision centered on a paleo-geographic profile containing a contiguous regional fault at the mouth of a paleo-valley. Expansion on the down-thrown block would create deeper water conditions and greater accommodation space to offset erosive processes, and promote deposition. This hypothesis may still be a valid interpretation but the (a) lack of observable expansion of section below and within the channel, and (b) the inability to directly measure expansion against the primary regional fault surface (Marchal et al., 2003) led to the previously presented six stage model. The possibility exists that the anticline may be a shale-cored feature or that the seismic “wash” zone may have been an active diapir ridge (Cohen and McKlay, 1996). Further speculation would suggest that the activity of a shale-ridge (and overall availability of Akata shales) may have structurally influenced valley incision or the subsequent valley fill (Cohen and McKlay, 1996).

Consequently, if there was no expansion into the regional fault then the roll-over anticline post-dates the formation of the valley and there was no contiguous regional fault at the paleo-valley mouth. Observed expansion above the valley fill, however,
corroborates the published models for depocenter evolution and provides a date for the shift in depocenter. Excepting this, the observation of regional extension during lowstand shore-line regression (Edwards, 2000; Back et al., 2001; Hodgetts et al., 2002) or after (Armentrout et al., 1999; this study) may prove pivotal to hydrocarbon exploration (Weber et al., 1978; Posamentier et al., 1992) in the area.
CHAPTER 6. CONCLUSIONS

1. The stratigraphic expression of the Ukpokiti Field channel in the downthrown block is a disconformity (seismically conformable surface). There are three distinguishable units (Seismic Units 1-3) of distal deposition.

2. The channel is an incised valley probably formed during a lowering of relative sea-level and the overlying section is an incised valley fill representing deposition occurring during the relative rise of sea-level position.

3. The chronostratigraphic control suggests that the channel unconformity and overlying valley fill may correlate to the 6.3 Ma Sequence Boundary and the 3.3 Third Order Cycle of the TB3 Super Cycle from the eustatic chart (Haq et al., 1988), respectively. If correct, then Ukpokiti highstand deposition (pronounced clinoforms) occurred between ~5.8 Ma and 5.5 Ma. Observed slope fill on the down-thrown block reflects lowstand deposition within the 3.4 Third Order Cycle.
   
   a. The up-dip portion of the channel evolved first as an unconformity marking, (i) a hiatus in deposition, (ii) a pathway of sediment by-pass, and (iii) an axis of deposition. There are three distinguishable up-thrown block units (U-Units) of proximal deposition. The obliquity between the unconformity surface and the underlying reflections, lithology found just below the unconformity surface, chrono-biostratigraphic data, and other observed absences of down-dip traceable unconformities imply that the paleo-shelf edge during the creation of the channel was found in the center of the study area (i.e., coincident with the present structural boundary).

   b. The down-dip portion of the channel evolved as (a) a sediment by-pass fairway and (b) a surface of deposition.
i. The lower most of the three Seismic Units of deposition is a preserved section of pro-delta and delta-front deposition (though more coastline/shoreline proximal sediments may be present). This unit, Seismic Unit 1, was deposited as the shoreline advanced basin ward with the lowering of relative sea-level. It is unclear as to how much, if any, of this unit is composed of the evacuated section from the up-thrown block.

ii. The top of Seismic Unit 2a is a transgressive deposit that meets the lower unit as a toplap surface. It represents a rise of relative sea-level which flooded the down-thrown block. Erosive processes at wave base may have been associated with this flooding event which represents the landward retreat of the coastline/shoreline.

iii. The lower boundary of the Seismic Unit 2b, is marked by a downlap surface that is parallel to the transgressive surface below it. The downlap surface represents a return to sedimentation outpacing the available accommodation. Seismic Unit 2b contains the distal foresets of deltaic clinoforms; pro-delta and turbidity current deposits. Presumably, this unit developed during the slow rise- and stillstand of relative sea-level. The top of Seismic Unit 2b is marked by a toplap surface which represents the completion of channel fill and a change in proximal depositional process.

c. The up-dip portion of the channel contains a basal lag deposit and an interval of aggradational fill (Seismic Unit 2), a series of transgressive backstepping onlap (Unit 2a), and a prograding deltaic clinoform package (Unit 2b).
i. Unit 2a is recognized just above the channel unconformity as a sharp
based, fining upward, coarse grained sands. This represents fluvial
by-pass and minimal fluvial deposition at the base of the channel. The
unit promotes the idea of shelfal incision due to stream profile
adjustment initiated during the fall of relative sea-level. Horizontal
sections at the maximum depth of channel incision reveals
fluvial/thalweg patterns. Only subtle seismic and well lithology detail
is offered as evidence for the top of this unit. A spike in a
characteristically aggradational Gamma Ray log marks the top of unit
1 and can be correlated to a subtle seismic response.

ii. Unit 2a is a discrete interval of onlapping reflections that are sub-
horizontal to slightly reverse dipping. The onlap surface (i.e., top of
Unit 2a) is irregular and unconformable. Preservation of Unit 2a into
the more landward extent of the channel is limited areally and in
vertical section. The top of the interval represents the intact
transgressive deposits formed during the initial relative rise of sea-
level.

iii. The lower boundary of Unit 2b is marked by a downlap surface, which
is also the toplap surface for the top of Unit 2a. This surface marks the
return of sediment influence over accommodation space and is
interpreted as the platform for the above prograding deltaic clinoforms.
The lithology log shows an upward coarsening interval of sands
characteristic of progradational units (i.e., becoming more proximal
up-hole) that correlates to the prograding clinoform reflections. The
lithology log correlation includes section stratigraphically above the Gamma Ray log spike at the top of U-Unit 1. No transgressive deposits appear to be preserved at the well location, so Units 2a and 2b are in direct contact. Clinoform reflections of this progradational package decrease in angle basin ward which is loosely interpreted as depocenter filling and loss of energy of environment in that direction. Loading associated with the rapid progradation of Unit 2b caused rotation of section in the underlying Unit 2a. The toplap surface that is the top of Unit 2b represents complete channel fill and a change in depositional processes to what is presumably lower coastal plain sedimentation. The top of Unit 2b is a surface just above the highest topset surface of clinoforms and has downlap onto it. The relative position of sea-level after channel fill is speculated to be at stillstand or continuing through highstand.
REFERENCES


VITA

Toby Latwan Stewart was born in Norfolk, Virginia, and spent the majority of his life in the Tidewater metro area. Upon graduation from Norview Senior High School in 1993, Toby began a full scholarship at Fort Valley State University and the University of Oklahoma. While matriculating at both universities, Toby assumed leadership roles in student housing and government, and Greek life. In 1998, Toby earned his Bachelor of Science degree in geology from the University of Oklahoma. He then worked at Conoco’s Gulf of Mexico Business Unit for a year and a half. During this time, Toby applied for graduate school at Louisiana State University and secured the release of a 3D seismic data set for his thesis program. In 2004, Toby marked the attainment of two of his longstanding goals; a master’s degree and a new career as a development geologist.