SEDIMENTOLOGY AND STRATIGRAPHY OF A DEEPWATER TRANSIENT FAN ON THE CONTINENTAL SLOPE: THE LATE MIOCENE ISONGO FORMATION, EQUATORIAL WEST AFRICA

by

Jeannette Marie Wolak

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Earth Sciences

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This dissertation has been read by each member of the dissertation committee and
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Jeannette Marie Wolak

April, 2011
DEDICATION

This dissertation is dedicated to my family, especially…

To my mother and father for their unending support, love and patience;

To my grandparents, Richard and Lillian DeLong, for their encouragement to pursue my dreams and education;

To my brother, Eddie, whose memory reminds me that love transcends both time and space.
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ABSTRACT

Deepwater clastic deposits of the Late Miocene Isongo Formation, located 50 km northwest of Bioko Island, characterize a sand-rich transient fan system developed in response to incipient structural growth on the continental slope. Approximately 1200 ft (366 m) of conventional core, 21 wells, 3-D seismic (maximum 40-60 Hz), biostratigraphy, chemostratigraphy and dynamic production data from the 100 km² study area are used to: (1) Define process-based sedimentological facies within the Isongo Fan; (2) Characterize porosity and permeability trends at three temporal and spatial scales; (3) Identify sedimentary bodies throughout cored and uncored intervals; and (4) Correlate stratigraphic sequences within a framework of adjustment, initiation, growth and retreat (AIGR). While the former two objectives capture small-scale geologic heterogeneities developed at the time of deposition, the latter two describe changes in fan geomorphology during coeval uplift and sedimentation.

Fifteen core-defined sedimentological facies reflect subaqueous depositional processes including turbidity currents, debris flows and pelagic settling. Pore space generated during deposition is correlated to grain size; pore connectivity is correlated to sorting. Sedimentation units and facies assemblages, which characterize depositional processes operating during a single sedimentation event, show patterns of accumulative flow in the confined, narrow portion of the Isongo Fan; depletive flow in the unconfined, southwestern portion. Erosional slope channel-levee systems in the northeast demonstrate very large sedimentation events, likely due to eruptive activity and uplift of Mount Cameroon 50 km updip. Partly confined to unconfined distributary channel-lobe systems in the southwest characterize a change in fan geomorphology off the flank of a growing structure.

Core-calibrated petrophysical facies and wireline log thicknesses allow identification of sedimentary bodies in uncored intervals throughout the Isongo Fan, a 2.3 million year episode of sand-rich deposition (3rd order sequence). High frequency 4th and 5th order sequences are used to describe changes in fan morphology over time relative to the growing anticline. A surface of adjustment marks the onset of syn-sedimentary growth, followed by 4th order phases of initial deposition that onlap the structure. Sand-rich fan growth, however, is greatest during a period of minimal uplift, followed by retreat of the Isongo depocenter to the north. Post-Isongo deposits suggest that renewed anticline growth resulted in avulsion of the system to the northwest after 8.2 Ma.
Coarse-grained clastic deposits of the Late Miocene Isongo Formation provide a unique opportunity to investigate the role of syn-sedimentary growth on deepwater transient fan development in a continental slope setting. Located approximately 50 km northwest of Bioko Island in equatorial West Africa, the Isongo Fan was deposited over a 2.3-million year period coincident with uplift of the Cameroon Volcanic Line (CVL) and emplacement of Mount Cameroon 75 km updip. Despite its proximity to the muddy Niger Delta and associated reservoirs (e.g., Zafiro Field, other fields), the Isongo Fan is markedly more sand-rich due to sediment influx from the volcanic line via the Cross River – Principe Channel system (Faminkawa et al., 1996; Shanmugam et al., 1997) (Figure 1.1).

Hydrocarbon exploration and production in the Isongo Formation (i.e., Alba Field) facilitated recovery of more than 1,200 ft. (366 m) of conventional core and drilling of more than 21 wells in the 100 km² study area. When combined with 3-D seismic data, biostratigraphy, chemostratigraphy, dynamic production data and fluid contact information, the Isongo Formation dataset allows correlation of sedimentary deposits at a range of spatial and temporal scales (Figure 1.2). At the smallest scale, sedimentological core descriptions establish fifteen process-based facies, which are ordered according to interpreted hydrodynamic energy conditions at the time of deposition. Building on this foundation, a sixfold process-response sedimentary hierarchy for the Isongo Fan includes:
• Facies – interpreted to record processes operating at the time of deposition (minutes to hours).

• Facies assemblages and sedimentation units – interpreted to record the suite of processes operating within a single sedimentation event (hours to days)

• Facies associations and sedimentary bodies – interpreted to record time-averaged processes that characterize a three-dimensional geometry (e.g., channelform, wedgeform, lobeform, drape, mass transport deposit).

• Fifth order stratigraphic sequences – interpreted to record changes in gradient and confinement that control sedimentary body distribution and stacking patterns (hundreds of thousands of years).

• Fourth order stratigraphic sequences – interpreted to record changes in fan geomorphology in response to longitudinal gradient (<0.5 million years).

• Third order stratigraphic sequences – interpreted to record sand-rich submarine fan deposition over 2.3 million years.

The former three hierarchical orders focus on the sedimentological response to changes in gradient and confinement, which control subaqueous deposition within a submarine fan setting (Gardner et al., 2008). As sedimentary bodies stack and migrate over time, however, large-scale 3rd, 4th and 5th order sequences capture changes in fan morphology and depocenter migration. Biostratigraphy in the Isongo Formation suggests sand-rich sedimentation occurred between 10.5 Ma and 8.2 Ma, a 2.3 million year (3rd order) period in the Late Miocene.
Manuscript Summaries

The following two manuscripts describe the sedimentary response to a growing anticlinal structure on the West African continental slope. The first manuscript, titled “A hierarchical approach to understanding reservoir property distribution (porosity and permeability) in the Isongo Formation, Equatorial West Africa”, focuses on correlating the amount and distribution of pore space in deepwater sedimentary rocks to depositional processes. More than 1,100 core-derived porosity and permeability measurements from the Isongo Fan are shown to record primary depositional processes and used to characterize: (1) fifteen process-based facies; (2) ten facies assemblages and sedimentation units; and (3) nine facies associations and sedimentary bodies.

In general, pore space is correlated to mean grain size, whereas pore connectivity (i.e., permeability) is correlated to sorting, the standard deviation of grain sizes in a deposit. Thus, deposits of turbulent flows demonstrate greater mean porosity values compared to deposits of cohesive debris flows. This is due to a combination of tighter grain packing, poorer sorting and higher clay content in debrites resulting in less pore space available for fluids. Likewise, permeability, as a function of porosity, is greatest in fine-grained sandstones deposited from low density turbulent flows. This suggests that hydraulic fractionation of fine sand particles results in the best deepwater reservoir rocks, characterized by both high porosity and high permeability.

Building upon process-based facies, facies associations are vertical trends in facies recording the longitudinal structure of a flow as it passes over a single point (cf. Kneller, 1995 and Kneller and McCaffrey, 2003). Unlike static facies models, facies
associations and sedimentation units capture dynamic changes in: (1) flow properties (density, viscosity); (2) flow behavior (turbulent, laminar); (3) flow steadiness (waxing, waning); and (4) flow uniformity (accumulative, depletive). The latter two attributes characterize confined (higher gradient) to unconfined (lower gradient) flow and correlate to porosity and permeability trends in sedimentary bodies distributed throughout the Isongo Fan.

Five elementary body types are defined in core and include channelforms, lobeforms, wedgeforms (levees), drapes and mass transport deposits. For example, the confined, narrow northeastern portion of the Isongo Fan is characterized by erosional slope channelforms and overbank wedgeforms. Porosity and permeability values of these features are markedly lower than freely migrating distributary channelforms and lobeforms distributed throughout the unconfined southwestern fan. Thus, time-averaged processes that control the amount and distribution of pore space are also correlated to facies associations and sedimentary bodies.

With regard to distribution of reservoir properties over a three-dimensional space, the threefold hierarchy of facies, facies assemblages and facies associations presented in the first manuscript provides a method to upscale porosity and permeability measurements while preserving core-defined geologic information.

The second manuscript, “Sedimentary response to incipient structural growth and transient fan development in the Late Miocene Isongo Formation, southeastern Niger Delta”, uses the sedimentological hierarchy of the first paper to describe the Isongo Fan morphology across an anticlinal structure. The present-day anticline trends northeast-
southwest and gently plunges to the southwest, coincident with the sand-rich fan axis. This suggests a relationship between increasing gradient due to structural growth and the distribution and stacking pattern of sedimentary bodies during fan construction.

To characterize bodies in uncored intervals, six petrophysical facies are defined, which link sedimentological processes to wireline log signatures. As illustrated in the first manuscript, the following core-calibrated sedimentary responses characterize the Isongo Fan and correlate to deposition from the crest to the flank of the anticline: (1) a higher proportion of coarse-grained deposits in erosional channel forms on the crest; (2) a higher proportion of accumulative (confined) facies assemblages on the crest; (3) a higher proportion of distributary channel forms and lobes on the flank; and (4) a high proportion of depletive (unconfined) facies assemblages on the flank. Moreover, thicker sedimentation units and sand-rich packages that onlap the southwestern flank of the uplift suggest coeval growth and deposition.

Thirteen 5th order and five 4th order stratigraphic sequences characterize sedimentary body stacking patterns and distributions in the 3rd order Isongo Fan, a 2.3 million year episode of sedimentation. These sequences are used to characterize patterns of submarine fan adjustment, initiation, growth and retreat via the AIGR model of Gardner et al. (2003) (see also Gardner et al., 2008). For example, in the Isongo Fan, slope adjustment is characterized by structural uplift and an increase in gradient coincident with the present-day anticline. Fourth order phases of fan initiation are marked by sand deposition in distributary channels and lobes that onlap the flank of the growing feature. Fan growth, however, is characterized by the thickest sandstone packages in the
Isongo Fan and development of incised erosional slope channelform – levee systems updip and distributary channelform – lobeform systems downdip. Backstepping of the channel-lobe transition zone (CLTZ) in the final phases of fan growth marks the beginning of fan retreat, likely during a period of structural quiescence. Fourth order phases of retreat are characterized by backfilling of the main channel system in the northeastern fan and avulsion of the system to the northwest.
5. Sedimentation Regions

Sedimentary architecture defined by process-based facies distributions and sedimentary body stacking patterns. The example shown below is from Gardner et al. (2003), a field-based study in the Permian Brushy Canyon Formation, West Texas.

4. Sedimentary Body Hierarchy

Stacking of sedimentary bodies reflects migration in response to evolving seafloor topography, which generates changes in local gradient.

1. Process-Based Facies

Record hydrodynamic energy and depositional processes operating at the time of deposition.

2. Sedimentation Units and Facies Assemblages

Record flow steadiness and uniformity as well as suites of depositional processes and evolving hydrodynamic energy conditions.

3. Sedimentary Bodies and Facies Associations

Reflect changes in gradient and confinement as well as time-averaged hydrodynamic energy conditions and depositional processes.

7. FACIES

SEDIMENTATION UNIT / FACIES ASSEMBLAGE

SEDIMENTARY BODY / FACIES ASSOCIATION

SEDIMENTARY BODY / FACIES ASSOCIATION

Figure 1.1. Spatial and temporal sedimentary hierarchy for evaluation of reservoir properties. Shaded boxes highlight the threefold hierarchy described in this contribution.
Figure 1.2. Location of the study area in the southeastern Niger Delta, adjacent to the Cameroon Volcanic Line and within the Cross River - Principe Channel drainage system. Major tectonic provinces and depobelts of the delta are modified after Heinio et al. (2007), Hooper et al. (2002) and Armentrout et al. (2000). The transient Isongo Fan (Box 1, inset) is located on the continental slope, approximately 400 km updip of the Calabar basin floor fan. Four major oceanic transform faults bisect the West African margin and are projected onto the African Craton (Meyers et al., 1996).
A HIERARCHICAL APPROACH TO UNDERSTANDING RESERVOIR PROPERTY DISTRIBUTION (POROSITY AND PERMEABILITY) IN THE ISONGO FORMATION, EQUATORIAL WEST AFRICA
Contribution of Authors and Co-Author

Manuscript in Chapter 2
Chapter 2:
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Primary author (Jeannette M. Wolak) compiled all analyses presented in this publication, including: (1) sedimentological core descriptions; (2) statistical analysis of porosity and permeability data; (3) identification of sedimentation units and facies assemblages; (4) identification of sedimentary bodies and facies associations; and (5) grain size and sorting analysis. Jeannette M. Wolak drafted all figures and tables presented and wrote the corresponding text.

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DEPOSITIONAL CONTROLS ON RESERVOIR PROPERTIES (POROSITY AND PERMEABILITY): A SEDIMENTOLOGICAL HIERARCHY, ISONGO FORMATION, EQUATORIAL WEST AFRICA

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ABSTRACT

Primary sedimentary processes operating at the time of deposition correlate to pore space and pore distribution within a resulting rock volume. In most cases, however, post-depositional effects such as compaction, heating and diagenesis overprint primary porosity and permeability. Accounting for these secondary effects allows for investigation of reservoir properties at a range of spatial and temporal scales.

More than 1,200 ft (366 m) of conventional core, 1101 core-derived porosity and permeability measurements, 21 wireline logs and 3D seismic from the Late Miocene Isongo Formation in West Africa are used to characterize a threefold sedimentological hierarchy, which provides a framework for correlating geologic processes to porosity and permeability. At the smallest scale, process-based facies analysis demonstrates that mean grain size is inversely correlated to porosity and sorting is positively correlated to permeability. Moreover, turbidity current deposits show a strong negative correlation between sediment concentration and porosity; in other words, hyper-concentrated SDF deposits have consistently lower porosity values than high-concentration or low-concentration SDF deposits. Cohesive debris flow deposits demonstrate the widest range of porosity and permeability values, likely due to increased clay content, highly variable grain packing and very poor sorting.

In addition to facies analysis, identification of sedimentation units and facies assemblages in Isongo Formation cores reflect depositional processes operating during a single event and provide context for vertical variations in porosity and permeability. Sedimentation unit thickness is a key indicator of subaqueous flow size (volume); thus, very thick sedimentation units in the Isongo Formation (>10.0 ft, > 3.0 m) suggest large-scale, event-driven sedimentation, possibly linked to volcanism and uplift along the adjacent Cameroon Volcanic Line. Ten common facies assemblages highlight suites of depositional processes and record flow steadiness (waxing, waning) and uniformity (accelerative, depletive).

Sedimentary bodies and facies associations record time-averaged processes (multiple events), and reflect changes in gradient, confinement and dispersion due to local topography. The sedimentological hierarchy presented in this study (i.e., process facies, sedimentation units and facies assemblages, sedimentary bodies and facies associations) is correlated to the amount and distribution of pore space at three temporal and spatial scales. This geologic process-based method of upscaling provides a robust set of sedimentary attributes for stratigraphic analysis and reservoir characterization.
1. INTRODUCTION

All sedimentary deposits are characterized by pore space and connectivity, which correlate to the material properties of the rock volume. For more than a century, a concentrated effort has been focused on the physical description and interpretation of two parameters that describe the nonmaterial rock volume: porosity and permeability (Darcy, 1856; Beard and Weyl, 1973; Mitra and Beard, 1980; Houseknecht, 1984; Scherer, 1987; Shepard, 1989.) Porosity, a measure of volume (%) of pore space within a rock, is generated during primary deposition and has been correlated to grain size, sorting, clay content, grain roundness and grain packing. Likewise, permeability, a measure of pore connectivity (md), is a function of porosity (i.e., the Carman-Kozeny equation) and records sorting, clay content and grain packing that may clog pore throats (Scheidegger, 1974; Costa, 2006).

Although porosity and permeability are generated during primary sedimentary deposition, they are almost always overprinted by the effects of compaction, temperature increase and diagenesis (Bloch, 1991; Ehrenberg, 1993; Ehrenberg et al., 2009). Thus, any attempt to correlate porosity and permeability to sedimentary processes must account for secondary effects on porosity and permeability. This contribution presents a unique subsurface dataset in which depth, temperature, fluid saturation and post-depositional diagenetic effects can be quantified such that reservoir properties correlate to fundamental geologic processes, i.e. hydrodynamic energy conditions operating at the time of deposition of discrete turbidity current events.
Process-based facies identified in cores from the Late Miocene Isongo Formation, located in equatorial West Africa, demonstrate statistical distributions for porosity and permeability that correlate to mean grain size, sorting and clay content. This suggests that flow properties (density and viscosity) and flow behavior (laminar vs. turbulent) control the development of pore space and connectivity in sediment deposited from turbidity currents. Moreover, these process-based correlations may be used to characterize subaqueous sedimentation events (i.e., sedimentation units and facies assemblages) and sedimentary bodies (i.e., facies associations), which comprise a threefold sedimentary hierarchy.

The objectives of this contribution are fourfold. First, post-depositional effects on porosity and permeability are summarized and accounted for, which allows correlation between primary geologic processes and reservoir properties. Second, detailed sedimentological description of conventional cores defines: (1) fifteen process-based facies, ordered according to interpreted hydrodynamic energy conditions for pebble conglomerate to clay-rich mudstone; and (2) porosity and permeability distributions for each facies. These distributions show that, in general, porosity is correlated to mean grain size, and permeability is correlated to sorting. The third objective is identification of sedimentation units and facies assemblages to capture vertical changes in porosity and permeability. Ten facies assemblages record sedimentation from unsteady and nonuniform turbidity currents, cf. Allen (1985) and Kneller (1995). Finally, five sedimentary bodies and nine facies associations are defined, which record time-averaged depositional processes operating to create a three-dimensional geometry. This approach
emphasizes the importance of geologic process-based interpretations at all scales to better understand the primary development and distribution of pore space over time.

1.1 Sedimentary Hierarchy

A three-fold sedimentary hierarchy for the Late Miocene Isongo Formation is presented (Figure 2.1) and captures scalar and temporal differences between: (1) hydrodynamic energy and depositional processes operating at the time of sedimentation; (2) sedimentation events which record deposition over minutes, hours and days; and (3) time-averaged depositional processes and hydrodynamic energy that vary according to changes in topographic gradient and confinement (i.e., dispersion). Shaded boxes in Figure 2.1 illustrate this hierarchy, as well as sedimentary body stacking patterns that change in response to evolving seafloor topography. Hierarchical orders, from small-scale to large-scale, are summarized below.

1.1.1 Process-based facies

Core-defined process-based facies relate textural attributes (e.g., grain size, sorting, clay content), lithology and sedimentary structures to hydrodynamic energy and flow conditions at the time of deposition (Box 1 in Figure 2.1). Density and viscosity control the behavior of turbidity currents; both may dominate different regions within the same turbidity current event (Kuenen and Migliorini, 1950; Bouma, 1962; Sanders, 1965;
Middleton, 1967; Hampton, 1972; Mutti and Ricci Lucchi, 1972; Lowe, 1982; Hiscott, 1994a; Major and Iverson, 1999). This has led to classification that distinguishes between flows in which: (1) sediment is supported primarily by fluid turbulence (Middleton and Hampton, 1976); and (2) sediment is supported by a mixture of interstitial fluid and fine particles (i.e., characterized by yield strength) (Middleton and Hampton (1976). However, as noted by Mutti et al. (2010), Kuenan specifically omitted an implied (and very controversial) sediment support mechanism in defining turbidity currents as ‘a current flowing in consequence of the load of sediment it is carrying and which gives it excess density’ (Kuenan in Sanders, 1965, p. 217). In this usage, “turbidity currents” emphasize the transient nature of depositional processes at a given point in space and makes no assumptions regarding sediment support mechanisms or flow size (vertical height).

High-density, low-density and cohesive debris flow facies models are emphasized in the literature (Fisher, 1971; Middleton, 1967; Middleton and Hampton, 1973; Haughton et al., 2003; Haughton et al., 2009; review in Mutti et al., 2009). For example, Mulder and Alexander (2001) provide a concise overview of turbidity currents with different sediment concentrations. In these facies models, high-density currents are characterized by sediment concentrations of > 20% by volume and may be further categorized as hyperconcentrated (containing > 40% sediment by volume) or high-concentration (containing 20 – 40% sediment by volume). Low density currents are characterized by sediment concentrations of < 20% by volume (Bouma, 1962; Lowe, 1982; Mulder and Alexander, 2001), and cohesive debris flow deposits demonstrate
sufficient cohesive material (mud) to suppress turbulent behavior and create yield strength.

Alternatively, multipartite subaqueous density flows are characterized by changing flow behavior (laminar, turbulent) and flow properties (density, viscosity) within a single sedimentation event. Flow transformations (cf. Fisher, 1983) result in facies that reflect a continuum of depositional processes not captured in traditional facies models.

1.1.2 Sedimentation units and facies assemblages

While process-based facies record a ‘snapshot’ of the flow at deposition, identification of vertical facies assemblages and sedimentation units is required to capture the longitudinal structure of a flow passing across the depositional site (Figure 2.1). Temporally, sedimentation units and facies assemblages record changes in a flow passing over a site for minutes, hours or days. Identification of sedimentation units in core emphasizes transitions between facies and measure nonuniform and unsteady changes in turbidity currents. As discussed by Kneller (1995) and Kneller and McCaffrey (2003), vertical facies assemblages and grain size grading correlate to longitudinal flow structure, which in turn provides a method for prediction of the event magnitude from vertical profiles.
1.1.3 Sedimentary bodies and facies associations

Sedimentary bodies, or architectural elements in the nomenclature of Miall (1996), are lithosomes that record time-averaged depositional processes (i.e., facies associations) creating seascapes and geomorphology (Figure 2.1). Sedimentary body geometry is fundamentally controlled by gradient and confinement. Five elementary sedimentary bodies are classically defined in the literature: channeliforms, lobeforms, wedgeforms, drapes (mudstone) and mass transport deposits (Gardner and Borer, 2000; Garder et al., 2003). In addition, elementary body stacking patterns generate variations related to: (1) confinement and preservation; (2) on-axis and off-axis sedimentation; and (3) hemipelagic (lateral and vertical components of transport) and pelagic (primarily vertical components of transport) mudstone drapes.

1.1.4 Sedimentary body hierarchies and sedimentation regions

This sedimentological hierarchy frames different scalar and temporal processes (small-scale) responsible for sedimentary architecture (large-scale). The two higher orders shown in Figure 2.1 (boxes 4 and 5) are analogs from the well-studied Permian Brushy Canyon Formation of West Texas (Gardner and Borer, 2000; Gardner et al., 2003; Gardner et al., 2008). In this example, elementary sedimentary body arrangements form composite and complex-scale features, which reflect changes in local gradient and dispersion (box 4 in Figure 2.1). Likewise, sedimentation regions defined by facies and
sedimentary bodies represent spatial domains analogous to geomorphic terrains (box 5 in Figure 2.1).

To characterize a sedimentary body hierarchy or sedimentation regions using a subsurface dataset, core-to-wireline log calibration is required, as well as integration of 2D/3D seismic volumes, biostratigraphy, chemostratigraphy and all other available datasets. In a companion paper, Wolak et al. (in prep) utilize the information to document stratigraphic evolution of the Isongo Formation.

2. GEOLOGIC SETTING

Deepwater clastic deposits of the Late Miocene Isongo Formation at Alba Field form a conglomeratic sand-rich reservoir located 50 km northwest of Bioko Island in Equatorial Guinea (Figure 2.2) (Rowell and Carballo, 2004; Wolak and Gardner, 2009). Gas and lesser oil in the Alba Field are sourced from the Late Cretaceous Akata Formation, a 2,000 – 7,000 m-thick shale unit that underlies much of the Niger Delta and sits atop oceanic basement and transitional crust (Burke, 1972; Doust and Omatsola, 1990; Meyers et al., 1996; Corredor et al., 2005). As shown in Figure 2.2, key tectonic controls on Miocene sedimentation in the Alba Field include: (1) uplift of the Cameroon Volcanic Line (CVL) to the north and east; and (2) emplacement of Mount Cameroon along the West African coast, approximately 75 km updip. Siderite conglomerates, the coarsest sediment recovered in the study area are likely derived from the CO2-rich CVL and sourced from the Cross River drainage system. Local structural deformation is
controlled by migration of the Niger Delta deformation front eastward across the study area and oceanic transform faults segmenting the West African margin (Wolak and Gardner, 2009).

The Isongo Formation at Alba Field forms a 30 km-long fan-shaped seismic amplitude that thickens and widens (> 20 km) to the southwest and thins and pinches out to the east (Figure 2.2). The narrow northeastern portion of the Isongo Fan is located on an anticlinal fold that plunges to the southwest. Expansion of sedimentation forming the fan morphology is correlated to transient slope fan development during Late Miocene outbuilding of the southeastern Niger Delta.

3. DATASET AND METHODS

Conventional cores recovered from five wells in the Alba Field characterize sedimentary processes over an entire suite of grain sizes ranging from pebble conglomerates to clay-rich mudstones. Detailed sedimentological descriptions of 1,200 ft (366 m) of slabbed core at a scale of 1:24 resulted in recognition of fourteen deepwater clastic process-based facies. The location of each core and 15 additional wells at Alba Field are shown in Figure 2.2. Cored wells are labeled A – E, and distribution includes: 211 ft (64 m) from Core A, 500 ft (366 m) from Core B, 91 ft (28 m) from Core C, 130 ft (40 m) from Core D, and 267 ft (81 m) from Core E. Wireline log data from a total of 23 wells (including cored wells), low resolution 3-D seismic (maximum frequency of 40 –
60 Hz), chemostratigraphic analysis of sandstones and mudstones constrain stratigraphic correlation.

3.1 Secondary effects on porosity and permeability

Core plug measurements of porosity ($n = 599$) and permeability ($n = 506$) show four orders of magnitude variation in values that do not appear to correlate to depth and/or individual well conditions (Figure 2.3). Porosity values range from 1.9 – 23.5% for all cored wells; permeability values from 0 – 507 md. One possible exception may be Core B, which demonstrates slightly lower permeability values with increasing depth. Given that the shift in permeability values for Core B is less than half and order of magnitude, the variation shown is considered negligible for this dataset.

To identify primary depositional controls on porosity and permeability in the Isongo Formation, the following secondary effects must be addressed:

- Geologic age
- Compaction
- Maximum burial depth
- Hydrocarbon saturation (pore fluids)
- Diagenesis
- Temperature

Geologic age and plate tectonic setting are known to affect reservoir properties in rock sequences spanning millions of years (Bloch et al., 2002; Ehrenberg et al., 2009) and over broad regional scales (Ehrenberg and Nadeau, 2005). In the Isongo Formation,
biostratigraphic data constrains deposition to 8.2 – 10.4 Ma, approximately a two-million year period during the Late Miocene. Given this relatively short depositional time frame, it is unlikely that porosity and permeability variations in the Isongo Formation reflect geologic age. Similarly, the limited spatial extent of the study area (~ 100 km²) is wholly contained within a single ocean sub-basin (i.e., the Gulf of Guinea on the West African passive margin). Thus, effects on porosity and permeability due to geologic age and tectonic setting likely do not vary across the study area.

Likewise, hydrocarbon saturation and fluid type may impact core-derived measurements of porosity and permeability (Figure 2.3). However, cores A, C, D, and E from the gas-saturated interval of the Isongo Formation do not appear to show significant offset of porosity and permeability values compared to measurements from Core B from within the oil- and water-saturated intervals. For the purposes of this study and to minimize any effects due to fluid differences, porosity and permeability measurements from the oil- and water-saturated intervals were excluded (shaded data points in Figure 2.3).

Diagenesis is a common secondary control on reservoir properties. Sedimentological descriptions of more than 218 thin sections from cored intervals document trace to minor amounts of the following authigenic minerals: (1) poorly-developed quartz and albite overgrowths; (2) calcite and dolomite cements; (3) siderite (< 3%); (4) pyrite; and (5) analcime. Most samples lack large volumes of mineral precipitates (cements). In general, sandstones may contain intergranular (primary), minor
intergranular (secondary) and microporosity; the latter likely formed during partial
dissolution of feldspars, volcanic rock fragments or detrital matrix clay.

The effects of burial depth, compaction, pore fluid type and diagenesis represent
the most important secondary controls on reservoir properties. They do not, however,
correlate to variations in porosity and permeability values in the Isongo Formation. These
data instead suggest that primary depositional controls such as grain size, sorting, clay
content, grain packing, etc. best explain rock property distributions. Therefore, this study
focuses on the critical correlation between: (1) grain size and porosity; and (2) sorting
and permeability. These fundamental textural attributes reflect sedimentological
processes.

4. SEDIMENTOLOGY OF THE ISONGO FORMATION

4.1 Facies Scheme

The deepwater clastic reservoir at Alba Field contains a broad grain size
distribution, ranging from pebble conglomerate to clay-rich mudstone. Table 2.1
summarizes the fifteen process-based facies correlated to hydrodynamic energy
conditions at the time of deposition. This scheme is based on lithology, grain size,
sorting, clay content and primary and secondary sedimentary structures. Facies 1, a sandy
matrix-supported, stratified pebble conglomerate, records the highest energy conditions,
whereas Facies 15, a clay-rich mudstone, the lowest. With the exception of Facies 7 and
8, structureless sandstones and soft-sediment deformed sandstone, all facies reflect one interpreted primary depositional process.

Sedimentological process interpretations presented in Table 2.1 characterize deposition from multipartite subaqueous SDFs (Figure 2.4). Unlike classification schemes that emphasize a singular behavior within a flow (e.g., Bouma, 1962; Lowe, 1982; Haughton, 2009), this approach recognizes that a single SDF may be comprised of zones of both turbulent and laminar flow controlled by sediment concentration, density and viscosity (Figure 2.4). Thus, process-based facies record flow behavior at the time of deposition; vertical facies assemblages, the longitudinal structure of the flow (Kneller and McCaffrey, 2003).

4.1.1 Porosity distributions by process-based facies

Porosity and permeability frequency distributions correlate to facies, illustrated in Table 2.1. General statistical information including number of measurements \((n)\), mean, variance and standard deviation for each distribution are summarized in Table 2.2. Core-derived porosity measurements from most sandstone facies are statistically significant \((n > 30)\), whereas conglomerate and mud-rich facies are undersampled \((n < 30)\). Despite this sampling bias, weak statistical trends are evident in fourteen of the fifteen facies. Clay-rich mudstones, however, are strongly undersampled \((n < 5)\) and omitted from this analysis.
Porosity values for individual facies show a clear tendency to cluster about the mean and define well-developed to poorly-developed Gaussian (normal) distributions, which suggest a strong correlation between depositional process and porosity. In general, higher $n$-values show low standard deviations (< 2.50%), and very low skewness values correspond to well-defined normal distributions, such as those shown in Facies 5 ($n = 94$, planar space stratified sandstone, upper flow regime).

Facies interpreted to reflect the highest depositional energy conditions, Facies 1 and 2 (matrix-supported pebble conglomerates), are characterized by mean porosities of 12.3% and 11.4%, respectively, and demonstrate very low negative skewness. Despite a sand-rich matrix, low mean porosity values in these facies correlate to very poor sorting, tight grain packing and high clay content. In both facies, pebbles are > 20% and comprised of siderite, feldspars, quartz and lithic fragments. Although undersampled, stratification in Facies 1 is correlated to a higher mean porosity than inverse- to normal-grading in Facies 2. This suggests that traction deposition may control the development of pore space, a correlation seen in finer grain size fractions as well.

In contrast to sand-rich deposits, Facies 3 is a mudclast conglomerate characterized by a muddy sandstone matrix and mm- to cm-scale intraclasts, derived from within the submarine channel system. Porosity values for Facies 3 show a much broader range, from 3.6% to 19.5%, than values for extraclast conglomerates of Facies 1 and 2 (Table 2.1). Likewise, standard deviation for Facies 3 is 4.2%, nearly twice as wide (Table 2.2). In part, this variation may reflect undersampling ($n = 14$); however, it may also correlate to a fundamental change from turbulent to cohesive flow behavior. Very
poor sorting and very high clay content are characteristic of Facies 3, which control the amount of poor space filled with mud during subaqueous deposition.

Porosity values of pebble to granule sandstones (Facies 4) characterize a well-defined bimodal distribution with peaks at approximately 10.0% and 13.5%, which suggests a secondary control on porosity in addition to depositional process (Table 2.1). Mean porosity is 12.0%, similar to values for coarser-grained Facies 1 and 2, and higher than the mean value for mud-rich Facies 3. Thus, deposits interpreted to reflect turbulent processes (i.e., Facies 1, 2 and 4) correlate to higher mean porosities than deposits of cohesive debris flows (Facies 3).

Facies 5 and 6, planar space stratified sandstones (upper flow regime) and angle of repose stratified sandstones, demonstrate mean porosity values of 15.1% and 14.6%, low standard deviations and low negative skewness (Table 2.2). An increase in mean porosity between these facies and Facies 1 – 4 correlates to better sorting, less mud and looser grain packing. Additionally, traction carpet deposition in Facies 5 correlates to a higher mean porosity than mixed traction and suspension deposition in Facies 6, a similar relationship to that seen between Facies 1 and 2.

Similarly, structureless sandstones (Facies 7) are characterized by a mean porosity value of 14.3% and a very well-defined normal distribution ($n = 157$). Multiple origins for structureless sandstone deposition include: (1) ‘collapse’ of a high density SDF triggered by a decrease in flow velocity (Middleton, 1970; Arnott and Hand, 1989; Lowe, 1982); (2) gradual aggradation from a quasi-steady SDF (Kneller and Branney, 1995); (3) uniformity of grain size obscuring structures; (4) penecontemporaneous dewatering and
liquefaction processes that occur under high sedimentation rates; and/or (5) extensive post-depositional bioturbation resulting in destruction of original sedimentary structures (Pemberton and MacEachern, 2006). In the latter two cases, cryptic remnants of grading, stratification or other primary or secondary structures were used to discriminate Facies 7 from Facies 8, soft-sediment deformed sandstones. Despite multiple origins for the generation of structureless sandstone, porosity values are similar to those from Facies 5 and 6, also interpreted to reflect deposition from a high density turbulent current.

Sandstones characterized by liquefaction and/or fluidization (e.g. dish/pipe structures, consolidation lamination) show porosity distributions \((n = 159)\) that closely mirror deposits of high density SDF processes (Facies 5, 6 and 7). Included in the S\(_3\) division of Lowe (1982), these facies record syn- to post-depositional soft-sediment deformation due to pore fluid movement during consolidation and rapid sedimentation (Lowe, 1975; Nichols, 1995). Given the similar porosity values for Facies 5, 6, 7 and 8, it is clear that turbulent flow behavior in fine- to coarse-grained sandstones correlates to pore space developed during deposition. Moreover, this suggests that textural attributes (grain size, sorting), which are the sedimentary responses to depositional processes, will also correlate to porosity (see Section 4.2).

A significant increase in mean porosity (18.0%) characterizes Facies 9, planar laminated sandstone (lower stage) deposited from a turbulent, low density subaqueous flow (Table 2.1 and Figure 2.4). Compared to coarser deposits, Facies 9 demonstrates much better sorting, looser grain packing and lower clay content. This is correlated to
hydraulic sorting of the fine fraction creating a more uniform grain size distribution and a
greater volume of pore space in the resultant sedimentary deposit.

Likewise, Facies 10 and 11, while undersampled (n = 8, n = 4), show similar high
mean porosity values of 17.1% and 16.5%, respectively. These facies are interpreted to
record turbulent processes, equivalent to the $T_c$ and $T_d$ divisions of Bouma (1962).

Traction deposition recorded in Facies 10, ripple cross-laminated sandstone, is correlated
to a higher mean porosity compared to Facies 11, which is dominated by suspension
deposition. As noted in comparisons between pebble conglomerate facies (Facies 1 and
2) and stratified sandstone facies (Facies 5 and 6), traction deposition correlates to higher
mean porosity values within each grain size fraction.

A significant decrease in mean porosity values to 12.4% is evident in Facies 12,
muddy sandstone deposits that record cohesive debris flows. Similar to Facies 3,
mudclast conglomerates, Facies 12 demonstrates a wide range of porosity values, weak
distribution and high standard deviation of 3.1%. This is due to an increase in clay
content, tighter packing and very poor sorting associated with debrite deposition. It is
clear that flow behavior, i.e. turbulent vs. laminar, strongly impacts pore space
development.

Silt-dominated and silt-bearing mudstones, Facies 13 and 14, are interpreted to
reflect low energy hemipelagic deposition, which is comprised of mixed traction and
suspension processes such as those described by Schieber et al. (2007). Classification of
mudstones is based on descriptive nomenclature of MacQuaker and Adams (2003), and
Facies 13 and 14 are equivalent to the $T_c$ division of Bouma (1962). Porosity distributions
for Facies 13 and 14 are very poorly developed, due in part to undersampling ($n = 18$, $n = 11$), and standard deviations are greater than observed in other facies (5.0% and 4.6%). This is correlative to very poor sorting and highly variable clay content, which may clog pore space.

Finally, the lowest energy facies is Facies 15, clay-rich mudstone, interpreted to reflect deposition from pelagic settling during periods of seafloor quiescence. Unfortunately, this facies lacks sufficient data ($n < 5$) to draw conclusions regarding porosity trends and pelagic processes; however, it is generally accepted that clay-rich deposits have low porosities and permeabilities due to the combined effects of high clay content, very poor sorting and tight grain packing.

In summary, first order controls on porosity in process-based facies are: (1) grain size population; (2) flow behavior (laminar vs. turbulent); and (3) dominant depositional process (suspension vs. traction). In other words, coarse-grained deposits of turbidity currents show lower porosity values than fine-grained deposits, which have been hydraulically fractionated. Cohesive debris flow deposits demonstrate lower porosities than turbulent SDF deposits; within the latter, deposits recording traction deposition have more pore space than deposits recording suspension settling.

### 4.1.2 Permeability distributions by process-based facies and facies groups

Permeability distributions for process-based facies are shown in the right-hand column of Table 2.1, and corresponding frequency distributions are provided in Table
2.2. Like porosity, permeability is correlated to facies ordered by hydrodynamic energy, which suggests the affect of depositional process is preserved and not overprinted by secondary controls. The following trends are evident in permeability distributions:

- Facies 1 and 2, interpreted to be the highest energy deposits, are characterized by low mean permeability values (9 md, 7 md). This correlates to poor sorting, tight grain packing and high clay content, which in turn record deposition from a high density turbulent flow.

- Facies 3, a mudclast conglomerate with muddy sandstone matrix, demonstrates a much broader range of permeability values (0 – 198 md) and a high standard deviation (60 md). While undersampled (n = 4), this trend may reflect variable sorting and clay content due to non-turbulent debris flow processes.

- Pebble to granule sandstones, Facies 4, demonstrate a slightly higher mean permeability (37 md) than Facies 1, 2 or 3. Likewise, medium-grained sandstones characterized by spaced stratification (Facies 5) and angle of repose stratification (Facies 6) show greater mean permeability values of 73 md and 79 md, respectively. This suggests a correlation between decreasing grain size and increasing permeability due to better sorting and looser grain packing.
• Structureless and soft-sediment deformed sandstones (Facies 7 and 8) are characterized by very similar permeability distributions and mean permeabilities of 65 md and 66 md. High standard deviations (67 md, 90 md) and broad ranges (388 md, 507 md) correlate to variable grain packing and clay content. In Facies 8, this is due to vertical water escape during liquefaction.

• Facies 9, plane parallel laminated sandstone, interpreted to be deposited under lower flow regime conditions in a low density SDF, is characterized by a high mean permeability value of 95 md. As noted in porosity distributions, this likely reflects hydraulic fractionation of fine-grained sediment during turbulent flow, which results in better sorting, less clay and looser grain packing.

• Ripple cross-laminated sandstones (Facies 10) and wavy laminated sandstones (Facies 11) are undersampled \((n = 7, n = 4)\), but demonstrate preliminary mean permeability values (63 md, 51 md) that suggest decreasing pore connectivity with increasing mud content.

• Muddy sandstones of Facies 12 are also undersampled \((n = 4)\) and show a lower mean permeability value of 18 md. The permeability distributions of Facies 10, 11 and 12 emphasize the importance of sorting on permeability,
and cohesive deposits of Facies 12, while undersampled, demonstrate low permeability values that may correlate to non-turbulent debris flow processes.

- Likewise, low energy silt-bearing and silt-dominated mudstones of Facies 13 and 14 also show lower mean permeability values (16 md, 6 md), which suggest that higher clay content and poor sorting block pore throats and decrease pore connectivity.

Permeability frequency distributions display similar trends to porosity distributions, including: (1) a negative correlation between grain size and permeability; and (2) a positive correlation between sorting and permeability. In addition, traction-dominated deposits tend to show higher permeability values compared to suspension-dominated deposits within the same grain size fraction. These similarities are likely a reflection of pore connectivity (i.e., permeability) as a function of pore space (i.e., porosity), which is linked to textural attributes such as grain size and sorting.

4.2 Grain size populations

Sedimentary textural attributes that may correlate to hydrodynamic energy and depositional process include: (1) grain size population and sorting (this study); (2) grain shape, which encompasses the form and roundness of grains; and (3) grain fabric, which includes grain packing and orientation. Of these attributes, mean grain size and sorting
are two first-order controls on porosity and permeability. In general grain size is correlated to porosity, which records flow competence (Middleton, 1976; Komar, 1985; Hiscott, 1994b). Likewise, sorting, a statistical measure of variance within grain size populations correlates to permeability.

4.2.1 Grain size and porosity

Grain size is a direct reflection of hydrodynamic energy and competence. Mean grain size was estimated using a visual grain size comparator. The coarsest deposits are sand matrix-supported pebble conglomerates with average clast sizes of 6 – 8 mm (Table 2.1); the finest deposits are silt-bearing and clay-rich mudstones, classified according to MacQuaker and Adams (2003). The variation in mean grain sizes represents a broad range of hydrodynamic energy conditions, from highest energy (Facies 1, mean grain size of pebble conglomerate) to lowest energy (Facies 15, mean grain size of clay).

When plotted by grain size, core-derived porosity measurements \( n = 587 \) show an inverse correlation between mean grain size and porosity (Figure 2.5). In general, the range of porosity values also appears to increase with decreasing grain size, and grain sizes smaller than coarse sand (< 1.0 mm) appear to be characterized by a much broader range of values. For example, porosity values for conglomerates and pebble to granule sandstones (Facies 1, 2 and 4) range from 5.9 – 17.0%, while finer-grained deposits range from 1.9 – 23.5% (Figure 2.5 and Table 2.2). Facies 7 (structureless sandstone) and Facies 8 (soft-sediment deformed sandstone) show the broadest ranges in porosity and
permeability values, 17.7% and 20.8%, respectively (Table 2.2). This may be due, in part, to a greater number of samples for these facies (n = 157, n = 159), and may also be a reflection of multiple depositional interpretations.

To investigate the relationship between porosity and depositional process, a subset of process-based facies is presented in Figure 2.6A. Facies interpreted to reflect deposition from turbulent SDFs are shown (see also Table 2.1); these include Facies 1, 2, 4, 5, 6, 9, 10 and 11. When compared to Figure 2.5, Figure 2.6A demonstrates a much stronger correlation between grain size and porosity, with smaller sand grain sizes corresponding to higher porosity values (correlation coefficient = 0.55). This suggests that sand grain size and porosity may be correlated in deposits that result from both high density and low density turbulent flows.

In contrast, deposits interpreted to reflect low energy hydrodynamic conditions (Facies 13 and 14) and cohesive debrites (Facies 3 and 12) do not show a strong correlation between mean grain size and porosity (correlation coefficient = 0.08) (Figure 2.6B). The clear differences in correlation between Figure 2.6A and 2.6B suggest that:

1. clay content and poor sorting affect the correlation of grain size to cohesive debrites and mudstones; and
2. flow properties (density, viscosity) are a first order control on pore space within a sedimentary rock.
4.2.2 Sorting and permeability

Grain size sorting is generally poorest in matrix-supported pebble conglomerates (Facies 1 and 2), mudclast conglomerates (Facies 3) and muddy sandstones (Facies 12). This is due to an increase in the amount of mud as matrix or clasts within these deposits and the presence of pebble to granule outsized clasts.

Within deposits of turbulent flows, sorting shows an inverse correlation to permeability. For example, porosity and permeability values for Facies 1 and 2, very poorly sorted pebbly conglomerates, are plotted alongside Facies 5, moderately sorted spaced stratified sandstones (upper flow regime) in Figure 2.7A. An increase in permeability with increasing sorting among these two facies is observed, which likely reflects lower clay content in the stratified sandstone population.

While undersampled, cohesive debrite facies (Facies 3 and 12) do not demonstrate a clear correlation between sorting and permeability (Figure 2.7B). This suggests that clay content plays a very important role in increasing the range of permeability values within interpreted non-turbulent deposits. Similar observations in debrite porosity distributions suggest that increasing clay content suppresses correlation of both: (1) mean grain size to porosity; and (2) sorting to permeability.
5. SEDIMENTATION UNITS AND FACIES ASSEMBLAGES

Sedimentation units, as defined here, record individual event-driven subaqueous SDFs, which are often characterized by more than one facies, a facies assemblage. This nomenclature emphasizes the importance of multiple depositional processes (i.e., multipartite) operating within a turbidity current, and the identification of facies assemblages and sedimentation units in the Isongo Formation builds upon the foundation of process-based facies classification to capture vertical geologic heterogeneity (Figure 2.8). With regard to reservoir properties, sedimentation units and facies assemblages provide a framework to investigate vertical variations in porosity and permeability, which reflect the evolution of the connected pore volume during deposition.

5.1 Sedimentation units

Sedimentation unit thickness is considered a direct proxy for flow size (volume) and duration. More than 340 sedimentation units are defined in the Isongo Formation cores. Recognition criteria for defining a discrete event include: (1) sharp basal bed contacts, possibly indicative of erosion; (2) abrupt grain size or lithology changes; (3) abrupt changes in sedimentary structures, even where contacts may be cryptic; (4) conspicuous termination of soft-sediment deformation; and (5) bioturbation at the bed top. Sedimentation unit thicknesses, shown in Figures 2.8 and 2.9, range from very thin (cm-scale) to very thick (> 18.0 ft, > 5.5 m).
Very thick sedimentation units in the Isongo Formation cores (>10.0 ft., >3.0 m) suggest large-scale, event-driven sedimentation, likely due to regional volcanism and tectonism. For example, Figure 2.8 illustrates a very thick sedimentation unit from Core B, 18.6 ft thick (5.7 m), characterized by little significant variation in grain size over approximately 14.0 ft (4.3 m). This suggests deposition from a subaqueous SDF sustained at relatively constant discharge over a significant period of time (hours to days), consistent with event-driven sedimentation following a large volcanic eruption and remobilization of unconsolidated sediment on the shelf (Kneller, 1995). Given the proximity of the study area to the Cameroon Volcanic Line (CVL), the timing of volcanism and uplift of Mt. Cameroon during the Late Miocene, and the location of the Cross River – Principe Canyon drainage, it is likely that large sedimentation events recorded in the Isongo Formation cores correlate to volcanic eruptions in the CVL. Further evidence of this correlation in sedimentation units includes: (1) large (cm-scale) siderite clasts in matrix-supported pebble conglomerates (Facies 1), derived from the CO2-rich CVL; (2) ash beds interbedded with clay-rich mudstones; and (3) unaltered, large grains (>3 mm) of biotite and sanidine within ash beds, suggesting little transport and modification.

5.2 Facies assemblages

Within sedimentation units, ten types of facies assemblages are identified and characterize unsteady and nonuniform flow conditions in the Isongo Fan (Figure 2.9).
Flow steadiness describes the change in velocity over time at a fixed point of deposition (du/dt), where t is time and u is the mean downstream velocity at a given point (Allen, 1985; Kneller, 1995). Waxing flow refers to flow with a positive du/dt; waning flow, a negative du/dt. Alternatively, flow uniformity captures the change in velocity over a given distance (du/dx), which may be accumulative (+du/dx) or depletive (-du/dx). Thus, spatial and temporal changes in flow velocity can be described using a simple matrix of steadiness and uniformity, shown in Figure 2.9.

Five conditions within the matrix are likely to produce deposition, while the remaining four are characterized by nondeposition or erosion (Kneller, 1995). Moreover, confined to unconfined submarine geomorphology controls the updip-to-downdip expression of facies within the acceleration matrix. In Figure 2.9, facies assemblages labeled ‘confined’ are described from cores C, D, and E recovered from the narrow channelized northwestern Isongo Fan (Figure 2.2). Facies assemblages labeled ‘unconfined’ are described from cores A and B, located in the sand-rich distributary channel-lobe complexes of the southeastern fan (Wolak et al., in prep). Thus, for each facies assemblages, is it possible to characterize flow steadiness and uniformity using: (1) the presence or absence of facies; (2) the vertical order of facies; (3) the thickness of individual facies; (4) grain size trends; (5) basal contacts; and (6) internal contacts between facies within an assemblage.
5.2.1 Depletive waning flow

**Description:** Facies assemblages characterizing depletive waning flow demonstrate: (1) a vertical facies succession from highest energy facies at the base to lowest energy facies at the top; (2) presence of all facies within the assemblage; (3) a fining-upward grain size trend; (4) sharp basal contacts; and (5) gradational internal contacts. As illustrated in the lower left field of Figure 2.9, these patterns are consistent for both confined and unconfined flow conditions; however, the updip (confined) facies assemblage may be characterized by coarser deposits.

**Interpretation:** Nearly all classical descriptions of deepwater facies assemblages assume depletive waning flow conditions, i.e., Bouma, 1962; Lowe, 1982; Haughton, 2003, 2009. The presence of all facies within a single vertical succession, while rarely observed, suggests progressive deposition of the coarsest fraction of a flow followed by finer components.

5.2.2 Uniform waning flow

**Description:** Within the Isongo Formation cores, uniform waning flow is suggested by: (1) absence of either the lower or upper facies within the facies assemblage; (2) absence of significant grading; (3) uniform thickness of facies within the assemblage; (4) sharp basal contacts; and (5) sharp internal contacts.
Interpretation: Of the various flow conditions, flow uniformity is the most difficult to ascertain from a single facies assemblage, as it assumes constant deposition over a given distance. Therefore, the criteria listed above emphasize similarities in facies thickness and grain size trends, indicative of uniform waning flow. The absence of lower facies in confined updip settings suggests bypass of coarse sediment fractions downslope, while the absence of upper facies may indicate either sediment bypass or subsequent erosion.

5.2.3 Waning accumulative flow

Description: Common characteristics of deposits produced by waning accumulative flow include: (1) absence of one of more facies from within the facies assemblage; (2) abrupt grain size changes; (3) highly variable thickness of facies within the assemblage; (4) sharp basal contacts; and (5) sharp internal contacts.

Interpretation: While similar to uniform waning flow, waning accumulative flow is characterized by significant sediment bypass downslope, indicative of flow acceleration over a given distance. The light gray arrows in the confined facies assemblages shown in Figure 2.9 highlight missing facies, which are preserved downdip in the unconfined assemblage.
5.2.4 Depletive steady flow

Description: The following observations characterize deposits of depletive steady flow: (1) uniform grain size trends within individual facies; (2) abrupt or gradual grain size variations between facies; (3) significant thickness variations in preserved facies; (4) sharp basal contacts; and (5) sharp or gradational contacts between facies.

Interpretation: In contrast to flow uniformity, flow steadiness is easier to ascertain from a single vertical succession as it records velocity variations at a given point in space. The most obvious indicator of velocity variations (i.e., energy) are grain size trends; thus, waning and waxing are linked to normal and inverse grading, respectively. Steady flow, however, is indicated by thick facies with little to no grain size variation, which suggest steady-state conditions over time.

5.2.5 Depletive waxing flow

Description: Finally, depletive waxing flow, shown in the upper left section of Figure 2.9, is suggested by the following: (1) a vertical facies succession from lowest energy facies at the base to highest energy facies at the top; (2) coarsening-upward grain size trends within individual facies; (3) sharp basal contacts; and (4) sharp or gradational internal contacts between facies.
Interpretation: An overall coarsening-upward grain size trend suggests an increase in flow velocity over time at a given point, which in turn is linked to an increase in flow energy.

6. SEDIMENTARY BODIES AND FACIES ASSOCIATIONS

The combination of process-based facies, facies assemblages and patterns of flow steadiness and uniformity allow identification of facies associations and sedimentary bodies. Facies associations are vertical facies successions that record multiple sedimentation events, a reflection of time-averaged processes operating within a defined spatial volume, a sedimentary body. Like the relationship between sedimentation units and facies assemblages, sedimentary bodies are the surface-defined ‘container’ and facies associations are the rock-defined ‘fill’. Porosity and permeability distributions in facies associations are a reflection of three-dimensional pore space and connectivity within a defined body volume.

6.1 Sedimentary bodies

Five basic types of sedimentary bodies are reported from the literature, and three of these bodies can be correlated to changes in gradient and state of flow confinement (citations). They include: (1) channelforms; (2) lobeforms; and (3) wedgeforms (levees).
The remaining two sedimentary body types, mudstone drapes and mass transport deposits, record pelagic deposition and *en masse* movement, respectively.

Sedimentary bodies in the Isongo Formation record a change from confined fan geomorphology in the northeast to unconfined fan geomorphology in the southwest (Figure 2.2). Thus, cores C, D and E (updip) are dominated by erosional slope channelform – wedgeform (levee) features, whereas cores A and B (downdip) are dominated by distributary channelform and lobeform features (Table 2.3). Porosity and permeability frequency distributions in these regions characterize a longitudinal change in pore space and connectivity in sedimentary bodies from the northeast to southwest.

In addition to variations in channelform type (i.e., erosional vs. distributary), lobeform features in cores A and B record both on-axis and off-axis sedimentation, which are dominated by different depositional processes (Table 2.3). For example, off-axis lobeform deposition characterized by thin-bedded sandstones and mudstones (e.g., Facies 9, 10, 11) is interpreted to record dominantly turbulent depositional processes, and demonstrates very high mean porosity values. However, off-axis lobeform deposition characterized by debrites (e.g., Facies 3, 12) is interpreted to record dominantly cohesive debris flow processes and demonstrates lower mean porosity values. Therefore, it is important to differentiate between on-axis and off-axis lobeform deposition.

Likewise, variations in mudstone drape style reflect the duration and nature of mudstone deposition, i.e. sediment bypass vs. condensed sections, and are characterized by different porosity and permeability distributions. Mudstone drapes and mass transport deposits, however, are undersampled in cores from the Isongo Fan (Table 2.3).
It is important to note that sedimentary bodies themselves stack and migrate over time to create a sedimentary body hierarchy (Figure 2.1) (see also Figure 8, Gardner, 2003). To better understand pore space and connectivity within individual bodies, the following discussion focuses on elementary-scale bodies identified in the Isongo Formation cores. A complete sedimentary body hierarchy and discussion of sedimentation regions is presented elsewhere (Wolak et al., in prep).

6.2 Facies associations

Facies associations, which consist of multiple facies assemblages, reflect time-averaged depositional processes operating during construction, fill and preservation of elementary sedimentary bodies. Gradient and confinement are therefore first-order controls on facies associations. For instance, as described by Kneller (1995), an increase in gradient will result in convergence of flow streamlines (i.e., accumulative flow), while a decrease in gradient will result in divergence of flow streamlines (i.e., depletive flow). Thus, sedimentary bodies recording higher gradients and increased confinement such as erosional slope channel forms will be characterized by facies assemblages and associations that reflect flow accumulation, i.e., accumulative waning or accumulative waxing. Alternatively, distal lobef orm deposits, which reflect unconfined subaqueous flow will be characterized by facies assemblages and associations that demonstrate flow depletion.
Nine core-defined facies associations and their corresponding sedimentary body styles are identified and summarized in Table 2.3. For each body type, sedimentation units, process-based facies proportions and reservoir properties are presented, from left to right. In addition to position on the longitudinal profile (updip vs. downdip), each facies association is defined by: (1) grain size; (2) sedimentary structures; (3) surfaces; (4) bioturbation; (5) bed thickness; and (6) sedimentation unit thickness. In addition, trends in flow steadiness and uniformity in facies assemblages, as described above, are utilized to determine body style.

6.2.1 Porosity distributions by facies association

Porosity and permeability distributions within sedimentary bodies and facies associations are a time-averaged reflection of pore space and connectivity created during deposition within a three-dimensional volume. Facies associations in the Isongo Formation are characterized by reservoir property distributions (Table 2.3) that reflect changes in gradient and dispersion, which correlate to hydrodynamic energy and style of deposition. In general, confinement and gradient are inversely correlated to porosity values. Sedimentary bodies interpreted to reflect high gradient and confined flow correlate to lower mean porosity values, whereas bodies that record moderate gradients and partly-confined to unconfined flow demonstrate greater mean pore space. Porosity distributions are summarized in greater detail below.
Channelforms: Erosional slope channelforms and distributary channelforms

Two facies associations characterizing channelform sedimentary bodies are identified in the Isongo Formation cores, which reflect variations in confinement and gradient: (1) erosional slope channelform deposits (cores C and E), which are characterized by confined flow and high gradient; and (2) distributary channelform deposits (cores A and B), which are characterized by confined to partly confined flow and high gradient (Table 2.3). While the facies associations of these channelforms share similar features, the following recognition criteria may be used for differentiation: (1) coarser grain sizes in facies associations of on-axis channelforms, which often includes matrix-supported pebble conglomerates; (2) facies assemblages characterized by accumulative flow in on-axis channelforms; and (3) thicker sedimentation units (0.1 m to 0.6 m) in on-axis channelforms compared to off-axis (0.1 m to 3.5 m). Both erosional and distributary channelforms demonstrate: (1) fining-upward grain size trends; (2) thick sedimentation units; (3) surfaces indicative of sediment bypass; and (4) sharp basal contacts.

Mean porosity values in erosional slope and distributary channelform facies associations are similar, 13.3% and 13.9%, respectively. However, the range of porosity values in erosional slope channelform deposits, from 5.9% to 21.2%, is greater than the range in values for distributary channelform deposits. This is likely due to the higher facies diversity predicted for confined channelform deposition, which include Facies 1 and 2, low porosity matrix-supported pebble conglomerates. Similarly, standard
deviations of porosity distributions are greater in erosional slope channelform facies associations (2.9%) compared to distributary channelforms (2.4%).

Lobeforms: On-axis and off-axis

Three lobeform facies associations capture changes in sediment dispersion due to decreasing gradient and confinement (Table 2.3). The first lobeform facies association is interpreted to reflect moderate gradient, partly confined to unconfined flow and low dispersion, i.e., proximal or on-axis deposition. On-axis lobeforms contain moderate hydrodynamic energy facies (Facies 5, 6 and 7) and are generally characterized by thick, amalgamated sandstones and facies assemblages that record depletive flow conditions. Differentiation between on-axis lobeform and off-axis channelform sedimentation, which share many similar facies, is based on: (1) increased amalgamation in on-axis lobeforms; (2) less pronounced fining-upward grain size variations in on-axis lobeforms (i.e., blocky vertical grain size trends); (3) less sediment bypass in lobeforms; and (4) lower facies diversity in on-axis lobeforms.

Two facies associations that record of off-axis or distal sedimentation in lobeforms are identified and correlated to lower gradients, less confinement and increased dispersion. While both are comprised of thin sedimentation units and facies assemblages characterized by depletive conditions, their facies associations record fundamentally different styles of deposition: (1) Off-axis debrite-dominated lobeform deposits record cohesive debris flow deposits; and (2) Off-axis turbidite-dominated deposits record low
density SDF deposits. Given these different depositional processes and their correlative mean porosities (and permeabilities), it is important to differentiate these two types of off-axis lobeform deposits using facies associations.

Mean porosity values in lobeforms (14.5%, 14.5%, and 16.9%) are higher than both on-axis and off-axis channel forms (13.3% and 13.9%), which suggests a correlation between pore space development and decreasing gradient and confinement. Of the three lobeforms facies associations, on-axis lobeform deposits demonstrate a similar porosity distribution compared to channel forms (Table 3), which are characterized by well-defined Gaussian (normal) distributions and low standard deviations (2.9%, 2.4% and 2.9%).

Off-axis lobeform deposits, however, show poorly-defined porosity distributions with much greater standard deviations, 4.4% and 3.2%, respectively. In off-axis debrite-dominated lobeform deposits, this variation in porosity distributions is a reflection of Facies 3 and 12 (i.e., cohesive debris flow deposits), which in turn correlate to decreasing sorting and increasing clay content. Similarly, off-axis turbidite-dominated lobeform deposits are characterized by thinly interbedded sandstones (Facies 9, 10 and 11) and mudstones (Facies 13 and 14); thus, the corresponding porosity distribution shows a wide range in values, from 5.9% to 15.4%.
Wedgeforms (Levees)

Wedgeforms in the Isongo Formation are located adjacent to erosional slope channelform features in cores C, D and E and reflect partly confined flow (Table 2.3). Of the sedimentary body styles, wedgeforms share many core-defined characteristics with turbidite-dominated lobeforms, but may be distinguished based on: (1) facies assemblages that record a combination of both accumulative and depletive flow; (2) absence of coarser-grained material such as Facies 5 and 6; (3) less bioturbation; and (4) increased preservation of ash beds within mudstone intervals.

Porosity distributions in wedgeforms show well-defined Gaussian trends (standard deviation of 2.1%), and are characterized by the highest mean values observed in sedimentary body styles, 18.6%. This is due to the presence of Facies 9, 10 and 11, which reflect turbulent SDF processes.

Mudstone drapes: Silt-dominated and clay-dominated

Two styles of mud-rich drapes are sedimentologically defined: (1) silt-dominated and silt-bearing mudstone drapes that record low gradient, high dispersion and unconfined flow; and (2) clay-rich mudstone drapes, which reflect very low gradient and high dispersion indicative of sediment starvation and dominantly pelagic deposition. Identification of these two drape styles depends on: (1) the abundance of Facies 15, clay-rich mudstone, in thick successions in clay-dominated drapes; (2) the presence of thin
sandstone beds in silt-dominated drapes; (3) the presence of ash beds, preserved more readily in clay-dominated drapes; and (4) less bioturbation, indicative of very low energy conditions in clay-dominate drapes.

Porosity values for drapes characterized by silty mudstones and thin sandstone beds are very similar to off-axis lobeform deposits, which demonstrate moderate mean porosities (14.6%, 14.6% and 14.4%) and high standard deviations (4.4%, 3.2% and 4.2%). As discussed previously, these distributions reflect the diversity of process-based facies, which include both thin sandstone and mudstone deposits. Drapes characterized by clay-rich intervals, however, are undersampled, but it is assumed that they contain low pore space and very low pore connectivity due to the abundance of clay minerals.

6.2.2 Permeability distributions by facies association

Like porosity, pore connectivity within sedimentary bodies and facies associations is correlated to gradient and confinement in the Isongo Formation. Permeability measurements, however, demonstrate less well-defined frequency distributions (Table 2.3), higher standard deviations and significant left-hand (negative) skewness. When combined with correlations between permeability, process-based facies and textural sorting trends (Sections 4.1.2 and 4.2), this suggests that permeability in facies associations is correlated to process-based facies diversity and time-averaged sorting trends. For example, off-axis lobeform deposits demonstrate very high facies diversity (see second column in Table 2.3) and include very poorly sorted clay-rich facies (Facies
3 and 12); thus, they demonstrate the highest standard deviation in permeability trends (115 md) (Table 2.4). In contrast, on-axis lobiform are characterized by very low facies diversity (mostly Facies 6, 7 and 8) and show much lower standard deviations of 56 md.

When compared to porosity distributions, permeability distributions demonstrate greater variation within sedimentary body types. Erosional slope channel forms and distributary channel forms, for instance, are characterized by mean permeability values of 44 md and 80 md, respectively. (Mean porosity values for these two facies associations is 13.3% and 13.9%). This suggests that the sedimentary body fill, and thus the sediment source, correlate to permeability trends in facies associations, whereas depositional processes and hydrodynamic energy correlate to porosity trends.

7. DISCUSSION

7.1 Scalar dependence of reservoir properties

Porosity and permeability distributions in the Isongo Formation demonstrate the importance of using scalar techniques to capture geologic processes operating at three temporal and spatial scales. Fundamentally, hydrodynamic energy and subaqueous flow processes operating at the time of deposition will be recorded in process-based facies, which in turn stack to form facies assemblages of discrete events (i.e., sedimentation units). Multiple events stack to form facies associations (i.e., sedimentary bodies). At the smallest scale, pore space and connectivity are controlled by subaqueous sediment
density flow processes; at the largest scale, they are a reflection of local changes in topographic gradient and confinement.

Flow behavior (laminar vs. turbulent) is a first-order control on porosity and permeability in turbidity current deposits. Porosity and permeability distributions by process-based facies show that cohesive debris flow deposits have significantly different trends than turbulent SDF deposits, including: (1) poorly defined distributions with high standard deviations (Table 2.1 and 2.2); and (2) poor correlation between grain size and porosity for cohesive debris flow deposits (Figure 2.6B). Very poor sorting and high clay content contribute to the suppression of turbulence within subaqueous sediment density flows.

Flow behavior (turbulent vs. laminar), flow properties (density and viscosity) and the velocity structure of a subaqueous sediment density flow (flow steadiness and uniformity) evolve over time and space during a single sedimentation event to generate a facies assemblage. Given that pore space and connectivity are linked to hydrodynamic energy and process, vertical and lateral trends will be a reflection of flow evolution and/or flow transformation during event-driven sedimentation. Sedimentation unit thickness at a given point, for instance, may be an indication of flow volume and duration; the corresponding facies assemblage and grain size trends will indicate unsteadiness (waxing or waning) and nonuniformity (accumulative or depletive).

Whereas porosity and permeability in small-scale process-based facies are reflections of hydrodynamic energy at the time of deposition, reservoir properties within sedimentary bodies and facies associations record time-averaged flow processes that
reflect changes in local topography, gradient, dispersion and confinement. Deposition within erosional slope channelforms, for example, is more confined than within distributary channelforms or lobeforms that migrate as a result of depositional topography. As a consequence, facies assemblages in slope channelforms exhibit less facies diversity and thus, a narrower range of porosity and permeability distributions. This variation of reservoir properties within sedimentary bodies has important implications for reservoir analysis that preserves geologic heterogeneity at multiple scales.

### 7.2 Implications for reservoir analysis

The sedimentary hierarchy presented here describes porosity and permeability over three spatial and temporal scales, and provides sedimentological attributes needed to establish a robust stratigraphic framework for reservoir characterization. The smallest scale sedimentary bodies are elementary features that stack and migrate to form composite channels and channel complexes (Gardner et al., 2003). Population of these features with porosity and permeability values based on sedimentological observations allows for more accurate reservoir modeling efforts.
8. CONCLUSIONS

Deepwater deposits of the Isongo Formation provide a unique opportunity to correlate primary porosity and permeability trends to a threefold spatial and temporal hierarchy that encompasses: (1) process-based facies; (2) sedimentation units and facies assemblages; and (3) sedimentary bodies and facies associations. Secondary effects on porosity and permeability such as burial depth, temperature and diagenetic alteration are accounted for, and the following conclusions may be summarized:

1. Fifteen hydrodynamic process-based facies are identified, which characterize both turbulent sediment density flow processes and cohesive debris flow processes operating during deposition of the Late Miocene Isongo Fan. Porosity and permeability distributions indicate that the distribution and amount of pore space in a sedimentary deposit is fundamentally linked on flow behavior (turbulent, laminar) and flow properties (viscosity, density). In turbulent deposits, grain size is inversely correlated to porosity and sorting is inversely correlated to permeability. Cohesive debris flow deposits, however, show much greater variation in reservoir properties, due to high clay content and very poor sorting.

2. Ten types of facies assemblages are identified, which capture suites of depositional processes and temporal-spatial velocity variations over a longitudinal distance (i.e., flow steadiness and uniformity). In addition, thickness of
sedimentation units indicates that event-drive sedimentation in the Isongo Formation resulted in very large flows, characterized by relatively constant discharge over a significant period of time and likely due to volcanic eruptions and uplift of Mt. Cameroon during the Late Miocene.

3. Nine facies associations are defined and used to characterize five classic sedimentary body styles in the Isongo Fan, including channelforms, lobeforms, wedgeforms, drapes and mass transport deposits. Porosity and permeability distributions within these bodies are a function of time-averaged depositional processes, which reflect changes in gradient, dispersion and confinement.
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REFERENCES


Table 2.1. Porosity and permeability distributions by facies in the Isongo Formation. Fifteen process-based facies are identified using grain size, sorting, primary and secondary sedimentary structures and clay content (see also Figure 2.4). In general, porosity is inversely correlated to grain size, and permeability is correlated to sorting.

<table>
<thead>
<tr>
<th>Core Photos</th>
<th>Description</th>
<th>Interpretation(s)</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
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<tbody>
<tr>
<td><img src="image" alt="Core Photos" /></td>
<td><strong>Facies 1</strong> Matrix-supported pebble conglomerate (extraclast, stratified): Matrix of medium-to-coarse-grained tan to gray sandstone. Pebble content &gt; 20%, very poorly to poorly sorted, subangular to rounded clasts. Stratification characterized by elongate pebbles and out-stood clasts subparallel to bedding contacts, grain imbrication and decreasing clast content upward. Rounded, elongate subaqueous clasts common, likely derived from the CVL-rich Cameron Volcanic Fine. (CVF) adjacent to the study area.</td>
<td>Deposition from a high density SDF, dominated by traction processes at the flow boundary zone. The current was insufficiently dilute to generate bedforms (planar stratification). Sediment support mechanisms likely included fluid turbulence, hindered settling, matrix buoyant lift and dispersive pressures from grain-grain collisions. [Equivalent to the R&lt;sub&gt;1&lt;/sub&gt; and R&lt;sub&gt;2&lt;/sub&gt; division of Lowe (1982).]</td>
<td>min=8.6 mca=12.3 max=15.4</td>
<td>min=0 mca=9 max=25</td>
</tr>
<tr>
<td><img src="image" alt="Core Photos" /></td>
<td><strong>Facies 2</strong> Matrix-supported pebble conglomerate (extraclast, graded): Matrix of fine- to coarse-grained tan to gray sandstone. Pebble content &gt;20%, very poorly to moderately sorted, subangular to rounded clasts. Coarse-tail inverse grading characterized by increasing clast size and/or concentration upward; normal grading, decreasing clast size and/or concentration upward.</td>
<td>Deposition from a high density SDF, dominated by mixed traction and suspension processes at the flow boundary zone. Sediment support mechanisms likely included fluid turbulence, hindered settling and matrix buoyant lift. (Equivalent to the R&lt;sub&gt;3&lt;/sub&gt; and R&lt;sub&gt;4&lt;/sub&gt; division of Lowe (1982).)</td>
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<td>min=0 mca=7 max=17</td>
</tr>
<tr>
<td><img src="image" alt="Core Photos" /></td>
<td><strong>Facies 3</strong> Matrix-supported mudclast conglomerate (intraclast): Matrix of fine- to coarse-grained light gray to dark gray sandstone containing &gt;20% mm-scaled to cm-scaled mudclasts. Clasts generally angular and elongate subparallel to bedding.</td>
<td>Deposition from a cohesive debris flow. Mudclasts and matrix mud are likely derived from erosion within the submarine channel system (i.e., intraclasts). Particles are suspended by the cohesiveness of the sediment-water mixture rather than by dispersive pressure among rigid grains. (Equivalent to the H3 division of Haughton (2009).)</td>
<td>min=3.6 mca=11.7 max=19.5</td>
<td>min=0 mca=24 max=198</td>
</tr>
</tbody>
</table>
In general, porosity is inversely correlated to grain size, and permeability is correlated to sorting.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Description</th>
<th>Interpretation(s)</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Pebble to granule sandstone: Medium- to coarse-grained sandstone with abundant pebble to granule-outsized clasts (&lt;20%). Very poorly- to moderately-sorted, subangular to rounded clasts.</td>
<td>Deposition from a high density SDF, dominated by suspension fallout processes at the flow boundary zone. Sediment support mechanisms likely included fluid turbulence, hindered settling and matrix buoyant lift. [Equivalent to the R&lt;sub&gt;4&lt;/sub&gt; division of Lowe (1982).]</td>
<td><img src="image-url" alt="Porosity (%) Frequency" /></td>
<td><img src="image-url" alt="Permeability (md) Frequency" /></td>
</tr>
<tr>
<td>5</td>
<td>Sandstone (planar spaced stratification, upper flow regime): Medium- to coarse-grained tan to gray sandstone with few outsized clasts. Poorly- to moderately-sorted, subangular to rounded grains. Stratification characterized by mud-rich or clast-rich laminations sub-parallel to bedding contacts. Spacing ranges from mm to cm. Basal contacts generally sharp, erosive.</td>
<td>Deposition from a high density SDF, dominated by traction processes at the flow boundary zone (i.e., traction carpet) (Middleton, 1967; Sohn, 1997). Traction deposition likely occurs by progressive bed aggradation rather than frictional freezing. Inverse grading, where present, indicates a gradient of dispersive pressure due to the nonuniform distribution of particles (Sohn, 1997). Sediment support mechanisms likely included fluid turbulence, hindered settling and matrix buoyant lift. [Equivalent to the S&lt;sub&gt;4&lt;/sub&gt; division of Lowe (1982).]</td>
<td><img src="image-url" alt="Porosity (%) Frequency" /></td>
<td><img src="image-url" alt="Permeability (md) Frequency" /></td>
</tr>
<tr>
<td>6</td>
<td>Sandstone (inclined stratification, angle of repose, lower flow regime): Medium- to coarse-grained tan to gray sandstone with few outsized clasts (&lt;10%). Poorly- to moderately-sorted, subangular to rounded grains. Inclined stratification characterized by mud-rich or clast-rich inclined laminae (&gt;30 degrees) and normal grading. Basal contacts generally sharp, erosive.</td>
<td>Deposition from a high density SDF, dominated by mixed traction and suspension processes at the flow boundary zone. Sediment support mechanisms likely included fluid turbulence, hindered settling and matrix buoyant lift. [Equivalent to the S&lt;sub&gt;5&lt;/sub&gt; division of Lowe (1982).]</td>
<td><img src="image-url" alt="Porosity (%) Frequency" /></td>
<td><img src="image-url" alt="Permeability (md) Frequency" /></td>
</tr>
</tbody>
</table>
Deposition from a high density SDF, dominated by suspension fallout processes at the flow boundary zone. Sediment support mechanism is primarily fluid turbulence.  

Table 2.1 (continued). Porosity and permeability distributions by facies in the Isongo Formation. Fifteen process-based facies are identified using grain size, sorting, primary and secondary sedimentary structures and clay content (see also Figure 2.4). In general, porosity is inversely correlated to grain size, and permeability is correlated to sorting.

<table>
<thead>
<tr>
<th>Core Photos</th>
<th>Description</th>
<th>Interpretation(s)</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone (structureless): Fine- to medium-grained tan to gray sandstone, outsized clasts common (&lt;10%). Inverse and normal grading common. Clasts may be grain-size to pebble-sized, clay-rich (intraclasts, derived from submarine channels) or extraclasts of quartz, metaquartzite, feldspar or siderite. Bioturbation common, characterized by mud- and sand-filled burrows (<em>Zoophycos, Ophiomorpha</em>).</td>
<td>1. Deposition from a high density SDF, dominated by suspension fallout processes at the flow boundary zone. Sediment support mechanism is primarily fluid turbulence. (Equivalent to the S3 division of Lowe (1982).) 2. Post-depositional bioturbation and destruction of primary structures resulting in structureless appearance.</td>
<td>min=3.9 mean=14.3 max=21.6</td>
<td>min=0 mean=65 max=388</td>
<td></td>
</tr>
<tr>
<td>Sandstone (soft-sediment deformed, liquified): Fine- to coarse-grained tan to gray sandstone, outsized (isolated) clasts common, water escape and liquefaction structures common, including: (1) consolidation lamination; (2) dishes; (3) pipes; and (4) load structures. Very poorly to poorly-sorted, angular to subrounded grains. Laminations may be mud-rich. Outsized clasts may be mudstone intraclasts, derived from within the channel system, or extraclasts of quartz or feldspar.</td>
<td>Rapid deposition from an SDF; high deposition rate suppresses turbulence and causes flow collapse (Allen, 1985; Arnott and Hand, 1989). Subsequent liquefaction due to water entrainment during deposition results in the formation of water escape structures (Nichols, 1995).</td>
<td>min=1.9 mean=15.3 max=22.7</td>
<td>min=0 mean=66 max=507</td>
<td></td>
</tr>
<tr>
<td>Sandstone (plane parallel lamination, mud &lt;25%, upper flow regime): Fine-grained to medium-grained gray to light tan sandstone interbedded with mm- to cm-scale plane parallel muddy laminations.</td>
<td>Deposition from a low density SDF, dominated by traction deposition at the flow boundary zone. Intermittent suspension characterized by muddy laminations. (Equivalent to the Tb division of Bouma (1962).)</td>
<td>min=13.0 mean=18.0 max=23.5</td>
<td>min=3 mean=95 max=297</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.1 (continued). Porosity and permeability distributions by facies in the Isongo Formation. Fifteen process-based facies are identified using grain size, sorting, primary and secondary sedimentary structures and clay content (see also Figure 2.4). In general, porosity is inversely correlated to grain size, and permeability is correlated to sorting.

<table>
<thead>
<tr>
<th>Core Photos</th>
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<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies 10</td>
<td>Sandstone (ripple cross-laminated, lower flow regime): Very fine to medium-grained gray to light tan sandstone with ripple cross laminations. Angle of climb is generally greater than stoss side angle (i.e., subcritical climbing ripples).</td>
<td>Deposition from a low density SDF, dominated by traction deposition at the flow boundary zone. [Equivalent to the T&lt;sub&gt;C&lt;/sub&gt; division of Bouma (1962).]</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Facies 11</td>
<td>Sandstone (wavy laminated, mud &gt;25%, lower flow regime): Very fine to fine-grained gray sandstone interbedded with mm- to cm-scale wavy muddy laminations.</td>
<td>Deposition from a low density SDF, dominated by suspension deposition at the flow boundary zone. Intermittent suspension characterized by muddy laminations (Middleton, 1967). [Equivalent to the T&lt;sub&gt;d&lt;/sub&gt; division of Bouma (1962).]</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Facies 12</td>
<td>Muddy sandstone: Very fine to medium-grained light to dark gray muddy sandstone, outsized clasts common (&lt;10%). Clasts are mm- to cm-scale, elongate, subangular, comprised of mudstone (intraclasts) and extraclasts of quartz, metaquartzite, or feldspars. Bioturbation common and includes sand- and mud-filled burrows, both horizontal and vertical.</td>
<td>Deposition from a cohesive debris flow. Particles are suspended by the cohesiveness of the sediment-water matrix rather than by dispersive pressure between rigid grains. [Equivalent to the H&lt;sub&gt;3&lt;/sub&gt; division of Haughton (2009).]</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>
Table 2.1 (continued). Porosity and permeability distributions by facies in the Isongo Formation. Fifteen process-based facies are identified using grain size, sorting, primary and secondary sedimentary structures and clay content (see also Figure 2.4). In general, porosity is inversely correlated to grain size, and permeability is correlated to sorting.

<table>
<thead>
<tr>
<th>Core Photos</th>
<th>Description</th>
<th>Interpretation(s)</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies 13</td>
<td>Silt-dominated mudstone: Mudstone with a high proportion of silt-sized grains (visual estimation), light gray to dark gray. Bioturbation common and includes sand- and mud-filled, sand-lined burrows.</td>
<td>Deposition from a low density SDF, dominated by suspension fallout processes at the flow boundary zone. Nomenclature (&quot;silt-dominated&quot;) after MacQuaker and Adams (2003), indicating an estimated &gt;90% silt-sized particles within a mudstone matrix. Hemipelagic deposition, interpreted to be similar to that described by Scheiber et al. (2007). [Equivalent to the T_e division of Bouma (1962).]</td>
<td>min=5.0 mean=12.8 max=20.7</td>
<td>min=0 mean=16 max=92</td>
</tr>
<tr>
<td>Facies 14</td>
<td>Silt-bearing mudstone: Mudstone with a low proportion of silt-sized particles (visual estimation), light gray to dark gray. Bioturbation common and includes sand-filled and mud-filled burrows.</td>
<td>Deposition from a low density SDF, dominated by suspension fallout processes at the flow boundary zone. Nomenclature (&quot;silt-bearing&quot;) after MacQuaker and Adams (2003), indicating an estimated &lt;30% silt-sized particles within a mudstone matrix. [Equivalent to the T_e division of Bouma (1962).]</td>
<td>min=7.2 mean=11.8 max=19.5</td>
<td>min=0 mean=6 max=35</td>
</tr>
<tr>
<td>Facies 15</td>
<td>Clay-rich mudstone: Mudstone with moderate amount of clay-sized particles (visual estimation), gray to very dark gray. Bioturbation uncommon.</td>
<td>Deposition from pelagic fallout, not associated with event-driven SDFs. Lack of bioturbation indicated low circulation and an oxygen poor environment. Nomenclature after MacQuaker and Adams (2003), indicating an estimated moderate amount (30 - 90%) of clay-sized particles within a mudstone matrix.</td>
<td>Insufficient data (n &lt; 5)</td>
<td>Insufficient data (n &lt; 5)</td>
</tr>
</tbody>
</table>
Table 2.2. General statistics of core-derived porosity (%) and permeability (md) measurements, organized by process-based sedimentological facies.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Porosity</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>min</td>
</tr>
<tr>
<td>Pebble conglomerate (extraclast, stratified)</td>
<td>11</td>
<td>8.60</td>
</tr>
<tr>
<td>Pebble conglomerate (extraclast, graded)</td>
<td>14</td>
<td>5.90</td>
</tr>
<tr>
<td>Mudclast conglomerate (interclast)</td>
<td>14</td>
<td>3.62</td>
</tr>
<tr>
<td>Pebble to granule sandstone</td>
<td>56</td>
<td>7.20</td>
</tr>
<tr>
<td>Sandstone (planar spaced stratification)</td>
<td>94</td>
<td>3.90</td>
</tr>
<tr>
<td>Sandstone (inclined stratification)</td>
<td>21</td>
<td>10.30</td>
</tr>
<tr>
<td>Sandstone (soft-sediment deformed)</td>
<td>159</td>
<td>1.91</td>
</tr>
<tr>
<td>Sandstone (planar laminated, mud &lt;25%)</td>
<td>21</td>
<td>12.97</td>
</tr>
<tr>
<td>Sandstone (ripple cross-laminated)</td>
<td>8</td>
<td>11.60</td>
</tr>
<tr>
<td>Sandstone (wavy laminated, mud &gt;25%)</td>
<td>4</td>
<td>14.72</td>
</tr>
<tr>
<td>Muddy sandstone</td>
<td>8</td>
<td>6.10</td>
</tr>
<tr>
<td>Silt-dominated mudstone</td>
<td>18</td>
<td>5.00</td>
</tr>
<tr>
<td>Silt-bearing mudstone</td>
<td>11</td>
<td>7.20</td>
</tr>
<tr>
<td>Clay-rich mudstone</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Pebble conglomerate (extraclast, stratified)</td>
<td>8</td>
<td>0.00</td>
</tr>
<tr>
<td>Pebble conglomerate (extraclast, graded)</td>
<td>14</td>
<td>0.00</td>
</tr>
<tr>
<td>Mudclast conglomerate (interclast)</td>
<td>4</td>
<td>0.00</td>
</tr>
<tr>
<td>Pebble to granule sandstone</td>
<td>48</td>
<td>0.07</td>
</tr>
<tr>
<td>Sandstone (planar spaced stratification)</td>
<td>89</td>
<td>0.04</td>
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<tr>
<td>Sandstone (inclined stratification)</td>
<td>20</td>
<td>9.12</td>
</tr>
<tr>
<td>Sandstone (structureless)</td>
<td>142</td>
<td>0.02</td>
</tr>
<tr>
<td>Sandstone (soft-sediment deformed)</td>
<td>134</td>
<td>0.00</td>
</tr>
<tr>
<td>Sandstone (planar laminated, mud &lt;25%)</td>
<td>21</td>
<td>3.33</td>
</tr>
<tr>
<td>Sandstone (ripple cross-laminated)</td>
<td>7</td>
<td>0.84</td>
</tr>
<tr>
<td>Sandstone (wavy laminated, mud &gt;25%)</td>
<td>3</td>
<td>4.98</td>
</tr>
<tr>
<td>Muddy sandstone</td>
<td>4</td>
<td>0.036</td>
</tr>
<tr>
<td>Silt-dominated mudstone</td>
<td>8</td>
<td>0.02</td>
</tr>
<tr>
<td>Silt-bearing mudstone</td>
<td>5</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Table 2.3. Porosity and permeability distributions for sedimentary bodies located in the northeastern, confined portion of the Isongo Fan. Erosional slope channelforms contain the highest proportion of coarse-grained facies (Facies 1 and 2) and demonstrate lower mean porosity and permeability than distributary channelform and lobeform deposits in the southwestern (unconfined) fan.

<table>
<thead>
<tr>
<th>Facies Associations</th>
<th>Facies</th>
<th>Recognition Criteria</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosional slope channelform (on-axis)</td>
<td>1-10</td>
<td>Grain size: Ranges from pebble conglomerates to medium-grained sandstones. Finer grained sediment very uncommon. Grain size generally fines upward within sedimentation units. Sedimentary structures: Stratification common (both inclined and parallel); convolution common at the tops of sedimentation units and may include injection of sandstone into overlying conglomerates. Surfaces: Basal surfaces of sedimentation units are sharp, irregular and cross-cut underlying beds. Surfaces separating facies within sedimentation units may be sharp or gradational.</td>
<td>Per = 0.0 0.01 0.02 0.04 0.06 0.08 0.1 0.12 0.15 0.2 0.5 0.8 1.0 2.0 4.0 8.0 Frequency</td>
<td>Per = 0.01 0.04 0.08 0.16 0.32 0.64 1.28 2.56 5.12 10.24 20.48 40.96 81.92 163.84 327.68 655.36 1310.72 2621.44 5242.88 10485.76 20971.52 41943.04 83886.08 167772.16</td>
</tr>
<tr>
<td>Overbank wedgeform (off-axis)</td>
<td>1-8</td>
<td>Grain size: Ranges from medium-grained sandstones to silt-dominated mudstone. Interbedded sandstone and mudstone common. Grain size generally fines upward within sedimentation units. Sedimentary structures: Plane parallel lamination and rippled cross-lamination common. Woody sand laminar common in silt-dominated or silt-bearing mudstones. Soft-sediment deformation common. Surfaces: Basal surfaces of sedimentation units are sharp, generally characterized by sandstone deposition on top of mudstone. Surfaces within sedimentation units may be sharp or gradational. Bioturbation: Common</td>
<td>Per = 0.0 0.01 0.02 0.04 0.06 0.08 0.1 0.15 0.2 0.5 0.8 1.0 2.0 4.0 8.0 Frequency</td>
<td>Per = 0.01 0.04 0.08 0.16 0.32 0.64 1.28 2.56 5.12 10.24 20.48 40.96 81.92 163.84 327.68 655.36 1310.72 2621.44 5242.88 10485.76 20971.52 41943.04 83886.08 167772.16</td>
</tr>
</tbody>
</table>

Min = 5.9  Mean = 13.3  Max = 21.2
Min = 0  Mean = 44  Max = 564
Min = 15.1  Mean = 18.6  Max = 23.5
Min = 10  Mean = 101  Max = 321
Table 2.3. Porosity and permeability distributions for sedimentary bodies located in the northeastern, confined portion of the Isongo Fan. Erosional slope channelforms contain the highest proportion of coarse-grained facies (Facies 1 and 2) and demonstrate lower mean porosity and permeability than distributary channelform and lobeform deposits in the southwestern (unconfined) fan.

<table>
<thead>
<tr>
<th>Facies Associations</th>
<th>Facies %</th>
<th>Recognition Criteria</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributary channelform (on-axis)</td>
<td></td>
<td>Grain size: Ranges from pebble to granule sandstone to fine-grained sandstones. Finer grained sediment uncommon. Grain size generally fines upward within sedimentation units.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Stratification common (both inclined and parallel), soft-sediment deformation common at the tops of sedimentation units and includes dishes, pipes and consolidation lamination.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Basal surfaces of sedimentation units are sharp, irregular and cross-cut underlying beds. Surfaces within sedimentation units may be sharp or gradational.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Absent to uncommon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Sedimentation unit thicknesses range from 0.3 ft (0.1 m) to 11.5 ft (3.5 m). Channelform body thicknesses range from 5.0 ft (1.5 m) to 22.0 ft (6.7 m).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facies Colors</td>
<td></td>
<td>![Pie chart]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>![Pie chart]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal lobeform (on-axis)</td>
<td></td>
<td>Grain size: Ranges from coarse-grained to fine-grained sandstone. Finer grained sediment uncommon. Uniform, ungraded grain size trends and significant amalgamation common.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Stratification common (both inclined and parallel), soft-sediment deformation common in blocky sedimentation units and includes dishes, pipes and consolidation lamination.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Surfaces between sedimentation units vary and may be sharp or cryptic and amalgamated. Surfaces within sedimentation units may be sharp or gradational.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Absent to uncommon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Sedimentation unit thicknesses range from 0.3 ft (0.1 m) to 8.2 ft (2.5 m). Lobeform body thicknesses range from 0.9 ft (0.3 m) to 19.7 ft (6.0 m).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facies Colors</td>
<td></td>
<td>![Pie chart]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>![Pie chart]</td>
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<td></td>
</tr>
</tbody>
</table>
Table 2.3 (continued). Porosity and permeability distributions for sedimentary bodies located in the northeastern, confined portion of the Isongo Fan. Erosional slope channeliforms contain the highest proportion of coarse-grained facies (Facies 1 and 2) and demonstrate lower mean porosity and permeability than distributary channeliform and lobeform deposits in the southwestern (unconfined) fan.

<table>
<thead>
<tr>
<th>Facies Associations</th>
<th>Facies %</th>
<th>Recognition Criteria</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Of-axis lobeform (turbidite-dominated)</td>
<td></td>
<td>Grain size: Ranges from medium-grained sandstones to silt-dominated mudstone. Interbedded sandstone and mudstone common. Grain size generally fines upward within sedimentation units.</td>
<td><img src="image1" alt="Porosity and permeability distribution" /></td>
<td><img src="image2" alt="Porosity and permeability distribution" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Stratification and lamination (plane parallel and ripple) common. Woody sand laminae in mudstone common.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Basal surfaces of sedimentation units are sharp, generally characterized by sandstone deposition on top of mudstone. Surfaces within sedimentation units may be sharp or gradational.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Common</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Sedimentation unit thicknesses range from 3.9 in (10 cm) to 19.7 in (50 cm). Lobeform body thicknesses range from 3.9 in (0.1 m) to 118.1 in (3.0 m).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Of-axis lobeform (debris-dominated)</td>
<td></td>
<td>Grain size: Ranges from medium-grained sandstones to silt-dominated mudstone. Mudclasts conglomerates and muddy sandstones common as well as mud interbeds.</td>
<td><img src="image3" alt="Porosity and permeability distribution" /></td>
<td><img src="image4" alt="Porosity and permeability distribution" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Parallel stratification and lamination (ripple and plane parallel) common. Mudclasts and outsized clasts common in sandstones. Soft-sediment deformation common and includes pipes and consolidation lamination.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Surfaces between sedimentation units are sharp and irregular. Surfaces within sedimentation units may be sharp or gradational.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Common and includes mud-filled and sand-filled burrows. Common ichnofacies include Zoophycos and Ophiomorpha.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Sedimentation unit thicknesses range from 0.2 ft (0.05 m) to 4.9 ft (1.5 m). Lobeform body thicknesses range from 1.0 ft (0.3 m) to 9.8 ft (3.0 m).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

min=11.3  mean=16.9  max=21.0  min=1  mean=20  max=92

min=3.6  mean=14.6  max=21.6  min=0  mean=66  max=507
Table 2.3 (continued). Porosity and permeability distributions for sedimentary bodies located in the northeastern, confined portion of the Isongo Fan. Erosional slope channelforms contain the highest proportion of coarse-grained facies (Facies 1 and 2) and demonstrate lower mean porosity and permeability than distributary channelform and lobeform deposits in the southwestern (unconfined) fan.

<table>
<thead>
<tr>
<th>Facies Associations</th>
<th>Facies %</th>
<th>Recognition Criteria</th>
<th>Porosity (%) Frequency</th>
<th>Permeability (md) Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silt-dominated mudstone drape</strong></td>
<td></td>
<td>Grain size: Ranges from fine-grained sandstone to silt-bearing mudstone. Mudstone contains varying amount of silt to sand-size particles.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Lamination (plane parallel or ripple) may be present in thin sandstone beds. Soft-sediment deformation common in thin sandstone beds. Ash beds may be common in some intervals.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Basal surfaces of sedimentation units are sharp and often characterized by deposition of sandstone on mudstone. Surfaces within sedimentation units may be sharp or gradational.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Common and includes sand-filled and mud-filled burrows. Ichnofacies including Ophiomorpha and Zoophycos common.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Bedding is very thin in mudstone intervals (&lt; 5.0 cm). Sandstone beds range from &lt; 5.0 cm to 50 cm. Drape body thicknesses range from &lt; 10 cm to 70 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Ash beds (bentonite) common, characterized by green clay-rich intervals (&lt; 10 cm).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Surfaces for individual sedimentation units cryptic within mudstone deposits.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Uncommon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Bedding is very thin in mudstone intervals (&lt; 5.0 cm). Drape body thicknesses range from &lt; 10 cm to 70 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clay-dominated mudstone drape</strong></td>
<td></td>
<td>Grain size: Ranges from silt-bearing to clay-rich mudstone. Washy sand laminae may be present. Mudstone dominated by dark gray to black clay and may contain varying amounts of silt to sand-sized particles.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary structures: Ash beds (bentonite) common, characterized by green clay-rich intervals (&lt; 10 cm).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surfaces: Surfaces for individual sedimentation units cryptic within mudstone deposits.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioturbation: Uncommon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: Bedding is very thin in mudstone intervals (&lt; 5.0 cm). Drape body thicknesses range from &lt; 10 cm to 70 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mass Transport</strong></td>
<td>Insufficient Data</td>
<td>Insufficient Data</td>
<td>Insufficient Data</td>
<td>Insufficient Data</td>
</tr>
</tbody>
</table>
Table 2.4. General statistics of core-derived porosity (%) and permeability (md) measurements, organized by sedimentary body.

<table>
<thead>
<tr>
<th>Sedimentary Body Description</th>
<th>Porosity</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>min</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>1 Erosional slope channelform (on-axis)</td>
<td>86</td>
<td>5.90</td>
</tr>
<tr>
<td>2 Overbank wedgeform (levee)</td>
<td>17</td>
<td>15.13</td>
</tr>
<tr>
<td>3 Distributary channelform (on-axis)</td>
<td>159</td>
<td>7.10</td>
</tr>
<tr>
<td>4 Proximal lobeform (on-axis)</td>
<td>229</td>
<td>1.91</td>
</tr>
<tr>
<td>5 Off-axis lobeform (turbidite-dominated)</td>
<td>75</td>
<td>3.62</td>
</tr>
<tr>
<td>6 Off-axis lobeform (debris-dominated)</td>
<td>14</td>
<td>11.30</td>
</tr>
<tr>
<td>7 Silt-dominated mudstone drape</td>
<td>51</td>
<td>6.50</td>
</tr>
<tr>
<td>8 Clay-dominated mudstone drape</td>
<td>2</td>
<td>n/a</td>
</tr>
<tr>
<td>9 Mass transport deposit</td>
<td>1</td>
<td>n/a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sedimentary Body Description</th>
<th>n</th>
<th>min</th>
<th>max</th>
<th>range</th>
<th>mean</th>
<th>variance</th>
<th>std. dev.</th>
<th>skewness</th>
<th>median</th>
<th>mode</th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Erosional slope channelform (on-axis)</td>
<td>72</td>
<td>0.00</td>
<td>564.00</td>
<td>564.00</td>
<td>43.81</td>
<td>5105.777</td>
<td>71.455</td>
<td>5.127</td>
<td>107.18</td>
<td>19.36</td>
<td>n/a</td>
<td>19.36</td>
<td>118.09</td>
</tr>
<tr>
<td>2 Overbank wedgeform (levee)</td>
<td>17</td>
<td>9.65</td>
<td>321.00</td>
<td>311.35</td>
<td>100.76</td>
<td>10401.894</td>
<td>102.904</td>
<td>1.130</td>
<td>31.77</td>
<td>50.12</td>
<td>9.67</td>
<td>50.12</td>
<td>312.43</td>
</tr>
<tr>
<td>3 Distributary channelform (on-axis)</td>
<td>148</td>
<td>1.76</td>
<td>242.00</td>
<td>240.24</td>
<td>80.02</td>
<td>3244.151</td>
<td>59.957</td>
<td>0.505</td>
<td>76.14</td>
<td>134.64</td>
<td>6.42</td>
<td>76.14</td>
<td>182.75</td>
</tr>
<tr>
<td>4 Proximal lobeform (on-axis)</td>
<td>200</td>
<td>0.00</td>
<td>537.00</td>
<td>537.00</td>
<td>51.31</td>
<td>3154.262</td>
<td>58.163</td>
<td>1.829</td>
<td>33.90</td>
<td>57.93</td>
<td>n/a</td>
<td>33.90</td>
<td>165.10</td>
</tr>
<tr>
<td>5 Off-axis lobeform (turbidite-dominated)</td>
<td>50</td>
<td>0.00</td>
<td>507.00</td>
<td>507.00</td>
<td>66.35</td>
<td>13327.504</td>
<td>115.445</td>
<td>2.236</td>
<td>94.34</td>
<td>94.34</td>
<td>9.41</td>
<td>94.34</td>
<td>354.85</td>
</tr>
<tr>
<td>6 Off-axis lobeform (debris-dominated)</td>
<td>14</td>
<td>1.15</td>
<td>91.70</td>
<td>90.55</td>
<td>19.71</td>
<td>527.880</td>
<td>22.976</td>
<td>2.302</td>
<td>16.65</td>
<td>2.22</td>
<td>1.14</td>
<td>16.65</td>
<td>90.68</td>
</tr>
<tr>
<td>7 Silt-dominated mudstone drape</td>
<td>27</td>
<td>0.02</td>
<td>366.00</td>
<td>365.98</td>
<td>23.25</td>
<td>4610.767</td>
<td>67.903</td>
<td>4.259</td>
<td>4.259</td>
<td>4.259</td>
<td>4.259</td>
<td>4.259</td>
<td></td>
</tr>
<tr>
<td>8 Clay-dominated mudstone drape</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>9 Mass transport deposit</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
5. Sedimentation Regions

Sedimentary architecture defined by process-based facies distributions and sedimentary body stacking patterns. The example shown below is from Gardner et al. (2003), a field-based study in the Permian Brushy Canyon Formation, West Texas.

4. Sedimentary Body Hierarchy

Stacking of sedimentary bodies reflects migration in response to evolving seafloor topography, which generates changes in local gradient.

2. Sedimentation Units and Facies Assemblages

Record flow steadiness and uniformity as well as suites of depositional processes and evolving hydrodynamic energy conditions.

1. Process-Based Facies

Record hydrodynamic energy and depositional processes operating at the time of deposition.

3. Sedimentary Bodies and Facies Associations

Reflect changes in gradient and confinement as well as time-averaged hydrodynamic energy conditions and depositional processes.

Figure 2.1. Spatial and temporal sedimentary hierarchy for evaluation of reservoir properties. Shaded boxes highlight the threefold hierarchy described in this contribution (see text).
Figure 2.2. Location of the study area in the southeastern Niger Delta (upper diagram), adjacent to the Cameroon Volcanic Line and sourced from the Cross River system. The Isongo Fan (bottom diagram) thickens and widens to the southwest and thins and pinches out to the east. Twenty-two wells (white circles) penetrate the Late Miocene Isongo Formation, and five conventional cores recovered from wells A-E (red circles) are used to characterize a complete suite of subaqueous sediment density flow (SDF) deposits. Sedimentation in the Isongo Fan is coeval with structural growth and anticline development (black arrows) (see Wolak et al, in prep).
Figure 2.3. Core-derived porosity (%) and permeability (md) trends plotted by depth for each core (A-E) within the Isongo Formation. In general, porosity and permeability distributions demonstrate little variation in Cores A, C, D and E over a depth range of < 1000 feet. Core B, however, shows slightly higher porosity and slightly lower permeability values with increasing depth. Depth shown is below a given reference datum, the top of the Isongo Formation. With the exception of the lower portion of Core B, all porosity are permeability measurements are from gas-saturated intervals. For the purposes of this study, values from oil-saturated and water-saturated intervals (shaded datapoints) were omitted from statistical analyses.
Figure 2.4. Facies tract produced by sand-rich and mud-rich sediment density flows (SDFs) demonstrating organization and transformations along the runout length of a single flow down a channel axis. Fifteen process-based facies identified in the Isongo Formation characterize hyperconcentrated, high-concentration and low concentration SDF deposits, as well as cohesive debris flow deposits.
Figure 2.5. Core-derived porosity (%) and permeability (md) trends plotted by grain size for all facies in the Isongo Formation. In general, the range of porosity and permeability values tends to increase with decreasing grain size, and the largest range of values is shown in structureless sandstone (Facies 7) and soft-sediment deformed sandstone (Facies 8).
Figure 2.6. Core-derived porosity (%) trends plotted by grain size for two subsets of process-based facies. Facies deposited by hyperconcentrated SDF, high-concentration SDF and low-concentration SDF flows are shown in (A), and demonstrate a negative correlation between porosity and grain size (correlation coefficient of 0.55). (B) presents grain size and porosity data for deposits of cohesive debris flows and hemipelagic processes, which lack a significant correlation (correlation coefficient of 0.08).
Figure 2.7. Core-derived porosity (%) and permeability (md) trends plotted for facies characterized by very poor to moderate sorting. (A) demonstrates a positive correlation between sorting and permeability for deposits of hyperconcentrated SDFs, characterized by very poor sorting, and high-concentration SDFs, characterized by poor to moderate sorting. In contrast, (B) shows porosity and permeability trends for facies deposited by cohesive debris flow and hemipelagic processes, both of which are characterized by very poor sorting and high clay content.
Figure 2.8. Thick, coarse-grained sedimentation units in the Isongo Formation and associated porosity and permeability measurements. Stratified pebble conglomerate (Facies 1) grades into pebble to granule sandstone (Facies 4) over approximately 20 ft. (6.1 m).
<table>
<thead>
<tr>
<th>Depletive (-ve)</th>
<th>Uniform</th>
<th>Accumulative (+ve)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waxing (+ve)</strong></td>
<td><img src="image1" alt="Unconfined" /></td>
<td><img src="image2" alt="Confined" /></td>
</tr>
<tr>
<td><strong>Steady</strong></td>
<td><img src="image4" alt="Unconfined" /></td>
<td><img src="image5" alt="Confined" /></td>
</tr>
<tr>
<td><strong>Waning (-ve)</strong></td>
<td><img src="image6" alt="Unconfined" /></td>
<td><img src="image7" alt="Confined" /></td>
</tr>
</tbody>
</table>

Figure 2.9. Acceleration matrix for facies assemblages in the Isongo Formation. Vertical facies successions, grain size trends, sedimentary structures and bed contacts characterize flow steadiness and uniformity from the confined northeastern fan to the unconfined southwestern fan. Matrix modified after Kneller (1995).
MANUSCRIPT 2

SEDIMENTARY RESPONSE TO INCIPIENT STRUCTURAL GROWTH AND TRANSIENT FAN DEVELOPMENT IN THE LATE MIOCENE ISONGO FORMATION,
SOUTHEASTERN NIGER DELTA
Contribution of Authors and Co-Authors

Manuscript in Chapter 2
Chapter 2:
Co-author: Michael H. Gardner (Montana State University)

Primary author (Jeannette M. Wolak) compiled all analyses presented in this publication, including: (1) sedimentological core descriptions; (2) core to wireline-log calibration via petrophysical facies analysis; and (3) construction of a sixfold stratigraphic hierarchy and corresponding stratigraphic correlations. J.M Wolak drafted all figures and tables presented and wrote the accompanying text.

Second author (Michael H. Gardner) provided oversight and input for this project, including: (1) preliminary analysis of Isongo Formation cores in 2004-2007 (Gardner, 2006); and (2) editing of text, figures and tables for this contribution. Funding was provided through the CORTES partnership between M.H. Gardner (Montana State University) and Marathon Oil Company.

Third author (Wayne S. Bayer) assisted in petrophysical facies analysis for all wells in the Isongo Formation and provided editorial assistance for this contribution.

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Publisher: American Association of Petroleum Geologists
Title Page

Title.

INCIPIENT STRUCTURAL GROWTH AND TRANSIENT FAN DEVELOPMENT IN THE LATE MIOCENE ISONGO FORMATION, SOUTHEASTERN NIGER DELTA

Author names and affiliations.

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Located in the southeastern Niger Delta, the Late Miocene Isongo Formation is characterized by development of a deepwater transient fan system in response to incipient structural growth on the continental slope. Anticlinal uplift is a result of deformation in the outer fold and thrust belt of the delta impinging upon volcanic horsts of the Cameroon Volcanic Line (CVL) to the east. Coarse-grained sediment deposited within the Isongo Fan is sourced from the Cross River drainage system, and large-scale event-driven sedimentation is linked to eruptive activity and tectonism of Mount Cameroon, located 50 km updip along the West African coast.

Within the Isongo Fan, core-calibrated sedimentary bodies demonstrate a change from confined erosional slope-levee complexes to unconfined distributary channel-lobe complexes downdip. Petrophysical facies, wireline log signatures and thicknesses allow identification of sedimentary bodies in uncored intervals. Integration with 3-D seismic, 21 wells, biostratigraphy, chemostratigraphy and dynamic production data forms the basis for correlations throughout the 100 km² study area.

Five 4th order sequences record deposition over <0.5 million years. The oldest sequences (1 and 2) onlap the southwestern flank of the Isongo anticline and record coeval structural growth and deposition. On the crest of the uplift, a seismic unconformity at the base of 4th order Sequence 1 indicates significant erosion, correlative to deposition on the flank. Fourth order Sequence 3 is characterized by the greatest volume of sand deposition and development of channel-levee complexes (~84 m-thick) in the northeast and distributary channel-lobe complexes (~50 m-thick) in the southwest. Sequences 4 and 5, however, demonstrate backfilling of the slope valley channel and subsequent filling of depositional topography during fan retreat. Younger chemostratigraphic packages (4th order), pressure breaks (dynamic production data), an increase in ash beds and thin, continuous sandstone deposition throughout the study area suggest a period of lower sedimentation and structural quiescence during fan retreat. Renewed structural uplift resulted in avulsion of the fan system to the northwest sometime after 8.2 Ma.
1. INTRODUCTION

Deepwater coarse-grained deposits of the Late Miocene Isongo Formation provide a unique opportunity to investigate the role of syn-sedimentary structural growth on transient fan development in the southeastern Niger Delta. Located approximately 250 km updip of the terminal basin-floor Calabar Fan, the Isongo Fan shows evidence for confined-to-unconfined submarine fan morphology on the upper slope controlled by incipient anticline growth. Changes in gradient determine the distribution and stacking patterns of sedimentary bodies within the Isongo Fan, a reflection of changing geomorphology in response to active uplift.

The present-day anticlinal trend and plunge is coincident with the axis of the Isongo Fan, which suggests a relationship between gradient on the growing structure and sand-rich deposition (e.g., Adeogba et al., 2005; Heiniö and Davies, 2007). Higher gradient in the narrow proximal fan, on the crest of the anticline, is characterized by incision, coarse-grained deposition, and development of erosional slope channel-levee complexes recording confined flow. The mid- to lower fan, however, is characterized by distributary channel-lobe complexes recording partly confined to unconfined flow on the lower gradient anticline flank.

More than 1,200 ft (366 m) of conventional core, 21 wireline logs, 3-D seismic (maximum 40-60 Hz), biostratigraphy, chemostratigraphy and dynamic production data are used to interrogate the sedimentary response in the 100 km² Isongo Fan, across the plunging anticline. A sixfold sedimentary hierarchy demonstrates temporal and spatial
variation using: (1) process-based facies (minutes to hours); (2) sedimentation units and facies assemblages (hours to days); (3) sedimentary bodies and facies associations (years to tens of years); (4) fifth order stratigraphic sequences (hundreds of thousands of years); (5) fourth order stratigraphic sequences (hundreds of thousands of years); and (6) third order stratigraphic sequences (millions of years). A companion publication by Wolak and Gardner (in prep) addresses the former three hierarchical orders in greater detail (smaller-scale), and this publication focuses on the latter three (larger-scale).

Phases of Adjustment-Initiation-Growth-Retreat (AIGR) best characterize migration of the Isongo depocenter and stratigraphic architecture developed in response to coeval structural growth and sedimentation (cf. Gardner et al., 2003; Gardner et al., 2008). In this case, the AIGR model is applied to 4th and 5th order stratigraphic sequences correlated across the study area. The onset of uplift, characterized by an unconformity or surface of adjustment, is followed by 4th order initial deposition on the flank of an active anticline. Phases of fan growth (not to be confused with structural growth) are marked by development of very thick channel-levee complexes updip and distributary channel-lobe complexes downdip, which are recorded in sedimentary body stacking patterns. Fourth order fan retreat marks a period of structural quiescence during which backfilling of the confined slope valley occurs and the Isongo depocenter migrates to the northwest; renewed anticlinal growth results in avulsion of the system away from the study area.
2. TECTONIC SETTING

2.1 The Isongo Fan

The Isongo Fan comprises one 2.3 million-year episode of deepwater sedimentation in the Rio Muni Basin, east of the Niger Delta and west of the Cameroon Volcanic Line (CVL) (Figure 3.1). Located approximately 30 km northwest of Bioko Island, the axis of the fan is oriented northeast-southwest, sub-parallel to the Principe Channel system, a through-going series of deepwater channels that feed the basin floor Calabar Fan 250 km downdip.

3-D seismic imaging of the Isongo Fan reveals a narrow northeastern portion (<2.5 km-wide) that widens abruptly to >16 km over a distance of <5 km (Figure 3.2). The thickest portion of the sand-rich fan measures 375 m and is located on the southwestern flank of a present-day structural high, illustrated in Figure 3.2B. The coincident location of the fan and the anticline, onlap of sandstone packages onto the anticline flank, and the downdip change from confined to unconfined fan morphology strongly suggest coeval sedimentation and structural growth in the Isongo Fan. Tectonic controls on deformation and sedimentation in the study area are described in the following sections and include: (1) Outbuilding of the southeastern margin of the Niger Delta; (2) Uplift and emplacement of volcanic edifices of the Cameroon Volcanic Line (CVL) to the north and east; (3) Discharge of the Cross River system into the Principe
Channel and Calabar Fan; and (4) Remnant transpression and transtension associated with development of post-rift transform faults along the West African margin.

2.2 The Niger Delta

2.2.1 Niger Delta stratigraphy

The Niger Delta is one of the world’s largest wave-dominated deltaic systems, encompassing approximately 75,000 km² (Doust and Omatsola, 1990) (Figure 3.1). A 12 km-thick wedge of clastic sediment onlaps the equatorial West African margin and records Paleocene to Holocene deposition, which includes the following formations, from oldest to youngest: (1) marine shales of the Akata Formation; (2) deep marine sandstones and mudstones of the Agbada Formation; and (3) shallow marine to nonmarine sandstones of the Benin Formation (Figure 3.3). Regional hydrocarbon accumulations, in general, are sourced from the Tertiary Akata Formation and undrilled Cretaceous strata that overlie oceanic basement rocks (Burke, 1972).

In regional stratigraphic correlations, the Isongo Formation is age-equivalent to the Agbada Formation in the Niger Delta west of the study area (Figure 3.3). Biostratigraphic analyses from 11 wells that penetrate the Isongo Formation suggest coarse-grained clastic deposition occurred between 8.2-10.5 Ma, constrained by planktonic and benthic foraminifera and nannofossil assemblages (Foulks, 1968; Clowser et al., 1984; Lunt et al., 1986; McEachern, 1990, 1992; Marshall and Wilson, 1999a,
1999b; Wilson, 2001; Marshall 2001; Micro-Strat, 2001a, 2001b; Attewell and Wilson, 2002; Wilson 2002a, 2002b; Wilson, 2003; Weston, 2004). The base of the Isongo Formation is marked by the disappearance of *Cyperaceaepollis* spp. and the occurrence of *Globo* *rotalia siakensis/mayeri*, *Bolivina tenuicosta*ta and *Orbulina suturalis* which define the intra-uppermost Serravallian sequence boundary at 10.5 Ma (Haq et al., 1987).

At the top of the study interval, *Pediastrum* spp. events suggest an age of 8.2 Ma and correlate to bathyal water depths during a regional lowstand systems tract. Additionally, palynological studies of the Isongo Formation, combined with regional pollen data, demonstrate migration of palynological zones southward during the Middle to Late Miocene during delta outbuilding (Morley and Richards, 1993).

The 2.3 million year episode of coarse-grained clastic sedimentation in the Isongo Formation is correlative to Late Miocene global cooling and falling eustatic sea level described by Haq et al. (1987), Miller et al. (2005), and Zachos et al. (2001) (Figure 3.4). Relative sea level changes along the equatorial West African margin record these global variations as well as regional variations due to epiorogenic uplift and tilting of the African craton. For example, tectonic reconstructions of the Congo and Angolan margins, south of the Niger Delta, demonstrate approximately 500m of uplift during the Miocene, which resulted in significant erosion of the continental shelf (Lavier et al., 2001). Seismic sections presented by Coterill et al. (2002) show a Late Miocene unconformity which extends from the northern Niger Delta to Namibia, likely coincident with lowstand sedimentation in the Isongo Formation.
2.2.2 Niger Delta structural styles and deformation

Deformation in the Niger Delta is dominated by gravitationally-driven contraction and extension associated with collapse of the deltaic sediment wedge (Damuth, 1994; Hooper et al., 2002). Recent work by Corredor et al. (2005) shows five structural domains in the modern delta, which are illustrated in Figure 3.1. Extensional provinces on the shelf are kinematically linked via transitional zones to contractional inner and outer fold-and-thrust belts. In the southeastern Niger Delta, these provinces converge west of Bioko Island, resulting in compressed zones of deformation. During the Late Miocene, the Niger Delta deformation front migrated eastward across the study area resulting in regional thrust-fault propagation in the eastern delta toe (Corredor et al., 2005).

Studies by Faminkawa et al. (1996), Shanmugam et al. (1997) and Shanmugam (2006) describe mud-rich debris flow-dominated sediments of the Mio-Pliocene Intra Qua-Iboe Member of the Agbada Formation (Zafiro Field), located approximately 75 km west-southwest of the study area. While these deposits are also located in the outer deformation zone of the southeastern Niger Delta, they present a striking contrast to pebble- and sand-rich deposits of the Isongo Formation, which suggests different sediment sources and dominant depositional processes over a relatively small area. Whereas deposits in the Isongo Formation reflect sedimentation through the Cross River-Calabar Fan system at the outermost edge of the deformation front, deposits of the Intra Qua-Iboe member likely reflect sediment sourced from the mud-rich delta.
2.3 The Cross River Drainage

Adjacent to the Niger Delta and west of the Cameroon Volcanic Line (CVL), the present-day Cross River drainage system is oriented northeast-southwest and may be traced from onshore Cameroon through the Principe Channel system to the basin floor Calabar Fan, approximately 200 km downdip of the study area (Figure 3.1) (Edet et al., 1996; Okereke et al., 1998). Deepwater channels of the Cross River system cross-cut contractional features of the southeastern Niger Delta and are associated with incision and development of Late Miocene submarine canyons such as the Principe Canyon and Qua Iboe Canyon described by Burke (1972).

2.4 The Cameroon Volcanic Line

Confinement and sedimentation in the Cross River-Principe Channel system are strongly tied to uplift and volcanism in the CVL, an offshore-onshore linear trend of volcanic edifices that extends from Lake Chad to Annobón Island in the Gulf of Guinea. During the Late Miocene, volcanic horsts of the CVL acted as a backstop for eastward migration of the Niger Delta deformation front (Figure 3.1). Regional seismic sections presented by Meyers et al. (1996) and Wilson et al. (2003) demonstrate onlap of deltaic sediments onto the flanks of the growing volcanic line in the Gulf of Guinea, which suggests large-scale coeval sedimentation and uplift in both the Rio Muni Basin (west of the CVL) and the Gabon Basin (east of the CVL).
Radiometric dating of volcanism and plutonism in the CVL yields ages that range from 68 Ma to present, summarized in Figure 3.5 (modified after Déruelle et al., 2007). Coincident with sedimentation in the Isongo Formation, intrusive igneous rocks of Mount Cameroon, located approximately 50 km updip of the study area, demonstrate ages from 4 Ma to 11 Ma; extrusive rocks, 8 Ma to 10 Ma (Fitton and Dunlop, 1985; Déruelle et al., 2001; Déruelle et al., 2007). It is therefore likely that episodic volcanism of Mount Cameroon: (1) served as a source of sediment for the Isongo Fan; and (2) acted as a trigger mechanism for deepwater sediment gravity flows on the adjacent continental slope.

As described in Wolak and Gardner (in prep, previous chapter), pebble conglomerates in the Isongo Formation are comprised of volcaniclastic fragments and large siderite clasts (mm-scale to 15 cm thick in conventional cores), likely derived from the CO2-rich CVL (Bernard and Symonds, 1989). Abundant ash beds and large (>3 mm) unaltered grains of biotite and sanidine in bentonite-rich mudstones suggest little transport and modification of volcaniclastic material as it was deposited in the Isongo Formation (Wolak and Gardner, in prep, previous chapter). Very thick sedimentation units (>10.0 ft, > 3.0 m) indicate prolonged periods of subaqueous deposition, likely due to eruptive events on Mount Cameroon or adjacent volcanic horsts. Thus, the CVL acted as both a sediment source and a control on the sediment routing system in the Rio Muni Basin.
2.5 Oceanic transform faults and fracture zones

The position of the Niger Delta, CVL and the resulting route of the Cross River – Principe Channel – Calabar Fan system are linked to Jurassic opening of the Atlantic and subsequent development of oceanic transform faults that bisect the equatorial West African margin (Figure 3.1). For example, the Benue Trough, a failed northeast-southwest trending aulocogen, forms the repository for sediments of the Niger River and associated delta system (Burke, 1972; Ofoegbu, 1985). To the south, the trough is bounded by Precambrian basement rocks of the African craton; to the north, the trough branches into the Gongola rift and Yola rift south of the Chad Basin (Benkhelil, 1989; Nnange et al., 2000). The northeast-southwest margins of the Benue Trough are subparallel to oceanic transform faults and fracture zones shown in Figure 3.1, i.e., the Romanche Fracture Zone, Chain Fracture Zone, Charcot Fracture Zone, and Ascension Fracture Zone. Thus, the clastic sediment wedge that comprises the Niger Delta sits within the Benue Trough and is bounded to the northwest by the Chain Fracture Zone and associated oceanic transform faults. Moreover, the Charcot Fracture zone bisects the sediment wedge in the southern Niger Delta, which controls deposition in: (1) two prominent deltaic lobes; and (2) the basin-floor Niger Fan (Figure 3.1).

With regard to deposition in the Isongo Formation, it seems likely that a northwest – southeast trending fracture zone underlies the Cross River – Principe Channel – Calabar Fan system. The proposed fracture zone is shown in gray in Figure 3.1, and bisects the Calabar Fan, parallel to four other regional fracture zones. If present,
the fracture zone forms the eastern boundary of the Niger Delta; thus, the deltaic system is situated in a graben between two prominent oceanic fracture zones, the Chain Fracture zone to the northwest and the proposed fracture zone to the southeast. Moreover, it appears that weaknesses in the oceanic lithosphere, i.e., fracture zones and oceanic transform faults, strongly control the placement of basin floor fans such as the Niger Fan and the Calabar Fan in the Gulf of Guinea. Several regional seismic studies have focused on transitional crust along the West African margin, and future studies may resolve the presence of the proposed fracture zone and the associated link to sedimentation (Meyers et al., 1996; Wilson et al., 2003).

3. PETROPHYSICAL CALIBRATION

Petrophysical calibration of sedimentological facies and wireline logs is required for stratigraphic correlation of 22 wells that penetrate the Isongo Fan (Figure 3.2). More than 1,200 ft (366 m) of conventional core recovered from five wells in the Isongo Formation is used to characterize a complete range of grain sizes and lithologies, from pebble conglomerates to clay-rich mudstones. Detailed core descriptions completed at a scale of 1:24 established fifteen process-based lithofacies, summarized in Wolak and Gardner (in prep). Facies are ordered from highest energy to lowest energy and classified according to: (1) lithology; (2) textural attributes (grain size, sorting); (3) clay content; and (4) primary sedimentary structures. Interpreted depositional processes, facies and petrophysical facies are shown in Figure 3.6.
With regard to stratigraphic analysis and geologic modeling, petrophysical calibration of process-based facies provides: (1) a method for prediction of process-based facies in uncored intervals; and (2) a method for estimation of porosity and permeability in both cored and uncored intervals. For example, Wolak and Gardner (in prep) present detailed analyses of porosity and permeability trends in the Isongo Formation at three spatial and temporal scales. At the smallest scale, reservoir properties correlate to grain size and sorting in process-based facies. This suggests that subaqueous flow behavior (laminar, turbulent) and flow properties (density, viscosity) at the time of deposition are linked to pore space and connectivity in the resulting sedimentary deposit. Thus, process-based petrophysical calibration captures both fundamental geologic processes as well as the distribution of porosity and permeability in a rock volume.

3.1 Petrophysical facies

As described by Sullivan et al. (2003), petrophysical facies are a ‘high-order lithofacies association from core descriptions that are grouped by similarity of log response.’ Additionally, petrophysical facies identified in the Isongo Formation, shown in Figure 3.6, reflect: (1) similar lithologies, textural attributes (grain size, sorting), clay content and sedimentary structures; (2) similar interpreted depositional processes (e.g., turbidites, debrites, etc.); and (3) similar porosity and permeability signatures (see Wolak and Gardner, in prep).
Petrophysical calibration in the Isongo Formation is based on a suite of four wireline logs, including gamma ray, resistivity, density and sonic compression. While similar to methods presented in a comprehensive study of the West African margin by Sullivan et al. (2003), deposits of the Isongo Formation present a more straightforward case in which secondary effects on petrophysical properties are less pronounced. Given the limited geographic and stratigraphic extent of the study area (~100 km²), compaction, temperature, hydrocarbon saturation and diagenesis do not appear to significantly impact log response between wells. This allows for robust calibration of each wireline log (gamma ray, resistivity, density and sonic compression) to sedimentological facies observed in core. Although a complete discussion of the core-to-log calibration technique is beyond the scope of this paper, a succinct summary of steps is provided below.

Step 1 – Identification of process-based facies

Detailed sedimentological descriptions and identification of process-based facies provides the foundation for petrophysical calibration of 22 wells in the study area. Approximately 1,200 ft (400 m) of conventional cores used in this research are described by Wolak and Gardner (in prep) and their observations are summarized in Figure 8. Fifteen process-based facies are organized by interpreted depositional energy, from highest (facies 1) to lowest (facies 15).
Step 2 – Statistical analysis of petrophysical response

For each wireline log (i.e., gamma ray, resistivity, density, and sonic compression) frequency distributions were analyzed to ascertain: (1) mean and standard deviations for log values by facies; and (2) mean and standard deviations for log values by groups of facies, organized by interpreted depositional process. In other words, statistical distributions of log values for deposits of high-density turbidites were compared to distributions of log values for low-density turbidites and debrites.

While individual process-based facies are nearly impossible to predict using petrophysical responses, grouping facies according to depositional process provides a way around this challenge while retaining sedimentological interpretations (Sullivan et al., 2003; this study). The fifteen process-based facies described in the Isongo Formation were grouped into six petrophysical facies, shown in Figure 8. These include, from highest energy to lowest energy:

(1) Petrofacies A – pebble conglomerates, stratified or graded, interpreted to reflect high density turbulent deposition [comparable to the \( R_1 \) and \( R_2 \) divisions described by Lowe (1982)].

(2) Petrofacies B – mudclast conglomerates or muddy sandstones, interpreted to reflect cohesive debris flow deposits [comparable to divisions described by Haughton et al. (2003) and Haughton et al., (2007)].
(3) Petrofacies C – granule to pebble sandstones and coarse- to medium-grained sandstones, stratified or structureless, interpreted to reflect high-density turbulent deposition [comparable to the R₃, S₁, S₂, and S₃ divisions described by Lowe (1982)].

(4) Petrofacies D – interbedded fine-grained sandstones and mudstones, planar-laminated, ripple cross laminated or wavy laminated, interpreted to reflect low density turbulent deposition [comparable to the Tₐ, Tₜ, and Tₖ divisions described by Bouma (1962)].

(5) Petrofacies E – silt-dominated or silt-bearing mudstones with thin sand laminae, interpreted to reflect low concentration and low density turbulent deposition (hemipelagic) [comparable to the Tₑ division of Bouma (1962)].

(6) Petrofacies F – clay-rich mudstone, interpreted to reflect dominantly pelagic deposition.

In addition to the four petrophysical facies described by Sullivan et al. (2003), the scheme presented in this publication identifies: (1) multiple coarse-grained fractions in petrophysical facies A and C; and (2) two types of mudstone fractions in petrophysical facies E and F.
Step 3 – Construction of a calibration matrix

Using statistical values from step 2, a simple program was created to assign petrophysical facies values in uncored intervals. For example, to predict petrofacies A, an IF/THEN statement was used, where \( GR \) = gamma ray log, \( RES \) = resistivity log, \( RHOB \) = density log, \( DTC \) = sonic compressional log and \( PF \) = petrofacies.

\[
\text{If } 30 < GR < 52, \text{ and } 12.0 < RES < 85.0, \text{ and } 2.355 < RHOB < 2.580, \text{ and } 68 < DTC < 77, \text{ then } PF = A. 
\]

Thus, for prediction of petrofacies A, criteria from all four wireline logs must be met. Two caveats for this type of analysis were identified. First, in cases in which multiple petrophysical facies were predicted, value statements were added to the program to assign one petrophysical facies over another. For example, petrophysical facies E and F (both mudstones) were often predicted in the same intervals, and a value statement was added to select petrophysical facies F over E. This is due to the broad range of statisti
cally-defined wireline log values for petrophysical facies E compared to F. Second, in cases in which criteria were not met to assign any of the six petrophysical facies, manual interpolation was required. This was most often the case at contacts between petrophysical facies, likely due to changing log values that fell between criteria for one facies or the other. It is unlikely that the petrophysical facies defined in this study do not capture the geologic heterogeneity in the Isongo Formation.
Step 4 – Assigning petrophysical facies within uncored intervals

Multiple iterations of the core-to-log program resulted in a 68% match between predicted petrophysical facies and observed petrophysical facies in cored intervals. While this value is lower than core-to-log calibration values presented by Sullivan et al. (2003) (75-92%), it has the added capacity to predict: (1) conglomeratic deposits that are indicative of very high energy depositional processes; and (2) organic-rich mudstones that suggest pelagic fallout during periods of sedimentological quiescence.

The finalized program was run in all 22 wells of the Isongo Formation, including the five cored calibration wells (locations in Figure 3.1).

3.2 Core-calibrated sedimentation units and facies assemblages

In addition to petrophysical facies analysis, sedimentation units and facies assemblages in the Isongo Fan are calibrated between two cores recovered from the same stratigraphic interval, illustrated in Figures 3.7 and 3.8. Well Q, located approximately 5.2 km downdip of Well G, is characterized by at least four sandstone packages that measure >125 ft (38 m) interbedded with thin mudstone deposits (Figure 3.7). Sandstone units in the lower portion of Well Q reflect older deposits that onlap the flank of the Isongo structure, not recorded in deposits of Well G which is located on the anticline crest.

Cored intervals in both wells are from the Upper Isongo, which is characterized by thick, amalgamated sandstone packages that measure 90 ft (27 m) thick in Well G to
145 ft (44 m) thick in Well Q. As shown in core-based sedimentological profiles (Figure 3.8), medium-grained sandstones sit abruptly on silt-bearing and silt-dominated mudstones in both wells. This contact marks the onset of deposition for the uppermost stratigraphic interval in the Isongo Formation, one of five 4th order sequences that comprise the 3rd order Isongo Fan. The stratigraphic framework illustrated in Figure 3.7 is described in greater detail in the following sections.

Sedimentation units in Wells G and Q range from cm-thick to 3.5 m-thick in amalgamated sandstone beds and are correlative across a distance of 5.2 km, which suggests very large subaqueous sedimentation events. The magnitude of these events is attributed to eruptive activity of Mount Cameroon, 50 km updip along the West African coast.

In general, sedimentation events are thicker in Well Q (downdip) than in Well G and are characterized by coarser grain sizes, including pebble to granule sandstones shown in Figure 3.8. This suggests that the relative slope gradient decreased from Well G to Well Q such that: (1) subaqueous sediment gravity flows were more attenuated, resulting in thicker sedimentation units; and (2) the coarse-grained fraction of SDFs bypassed Well G, which suggests nonuniform and unsteady SDF flow conditions between the two wells (*sensu* Kneller, 1995). With respect to the former observation, sedimentation unit thickness is considered a proxy for flow size (volume) and duration (Kneller and McCaffrey, 2003; Talling et al., 2007; Sumner et al., 2009; others?). Given that both wells record the same subaqueous events, it seems unlikely that flow volume would increase significantly from Well G to Well Q resulting in thicker sedimentation
units. Flow duration, however, and the longitudinal structure of the flow, i.e., attenuation over distance, provides a more likely explanation for downdip increases in sedimentation unit thickness. Moreover, this small-scale pattern matches the much larger-scale pattern of increased sand deposition on the flank of the Isongo anticline.

3.2.1 Unsteady and nonuniform flow

In addition to variations in grain size and sedimentation unit thicknesses, patterns of unsteady and nonuniform flow suggest less flow confinement in the cored interval of Well Q compared to Well G (Figure 3.8). As defined by Allen (1985), unsteady flow is defined by changes in flow velocity over time at a given point (du/dt) (i.e., waxing and waning flow); nonuniform flow, changes in flow velocity over a given distance (du/dx) (i.e., accumulative and depletive flow). Thus, the concepts of unsteady and nonuniform flow can be used to describe longitudinal variations in flow behavior over time via the acceleration matrix of Kneller (1995). Criteria such as the preservation of different grain size fractions and fining- or coarsening-upward grain size trends are the sedimentary response to changes in flow velocity during event-driven sedimentation (Kneller, 1995; Wolak and Gardner, in prep).

30 sedimentation units are correlated between Wells G and Q, and the most common pattern of flow steadiness and uniformity is depletive waning flow \( (n = 12) \), highlighted in Figure 3.8. In most cases, sedimentation units in both wells are sharp based and demonstrate fining-upward grain size patterns consistent with a decrease in flow
velocity over time (flow waning). A wider range of grain sizes, from pebble sandstones to fine-grained sandstones in Well Q suggests a decrease in flow capacity between the two wells allowing deposition of all grain size fractions as a result of decreasing velocity (flow depletion) (Hiscott, 1994). This observation is consistent with a decrease in gradient from Well G to Well Q, divergence of streamlines (i.e., more unconfined flow) and flow deceleration (see Figure 3 in Kneller, 1995).

3.3 Core-calibrated sedimentary bodies and facies associations

Gradient and flow confinement are also reflected in the vertical distribution of sedimentary bodies and facies associations illustrated in Figures 3.7 – 3.12. Whereas sedimentation units record individual subaqueous events that may occur over minutes, hours or days, sedimentary bodies are three-dimensional geometries that represent time-averaged processes operating at longer time scales, from days to tens of years. Five basic sedimentary body shapes are classically recognized in the literature and include channelforms, lobeforms, wedgeforms (levees), mudstone drapes and mass transport deposits (MTDs) (Walker, 1978; Clark and Pickering, 1997; Gardner et al., 2003).

All five sedimentary body geometries are identified in cored intervals of the Isongo Formation, as well as variations in body fill due to on-axis vs. off-axis deposition (e.g., on-axis lobeform deposition vs. off-axis lobeform deposition). Petrophysical facies, wireline log trends and thicknesses allow calibration and identification of sedimentary bodies in uncored intervals throughout the study area. Moreover, vertical stacking
patterns of sedimentary bodies identified in core are described using the Build-Cut-Fill-Spill (BCFS) model of Gardner and Borer (2000) (see also Gardner et al., 2003; Gardner et al., 2008). BCFS phases capture the change from confined to unconfined flow, which results in the deposition of channelforms or lobeforms, respectively, i.e. the channel-lobe transition zone (CLTZ) (Figure 3.13). In cored intervals, the BCFS emphasizes a hierarchy of sedimentary bodies that migrate through space and time, which characterize higher order stratigraphic sequences (i.e., 3rd order sequence of the Isongo Fan, etc.).

3.3.1 Erosional slope channel-levee complexes

Sedimentological descriptions of cores recovered from the northeastern portion of the Isongo Fan suggest deposition in channelforms and wedgeforms (levees) confined within an erosional deepwater slope valley (Wolak and Gardner, in prep). Wells K and H are both located within the narrow thick portion of the Isongo Fan, illustrated in Figures 3.9 and 3.10. Both wells are characterized by sandstone packages that measure up to 100 m thick interbedded with mudstone packages that range from <10 m thick to 90 m thick. Compared to wells G and Q, described in the previous section, Wells K and H demonstrate net to gross values that are similar to Well G, also located in the narrow northeastern portion of the Isongo Fan. Much higher net to gross values in Well Q, located >4 km to the southwest, are attributed to: (1) deposition of older sandstone packages on the flank of the growing Isongo anticline; and (2) decreased confinement due to structurally-controlled gradient changes.
Core-defined petrophysical facies in Well K are interpreted to reflect high-energy deposition in erosionally-confined slope channelforms, and include, in decreasing abundance: (1) petrophysical facies C – pebbly sandstones to medium-grained sandstones; (2) petrophysical facies A – pebble conglomerates; and (3) petrophysical facies D – fine-grained sandstones. Gamma ray log patterns shown in Figure 3.9 are blocky to coarsening-upward within the cored interval, with higher gamma ray values indicative of either: (1) pebbly conglomerates at the base of sedimentation units; or (2) fine-grained sandstones capping sedimentation units. Erosional channelform thicknesses range from 12 ft (3.7 m) to 20 ft (6.1 m), and may appear much thicker in sand-rich uncored intervals. For example, the base of the uppermost channelform feature defined in core from Well K is characterized by pebble to granule sandstone that overlies coarse-grained sandstone, both of which are grouped into petrophysical facies C (Figure 3.9). Thus, without core, these two channelform features would be difficult to distinguish from petrophysical facies and wireline logs alone. This is likely the case in the interval directly above the cored section of Well K, noted on Figure 3.9.

In contrast, the cored interval in Well H is characterized by thin-bedded sandstones and mudstones interpreted to reflect overbank deposition adjacent to erosional slope channelforms in the confined portion of the Isongo Fan (Figure 3.10). Well H, shown on the seismic isochron map, is located <0.5 km from the northeast – southwest trending channelized thick and is characterized by low net to gross and mudstone packages that measure up to 90 ft (27 m) thick. Petrophysical facies in the upper portion of the cored interval of Well H, interpreted to reflect levee deposition, include: (1)
petrophysical facies D – fine-grained sandstones; (2) petrophysical facies E – silt-bearing and silt-dominated mudstones; and (3) petrophysical facies F – organic rich mudstones. Minor sandstones (petrophysical facies C) are also present, and are significantly thinner (<5 ft, <1.5 m) than in interpreted channelform sedimentary bodies of Well K.

Similar petrophysical facies and wireline log signatures also characterize slumped levee and mass transport deposits (MTDs) in Well H (Figure 3.10). MTD thickness measures 9 ft (2.7 m) and includes overturned beds of soft sediment-deformed sandstone and thin-bedded sandstone and mudstone deposits. It is important to recognize that petrophysical facies, wireline log signatures and thicknesses within MTDs appear nearly identical to adjacent levee deposits, which makes identification of MTDs in uncored intervals nearly impossible.

Finally, the base of Well H is characterized by thin sandstone packages (petrophysical facies C) overlying organic-rich mudstones (petrophysical facies F), interpreted to reflect the onset of sand deposition in the northeastern Isongo Fan. Abundant thin (mm-thick) ash beds and clay-rich mudstones observed in the lowermost cored interval of Well H suggest deposition dominated by pelagic fallout with periodic input from the Cameroon Volcanic Line. A significant pressure break in dynamic production data and biostratigraphic analysis by Wilson (2001) provide further key evidence for this interpretation. Thus, the sandstone-mudstone contact described in core from Well H is interpreted to be the base of the 3rd order Isongo Fan sequence, adjacent to the northeast – southwest trending erosional channelform pattern (Figure 3.10).
3.3.2 Distributary channel-lobe complexes

In striking contrast to erosional slope channel-levee complexes preserved in the northeastern portion of the Isongo Fan, distributary channel-lobe complexes characterize the western and southern regions of the study area (Figure 3.2 and Figure 3.11). This change in sedimentary body style and distribution is a function of decreasing gradient and confinement on the flank of the Isongo anticline. Higher net to gross and connectivity between sandstone packages suggest freely migrating distributary channelform and lobeform systems such as those shown in Wells P and Q (Figures 3.7, 3.11 and 3.12).

Distributary channelforms demonstrate similar petrophysical facies patterns, wireline log trends and thicknesses to erosional slope channelforms located in the northeastern portion of the Isongo Fan. For example, channelforms identified in Well P, shown in Figure 3.11, are characterized by a high proportion of petrophysical facies C (sandstone) with lesser proportions of petrophysical facies A (pebble conglomerates) and petrophysical facies D (fine-grained sandstones). Gamma ray log trends in the cored interval of Well P compared to Well Q are more uniform and blocky; however, this is partly a reflection of the abundance and composition of pebble conglomerates within each channelform feature. Thicknesses of distributary channelforms range from 8 ft (2.4 m) to 25 ft (7.6 m) within cored intervals of Well P. Given the similarities in core-defined erosional slope channelforms and distributary channelforms, it is therefore necessary to use additional criteria for differentiation of these sedimentary bodies, including: (1) location within the deepwater Isongo Fan (confined vs. unconfined portions); (2) vertical
wireline log trends in uncored intervals; (3) petrophysical facies analysis; and (4) stratigraphic context.

Similarly, distributary channel forms and on-axis lobefoms, both sandstone-rich sedimentary bodies, are characterized by thick, blocky wireline log signatures and high proportions of petrophysical facies C (sandstone) (Figure 3.11). To distinguish between these two sedimentary body styles, the following criteria may be used: (1) higher proportions of petrophysical facies A in distributary channel forms than in lobefoms; and (2) slight coarsening-upward to fining-upward wireline log trends in distributary channel forms due to the presence of pebble conglomerates. As illustrated in Figure 3.11, lobefoms and distributary channel forms may be vertically stacked to form distributary channel form-lobefom complexes, which reflect migration of these two types of sedimentary bodies in response to evolving seafloor topography (i.e., lobe switching and topographic compensation).

On-axis and off-axis sedimentation in core-defined lobefoms may produce significantly different patterns of petrophysical facies, wireline log trends and thicknesses, shown in Figures 3.11 and 3.12. For example, on-axis lobefom bodies described in core from Well P are characterized by amalgamated sandstone beds than range in thickness from <0.5 m to 3.0 m thick and show very little grain size variation over 30 ft (9.1 m) (Figure 3.11). In general, the tops of lobefom bodies are capped by soft-sediment deformed sandstones (i.e., liquefied sandstones) and bioturbated horizons with an abundance of vertical and horizontal burrows (e.g., Ophiomorpha, Zoophycos). However, these features are impossible to distinguish using wireline logs and
petrophysical facies analysis such that on-axis lobeform intervals show little to no
evidence for contacts between individual lobes. Thus, it is necessary to identify intervals
as lobe complexes as opposed to individual lobes and to interpolate the number of lobes
using analogue data from other deepwater settings.

Off-axis lobeforms, such as those shown in Figure 3.12, are more easily identified
in uncored intervals due to thinner wireline log signatures and a higher diversity of
petrophysical facies. Off-axis lobeform thicknesses range from <5 ft (1.5 m) to 20 ft (6.1
m) and are characterized by: (1) petrophysical facies C – pebble sandstones to medium-
grained sandstones; (2) petrophysical facies D – fine-grained sandstones; (3)
petrophysical facies E – silt-bearing and silt-dominated mudstones; and (4) petrophysical
facies B – mudclast conglomerates and muddy sandstones. One distinguishing attribute of
off-axis lobeforms compared to other sedimentary bodies is a higher proportion of
petrophysical facies B, which reflect runout and deposition of cohesive debris flows on
lobeform margins (Haughton et al., 2003). Likewise, petrophysical facies B is a key
indicator of on-axis vs. off-axis lobeform deposition as well as proximal vs. distal
lobeform deposition (i.e., higher proportions of petrophysical facies B expected in distal
lobeform deposits).

In summary, sedimentary bodies within the Isongo Fan characterize an overall
change in longitudinal gradient and confinement from the northeastern fan region to the
south and west. Erosional slope channelform deposits and corresponding overbank
deposits in Wells K and H correlate to higher gradients on the crest of the Isongo
structure, whereas distributary channelform and lobeform deposits in Wells G, Q and P correlate to lower gradients and unconfined flow off the flank.

4. ISONGO FAN GEOMORPHOLOGY

Sandstone deposition in the Isongo Fan characterizes one 3rd order sequence that spans 2.3 million years and includes: (1) five 4th order sequences, interpreted to reflect deposition over <0.5 million years; and (2) thirteen 5th order sequences, interpreted to reflect deposition over hundreds of thousands of years. Higher resolution temporal constraints for 4th and 5th order sequences are more tenuous than 3rd order sequences, which are based on biostratigraphic analyses from the Isongo Fan (Foulks, 1968; Clowser et al., 1984; Lunt et al., 1986; McEachern, 1990, 1992; Marshall and Wilson, 1999a, 1999b; Wilson, 2001; Marshall 2001; Micro-Strat, 2001a, 2001b; Attewell and Wilson, 2002; Wilson 2002a, 2002b; Wilson, 2003; Weston, 2004). Temporal durations of 4th and 5th order sequences, however, are well-established in many other stratigraphic studies (Vail et al., 1977; Mitchum and Van Wagoner, 1991; Gardner, 1995; Gardner et al., 2008).

Syn-sedimentary structural growth and deposition of the Isongo Fan suggests a 3rd order cycle of anticlinal development followed by structural quiescence and topographic healing (i.e., backfilling) that occurs over a period of <2.3 million years. With regard to stratigraphic models, this pattern is best described using the Adjustment – Initiation – Growth – Retreat (AIGH) model of Gardner et al. (2003) and Gardner et al. (2008) (see
also Hadler-Jacobsen et al., 2005). Structural adjustment, in this case uplift, is followed by deposition on the flank of the structure (initiation), migration of the depocenter basinward (growth) and topographic backfilling (retreat). The dip-oriented seismic cross section shown in Figure 3.14 illustrates this pattern in the 3rd Order Isongo Fan and shows migration of depocenters through time and space resulting from an active structural high. A basal reflector marks the surface of adjustment, which is capped by 4th order: (1) initiation sequences that onlap the structure; (2) growth sequences that blanket the entire dip section; and (3) retreat sequences that thin to the south and west. Above the Isongo Fan interval, seismic packages that thicken downdip of the structure suggest than syn-sedimentary growth continued after the main phase of fan deposition (<8.2 Ma). Furthermore, thick mudstone packages above the Isongo Fan indicate that local sandstone deposition subsequently shifted away from the study area, likely due to the topographic high. Thus, deposits within the Isongo Fan episode record sand-rich sedimentation and coeval incipient structural growth.

To better characterize changes in fan geomorphology over time, the following sections describe 4th and 5th order stratigraphic sequences constrained by: (1) petrophysical facies proportions; (2) wireline log data; (3) low resolution 3-D seismic (average of 18 Hz, maximum of 40-60 Hz); (4) biostratigraphic analysis; (5) chemostratigraphic analysis; and (6) dynamic production data (Figures 3.15 – 3.21). Sequences are described in the context of the AIGR stratigraphic matrix, which has previously been used to describe slope-to-basin changes in lithology, sedimentary bodies and stacking patterns. In this case, the AIGR model is extended to describe deposition
with respect to a growing structural high, which results in similar changes in gradient and confinement over a shorter longitudinal distance (Figure 3.22).

Strike-oriented cross sections presented in Figures 3.15 – 3.21 illustrate 4th and 5th order stratigraphic sequences that include:

- **4th Order Sequence 1** – interpreted to reflect a 4th order *initiation* phase within the Isongo Fan, comprised of three 5th order sequences (1.1, 1.2 and 1.3).

- **4th Order Sequence 3** – interpreted to reflect a 4th order *growth* phase within the Isongo Fan, comprised of six 5th order sequences (2.1, 2.2, 3.1, 3.2, 3.3 and 3.4).

- **4th Order Sequences 4 and 5** – interpreted to reflect 4th order *retreat* phases within the Isongo Fan, comprised of five 5th order sequences (4.1, 4.2, 4.3, 5.1 and 5.2).

Moreover, 5th order sequences are also characterized by initiation-growth-retreat patterns such that a two-fold stratigraphic hierarchy is created using the AIGR model in Figures 3.15 – 3.21. For example, 5th order Sequence 3.3 is characterized by significant sand-rich deposition across the field, which is a reflection of growth within a 5th order sequence superimposed on growth within a 4th order sequence. Likewise, the uppermost deposits of the Isongo Fan, Sequence 5.2, reflect updip deposition in the north and west, a result of retreat within a 5th order sequence superimposed upon retreat within a 4th order sequence. This approach provides context for describing depocenter migration over time.
with respect to multiple orders of cyclicity. It is important to note that unlike many other stratigraphic models, the AIGR model is not implicitly linked to forcing functions such as eustatic sea level, regional tectonism, salt withdrawal etc. (Vail et al., 1977; Mitchum and Van Wagoner, 1991; Prather et al., 1998). Rather, AIGR simply provides a framework to capture updip and downdip expressions of stratigraphic architecture at multiple temporal and spatial scales (Gardner et al., 2003; Gardner et al., 2008).

4.1 Adjustment Phase

The base of the Isongo Fan is characterized by an unconformity in the north and east that grades into conformable deposits in the south and west. Three-dimensional seismic data illustrates this relationship, shown in Figure 3.14 and Figures 3.15 – 3.21. This is likely due to erosion of older material on the crest of the Isongo anticline during adjustment and subsequent IGR phases. Seismic reflector continuity to the southwest suggests local slope adjustment centered on the Isongo structure rather than regional-scale deformation which would result in an unconformity throughout the entire study area.

In most wells, the adjustment surface is characterized by silt- or sand-rich deposits overlying clay-rich organic mudstones, petrophysical facies F. These mudstones, described in core from Well H (Figure 3.10), contain numerous mm- to cm-thick ash beds, very little bioturbation and wispy, thin sand laminae. Thus, they are interpreted to
represent dominantly pelagic deposition in a deepwater slope setting prior to the onset of sand-rich sedimentation at ~ 10.5 Ma.

The sharp lithologic contact between mudstones and overlying medium-grained sandstones in Well H is interpreted to reflect the base of the 3rd order Isongo Fan sequence. It is likely that this surface corresponds to mass transport deposits downdip, which may be: (1) unresolvable in the seismic dataset; or (2) located outside the study area. Other deepwater studies, however, suggest that MTDs are commonly associated with slope adjustment, e.g., Hadler-Jacobsen et al. (2005) and Gardner et al. (2008). Additionally, chaotic seismic patterns interpreted to be deposits of mass transport events are identified in younger deposits on the flanks of the Isongo anticline. Thus, the onset of growth may have produced smaller volume (unresolved) MTDs relative to deposits generated during continued uplift.

4.2 Initiation Phase

4th order Sequence 1 records initial downdip sedimentation coeval with early phases of structural uplift. Seismic reflectors onlap the adjustment surface in Figure 3.14, and suggest deposition off the southwestern flank of the growing anticline.
4.2.1 Fifth Order Sequences

5th order sequences within the 4th order initiation phase (1.1, 1.2 and 1.3) demonstrate development of a freely-migrating distributary channel-lobe system in the Lower Isongo. Depositional maps showing the geographic extent of each sequence are shown in Figure 3.23 and highlight the distribution of sand-rich packages.

Sequence 1.1, interpreted to reflect the onset of sand-rich sedimentation in the Isongo Fan, is characterized by deposition in east-west oriented distributary channelforms and lobeforms, parallel to the northern margin of the unconfined fan (Figure 3.23). Petrophysical facies and wireline log signatures in Well P, for example, demonstrate ~29 m of coarse-grained sediments that overlie organic-rich mudstones. Sedimentary bodies interpreted in this interval, shown in Figure 3.11, include a 45 ft (13 m) lobeform complex capped by a 52 ft (16 m) distributary channelform complex. To the west and south, these deposits are correlated to thin-bedded sandstones and mudstones, which likely record the distal extent of lobeform complexes.

Petrophysical facies proportions in Sequence 1.1 demonstrate an increase in coarse-grained deposits down-dip (Figure 3.24). Pebbly conglomerates and sandstones, petrophysical facies A and C, respectively, are preserved in the most distal wells (i.e., Well S), whereas fine-grained sandstones and mudstones characterize updip deposits. Sequence 1.1 is absent from wells within the confined portion of the Isongo Fan (Wells A-I), likely due to either: (1) sediment bypass through the northeast-southwest confined
channel system; or (2) a second sediment source located outside the study area, possibly to the northwest.

Sequences 1.2 and 1.3 record 5th order growth and retreat within a 4th order initiation phase. Depositional map patterns show a significant increase in the extent of sand-rich packages in Sequence 1.2, which suggests continued development and migration of the distributary channel-lobe complex over a much broader geographic area (Figure 3.23). Significant thinning and sand-poor sedimentation, however, indicate depositional retreat to the north during Sequence 1.3. Petrophysical facies proportions, shown in Figure 3.24, highlight the significant increase in sand distribution during growth followed by mudstone deposition during retreat.

4.3 Growth Phase

4th order Sequences 2 and 3 record stratigraphic growth and the broadest deposition of sandstone packages throughout the study area. Unlike phases of initial sedimentation recorded in Sequences 1, seismic reflectors in Sequences 2 and 3 do not appear to onlap the Isongo structure. Instead, thick sandstone packages in Sequence 3 record continued development of: (1) channel-levee complexes in the confined northeastern fan; and (2) migrating distributary channel-lobe complexes in the unconfined southwestern fan. The youngest deposits in Sequence 3 record initial backfilling of the incised slope channel system and subsequent ‘spilling’ along the
margins of the Isongo Fan. Thus, this sequence is interpreted to reflect minimum structural uplift and maximum deposition.

4.3.1 Fifth Order Sequences

While the onset of sedimentation in Sequences 1.1, 1.2 and 1.3 appears to be gradual, Sequences 2.1 and 2.2 are marked by a significant increase in sand-rich sedimentation over the study area. Sequence 2.1, interpreted to reflect 5th order growth, is characterized by the most distal deposition in the 4th order initiation phase and sand-rich deposition parallel to the Isongo Fan axis (Figure 3.25). Petrophysical facies and wireline log signatures suggest deposition of erosionally confined channelforms within the narrow northeastern Isongo Fan and distributary channelforms and lobeforms in the unconfined southwestern fan. Thus, Sequence 2.1 marks the earliest record of slope valley incision and establishment of the confined to unconfined fan geometry. The channel-lobe transition zone (CLTZ), interpreted from the distribution of sedimentary bodies identified in Sequence 2.1, is labeled in Figure 3.25 and is located on the southwestern flank of the Isongo structure.

Petrophysical facies proportions in Sequence 2.1 show very high net to gross patterns compared to 4th order initiation sequences (Figure 3.26). Furthermore, erosional slope channelforms, illustrated in cross sections B and C (Figures 3.16 and 3.17), have much greater proportions of petrophysical facies A (pebbly sandstones) than down-dip
distributary channel forms and lobeforms shown in cross sections E and F (Figures 3.19 and 3.20).

Sequence 2.2, interpreted as a 5th order retreat phase within the 4th order growth phase, is characterized by sand-poor deposits with a limited lateral extent, shown in Figure 3.25. Sedimentary bodies identified in Sequence 2.2 are dominately thin lobeform deposits (updip) and mudstone drape deposits (downdip). Thus, this sequence is interpreted to reflect a period of depositional and structural quiescence following a pulse of growth in Sequence 2.1.

Two subsequence 5th order phases of initiation are identified within the 4th order phase of growth, Sequences 3.1 and 3.2. Compared to older deposits of Sequences 1.1–2.2, depositional map patterns in these sequences show significantly broader areas of sedimentation and much higher net to gross values (Figures 3.25 and 3.26). In general, both sequences record distributary channel-lobe bodies deposited in the unconfined portion of the fan to the west and south. The absence of Sequences 3.1 and 3.2 in the confined upper fan is likely due to a combination of: (1) bypass through an active channel system; and (2) subsequent erosion during Sequence 3.3.

Petrophysical facies proportions in Sequences 3.1 and 3.2 demonstrate significant sandstone deposition (petrophysical facies C) and an increase in petrophysical facies diversity downdip. In other words, the entire petrophysical facies suite, from pebbly conglomerates to clay-rich mudstones, is present in interpreted lobeform deposits of the distal southwestern fan, highlighted in Figure 3.26.
Sequence 3.3 marks the broadest lateral extent and thickest deposition of sandstone packages in the 3rd order Isongo Fan system. As such, it is interpreted to reflect phases of growth in both 5th and 4th order sequences which correlate to the most basinward position of the Isongo depocenter (Figure 3.25). As its thickest point (Well F), Sequence 3.3 is characterized by 73 m of blocky sandstone packages deposited within a series of stacked, confined channel-levee complexes, shown in cross section B (Figure 3.16). Petrophysical facies proportions, as noted in Sequence 3.1 and 3.2, are sandstone-dominated and record a range of grain-size distributions (petrophysical facies A – F) (Figure 3.26).

The location of the CLTZ during Sequence 3.3, shown on Figure 3.25, correlates with the change from confined to unconfined fan morphology in the 3rd order Isongo Fan isochron. Moreover, the CLTZ appears to migrate approximately 2km to the northeast when compared to older deposits of the 4th order initiation phase (Figure 25). This suggests that growth within Sequence 3.3 marks the largest volume of sediment delivered to the Isongo Fan, which results in widespread deposition and backfilling of the system.

Stratigraphic growth in Sequence 3.3 is followed by 5th order retreat within the 4th order growth phase, Sequence 3.4, which records a decrease in net to gross, widespread mudstone deposition and depocenter migration to the northeast (Figures 3.25 and 3.26). Only one well demonstrates significant sandstone deposition (Well L), which likely reflects initial backfilling of the northeastern channel and a subsequent shift in deposition away from the sand-rich topographic high (Figure 3.18). For the most part, petrophysical facies in Sequence 3.4 record fine-grained sandstone and mudstone deposits, shown in
Figure 3.26, interpreted to reflect thin lobeform deposition, i.e., ‘depositional spilling’, in the northeastern fan.

**4.4 Retreat Phase**

The 4th order retreat phase, comprised of five 5th order sequences (4.1, 4.2, 4.3, 5.1 and 5.2) is characterized by a much thinner seismic expression and marks a shift in deposition from the southeast to the northwest portion of the Isongo Fan (Figure 3.14). Structural growth is minimal, which allows backfilling of topography generated during the 4th order growth phase by distributary channel and lobe systems throughout the study area.

**4.4.1 Fifth Order Sequences**

Sequence 4.1 marks the turnaround from 4th order growth and 5th order retreat (Sequence 3.4) to 4th order retreat and 5th order initiation (Sequence 4.1). As such, it is markedly sand-poor compared to sequences above and below and is characterized by mudstone deposition along the northern margin of the fan (Figure 3.27). Variable thickness within Sequence 4.1 is attributed to both: (1) infilling of depositional topography; and (2) subsequent minor erosion during Sequence 4.2. Petrophysical facies proportions suggest coarse-grained deposition updip and fine-grained sandstone and mudstone deposition downdip; however, intervals of Sequence 4.1 may be very thin such
that petrophysical facies proportions appear misleading, e.g., an abundance of petrophysical facies A in an interval of only 4m (Figure 3.28).

Sandstone deposition is more widespread in Sequence 4.2, interpreted as a 5th order growth phase within the 4th order retreat phase; however, it is still much thinner than sandstone packages in Sequence 3 (Figure 3.27). Isolated sands preserved in the northeastern and southwestern fan characterize distributary channel-lobe complexes oriented west-northwest. For example, wireline log trends from Wells S and T in cross section G show blocky patterns that measure >10 m-thick and are characterized by high proportions of petrophysical facies C (sandstone) (Figure 3.21). Likewise, a much higher proportion of petrophysical facies D and E (fine-grained sandstones and mudstones) suggest lobeform deposition in topographic lows.

A similar pattern of deposition characterizes 5th order retreat in Sequence 4.3, and thin sandstones deposited in the eastern and western portions of the fan are interpreted to reflect freely-migrating lobeform complexes (Figure 3.27). Widespread mudstone deposition, including petrophysical facies F (clay-rich mudstone), suggests a period of quiescence prior to the final phase of retreat (Sequences 5.1 and 5.2) (Figure 3.28). Downdip proportions of petrophysical facies also show an increase in facies B, cohesive debris flow deposits, which suggest deposition in off-axis lobeforms, i.e., distal or marginal lobeform deposits.

Two final phases of sedimentation within the 4th order retreat phase are characterized by sand-rich deposition that appears to migrate north from the 3rd order Isongo Fan isochron (Figure 3.27). Sequences 5.1 and 5.2 demonstrate relatively thick
sandstone packages correlative over a distance of ~7 km by 16 km, oriented west-northwest. Distributary channel-lobe complexes within these sequences are characterized by: (1) blocky wireline log patterns; (2) high proportions of petrophysical facies C (sandstones); and (3) a wide diversity of petrophysical facies.

Sequences 5.1 and 5.2 are interpreted to reflect the final phase of sand-rich sedimentation in the Upper Isongo, which resulted in the creation of topographic highs. Combined with another pulse of structural uplift, this likely resulted in the avulsion of younger sediments away from the anticline, possibly to the northwest.

5. SYN-SEDIMENTARY GROWTH IN THE ISONGO FAN

Sedimentation in the deepwater Isongo Fan records the onset of structural growth in the study area, likely linked to regional tectonic deformation in the southeastern Niger Delta. Similar studies by Adeogba et al. (2005) and Heiniö and Davies (2007) describe this phenomenon in the western delta, where uplift is controlled by shale diapirism and normal faulting; however, in this case, local anticline development is driven by eastward outbuilding of the delta against the backstop of the Cameroon Volcanic Line (CVL). Like these studies, local gradient changes generated during uplift impact: (1) sedimentary body distributions; (2) stacking patterns; and (3) stratigraphic architecture.

The 2.3 million year episode of sedimentation in the 3rd order fan records a cycle of syn-sedimentary growth followed by depositional backfilling during a period of structural quiescence. Thus, the sand-rich Isongo Fan is a transient feature developed in
response to incipient uplift on the continental slope. Continued anticlinal development following fan deposition ultimately resulted in a shift in deposition away from the study area, likely to the northwest. Seismic packages that thin away from the anticline suggest that growth continued throughout the Late Miocene and into the Pliocene (Figure 3.14).

Within the 3rd order fan, 4th and 5th order sequences record changes in fan geomorphology in response to penecontemporaneous growth and deposition. The 4th order phases of adjustment and initiation, which include 5th order sequences 1.1, 1.2 and 1.3, are interpreted to record the largest amount of structural growth. Slope adjustment is characterized by an unconformity on the crest of the anticline, which suggests erosion and removal of material due to uplift. Initiation packages onlap the southwestern flank of the anticline and mark the onset of deposition within the 3rd order fan.

The oldest deposits of the 4th order growth phase, i.e., Sequences 2.1 and 2.2, record a gradual decrease in structural growth and development of the confined to unconfined pattern of sand-rich sedimentation that characterizes the 3rd order Isongo Fan isochron. Establishment of updip channel-levee systems and downdip distributary channel-lobe systems marks the turnaround from 4th order initiation to 4th order growth, and the channel-lobe transition zone is located off the southwestern flank of the structure.

Whereas structural growth is greatest in the 4th order adjustment and initiation phases, stratigraphic growth is greatest in the 4th order growth phase of the AIGR model (Sequences 2.1, 2.2, 3.1, 3.2, 3.3 and 3.4). Establishment of a through-going channel system in the northeastern confined portion of the fan and freely migrating distributary channel-lobe complexes in the southwest suggest that structural growth during this time
was minimal. Very high net to gross and widespread deposition characterize 4th order growth phases. Moreover, northeastern migration of the CLTZ and thick, erosionally confined channelform complexes in Sequence 3.3 suggest widespread sandstone deposition during a phase of 4th and 5th order stratigraphic growth.

Structural quiescence marks the end of the 4th order growth phase and the turnaround to stratigraphic retreat in Sequences 4.1, 4.2, 4.3, 5.1 and 5.2. Widespread mudstone deposition and freely-migrating distributary channel-lobe systems suggest infilling of topography generated during earlier stratigraphic phases and migration of the Isongo Fan depocenter to the north.

5.5 The AIGR Model

In addition to describing slope-to-basin variations in gradient, confinement and resulting sedimentary body distributions (i.e., Gardner et al., 2003; Gardner et al., 2008), the AIGR stratigraphic model may be used to characterize phases of sedimentation due to syn-sedimentary structural growth (Wolak and Gardner, 2009). Application of the AIGR model to the Isongo transient fan system provides a framework to investigate depocenter migration relative to the growing anticline.
6. SUMMARY AND CONCLUSIONS

With respect to structural deformation in the southeastern Niger Delta, the Late Miocene Isongo Formation records development of a transient, sand-rich fan system during incipient anticlinal growth. The onset of sedimentation at approximately 10.5 Ma marks the base of a 2.3 million year episode of coarse-grained deposition, the 3rd order Isongo Fan sequence, which persists until 8.2 Ma. Integration of conventional cores, wireline logs, 3D seismic, biostratigraphy, chemostratigraphy and dynamic data allow correlation of five 4th order sequences and thirteen 5th order sequences across the study area. Key conclusions are summarized below:

1. The 3rd order Isongo Fan is characterized by a narrow, confined northeastern portion that thickens and widens to the southwest, parallel to the axis of a growing anticlinal structure. Sedimentation in the Isongo Fan records incipient structural growth; renewed growth after Isongo deposition resulted in depocenter migration away from the study area, likely to the northwest.

2. Core-calibrated sedimentary bodies within the Isongo Fan demonstrate a change from confined channel-levee complexes in the northeast to unconfined distributary channel-lobe complexes in the south and west. Six core-defined petrophysical facies allow identification of dominant depositional processes in uncored intervals, and petrophysical facies, individual log signatures and
thicknesses provide criteria for identification of sedimentary bodies throughout the Isongo Fan system.

3. Fan geomorphology is evident in correlations of 4th and 5th order stratigraphic sequences, which may be described using the AIGR model of Gardner et al. (2003) and Gardner et al. (2008). Patterns of initiation, growth and retreat are identified and characterized by changes in depocenter migration, sedimentary body distribution and petrophysical facies proportions.

4. The greatest amount of coeval structural growth and sedimentation is recorded in 4th order adjustment and initiation phases within the Isongo Fan, which are characterized by unconformity development and seismic onlap onto the growing anticline. Stratigraphic growth, however, is greatest in the 4th order growth phase, during which uplift is minimal and sand-rich deposition is highest. During this period, erosional slope channel-levee complexes are well-developed in the northeast and correlate to distributary channel-lobe complexes in the southwest. The final phase of growth is marked by backfilling of the channel system, followed by stratigraphic retreat and migration of the depocenter to the north.

These conclusions imply that the onset of structural growth may be marked by significant coarse-grained deposition, which seems counterintuitive. Incipient uplift is related to gradient changes that result in the establishment of confined-to-unconfined fan
architecture, a key control on sand-rich sedimentation. Ultimately, continued growth causes deposition to shift away from the topographic high (post-Isongo Fan), but not before creation of a sandy transient fan system.
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REFERENCES


Figure 3.1. Location of the study area in the southeastern Niger Delta, adjacent to the Cameroon Volcanic Line and within the Cross River - Principe Channel drainage system. Major tectonic provinces and depobelts of the delta are modified after Heinio et al. (2007), Hooper et al. (2002) and Armentrout et al. (2000). The transient Isongo Fan (Box 1, inset) is located on the continental slope, approximately 400 km updip of the Calabar basin floor fan. Four major oceanic transform faults bisect the West African margin and are projected onto the African Craton (Meyers et al., 1996).
Figure 3.2. Location of wells within the study area. (A) is an isochron map of the Isongo Formation showing the fan-shaped amplitude pattern. Thickening of sand deposits to the southwest is correlative to local anticline development, illustrated in (B). Cross sections presented in this study highlight on-axis to off-axis sedimentation associated with coeval structural growth.
Figure 3.3. Regional stratigraphy of the Niger Delta after Corredor et al. (2005) and Lawrence et al. (2002). The Isongo Formation, located off the southeastern toe of the Niger Delta is age-equivalent to the Late Miocene Agbada Formation.
Figure 3.4. Global sea level and climate proxies for the Cenozoic. Biostratigraphic ages for the Isongo Formation suggest deposition between 8.2-10.6 Ma (shaded red box) during a Late Miocene eustatic sea level fall (Haq et al., 1987; Miller et al., 2005).
Figure 3.5. Timing of volcanism and uplift of the Cameroon Volcanic Line (modified after Deruelle et al., 2007). Ar-Ar dating of volcanic rocks from Mount Cameroon demonstrate ages of 4-12 Ma (shaded blue box), coincident with biostratigraphic ages of sedimentation in the Isongo Formation (8.2 - 10.5 Ma) (shaded red box).
Figure 3.6. Process-based petrophysical facies tracts in the Isongo Formation. Five petrophysical facies (PF) are identified and ordered from highest energy, PF A, to lowest energy, PF F. Petrophysical facies A, C, D and E record high-to-low density sediment flow processes, while PF B reflects cohesive (mud-rich) debris flow processes. PF F, clay-rich mudstone, records pelagic deposition during periods of quiescence.
Figure 3.7. Stratigraphic correlation demonstrating a significant increase in net-to-gross from the confined upper Isongo Fan (well G) to the unconfined lower Isongo Fan (well Q) over a distance of 5.2 km. Conventional cores from wells G and Q record the same stratigraphic interval, i.e., 5th order sequence 5.1, shown in detail in Figure Y.
Figure 3.8. Correlation of sedimentation units and facies assemblages in cores recovered from the same stratigraphic interval in the Upper Isongo. Sedimentation units in Well G (updip) and Well Q (downdip) can be correlated over a distance of 5.2 km.
Well K: Core to wireline log calibration and location within the Isongo Fan amplitude suggest deposition on the margin of an erosionally-confined channel form complex.

Location within the Isongo Fan Seismic Amplitude

Figure 3.9. Core to wireline log calibration for confined channel complexes located in the narrow northeastern portion of the Isongo Fan. Channel forms are characterized by a high proportion of petrofacies A (conglomerates) and petrofacies C (sandstones).
Well H: Core to wireline log calibration and location within the Isongo Fan amplitude suggest overbank levee deposition adjacent to confined channel forms such as those shown in Well K (previous figure). The cored interval at the base of Well H is characterized by organic-rich claystone, which forms the base of the incised Isongo Formation.

Mass transport deposit comprised of slumped levee beds.

Process-Based Petrophysical Facies Explanation
- Sediment Density Flows
  - Petrophysical Facies A
  - Petrophysical Facies C
  - Petrophysical Facies D
  - Petrophysical Facies F
- Cohesive Debris Flows
  - Petrophysical Facies B
- Pelagic Deposits
- Petrophysical Facies F

Location within the Isongo Fan Seismic Amplitude

Figure 3.10. Core to wireline log calibration for overbank deposits located in the upper fan.
Well P: Core to wireline log calibration, high net to gross, and location within the Isongo Fan amplitude suggest deposition in distributary channel forms and lobe complexes which migrate in response to evolving seafloor topography.

Figure 3.11. Core to wireline log calibration for distributary channels in the mid-Isongo Fan.
Well P: Core to wireline log calibration, high net to gross, and location within the Isongo Fan amplitude suggest deposition in distributary channel forms and lobe forms which migrate in response to evolving seafloor topography.

Figure 3.12. Core to wireline log calibration for lobeform deposits in the mid-Isongo Fan.
Figure 2.13. Build-cut-fill-spill (BCFS) model of submarine channel-lobe deposition (after Gardner et al., 2003). Developed to describe migration of the channel-lobe transition zone (CLTZ) in the Brushy Canyon Formation of West Texas, the BCFS relates facies proportions to three-dimensional sedimentary bodies, which are a reflection of changes in confinement and gradient over time (Gardner and Borer, 2000; Gardner et al., 2008).
Figure 3.14. Structural down-plunge cross section oriented along depositional dip. Upper diagram illustrates the 2.3 million year (3rd order) sand-rich Isongo Fan interval; lower diagram, 4th order phases of adjustment, initiation, growth and retreat. Approximate locations of cross sections A-G are labelled and shown in Figures 15-21.
Chemostratigraphy in Wells A and C demonstrate a change in composition between 4th order growth and retreat phases.

This suggests backfilling of a 50 m-thick confined channel complex during 4th order retreat.

Dynamic data show a pressure break between 4th order growth and retreat phases due to widespread mudstone deposition.

Figure 3.15. Cross Section A-A’
Dynamic data demonstrate pressure breaks at the base of the 3rd order Isongo Fan and between 4th order growth and retreat phases. Both are due to widespread mudstone deposition characterized by extensive continuous drapes (petrophysical facies F).

Figure 3.16. Cross Section B-B'
Increasing ash bed preservation down-dip compared to cross sections A-A’ and B-B’. Ash beds in well H characterize 5th order initiation on 4th order growth (Sequence 3.2); ash beds in well I characterize 5th order retreat on 5th order retreat (Sequence 5.2).

Confined channel complexes in Sequences 1.2 and 2.1 characterized by pebble conglomerates (petrophysical facies A in red) and 91 m-thick coarsening-upward gamma ray log trend.

Cored interval of the base of the 3rd order Isongo Fan episode and 5th order sequences 3.1, 3.2 and 3.3. Older sequences are eroded. Basal mudstone-sandstone contact shown in Figure 9 and characterized by coarse- to medium grained sandstones (petrophysical facies C) overlying organic-rich dark gray mudstones (petrophysical facies F).

Cored interval of Sequences 4.3 and 5.1. Sedimentation units are correlated to Well Q down-dip in Figures 7 and 8.

CROSS SECTION C-C’

Cross Section Scale
Vertical Exaggeration = 10x

Seismic Scale
500 s

Figure 3.17. Cross Section C-C’
Cored interval in Well K characterized by a 31 m-thick coarse-grained sandstone package (petrophysical facies A and C), located on the margin of an erosionally-confined slope channel complex. Well L, 1.23 km west along strike, is characterized by very thick sandstone packages that measure 11 - 49 m, interpreted to be within the axis of the channel complex.

Increasing preservation of 4th order initiation phases (Sequences 1.1, 1.2, 2.1 and 2.3) down-dip, which onlap the growing structure.

Figure 3.18. Cross Section D-D’
Well-developed slope channel-levee complexes in 4th order Sequence 3 are characterized by: (1) thick, coarsening-upward gamma ray signatures and petrophysical facies A and C (i.e., channels); and (2) thin, serrated gamma ray signatures and petrophysical facies C, D and E (i.e., levees). See Figures 9 and 10 for core descriptions of these features.

4th order sequences demonstrate an overall migration from older deposits in the southeast (Sequences 1.1, 1.2, 2.1 and 2.2) to younger deposits in the northwest (Sequences 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 5.1 and 5.2)

Figure 3.19. Cross Section E-E'
Cored intervals within Wells P and Q characterize distributary channel-lobe complexes shown in Figures 11 and 12. Compared to erosional slope channel-levee complexes updip, these complexes demonstrate blocky gamma ray log signatures and thick (>35 m-thick) sandstone packages (petrophysical facies C).

**Figure 3.20. Cross Section F-F’**
Figure 3.20 (continued). Cross Section F-F'

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Chemostrat Pkg 3
Figure 3.21. Cross Section G-G'.

Vertical Exaggeration = 10x

Cross Section Scale

km | 0  | 1  | 2
50 m | - | - | -
Figure 3.21 (continued). Cross Section G-G’.
Figure 3.22. Adjustment-initiation-growth-retreat (AIGR) model of sedimentary architecture (after Gardner et al., 2008). Although originally developed to describe depocenter migration in slope-to-basin settings, i.e., the Permian Brushy Canyon Formation of West Texas, the AIGR model may also be applied to inter-slope settings undergoing active deformation such as the 3rd order transient Isongo Fan.
Figure 3.23. 5th order sequence maps illustrating 4th order initiation phases superimposed on the Isongo Fan seismic isochron. Dashed red lines show depositional limits interpreted from 3D seismic and wireline log data; shaded yellow areas highlight sand-rich deposition within each sequence.
Figure 3.24. Longitudinal distribution of petrophysical facies for 4th order fan initiation and growth sequences.
Figure 3.25. 5th order sequence maps illustrating 4th order growth phases superimposed on the Isongo Fan seismic isochron. Dashed red lines show depositional limits interpreted from 3D seismic and wireline log data; shaded yellow areas highlight sand-rich deposition within each sequence.
Figure 3.26. Longitudinal distribution of petrophysical facies for 4th order fan growth sequences.
Figure 3.27. 5th order sequence maps illustrating 4th order retreat phases superimposed on the Isongo Fan seismic isochron. Dashed red lines show depositional limits interpreted from 3D seismic and wireline log data; shaded yellow areas highlight sand-rich deposition within each sequence.
Figure 3.28. Longitudinal distribution of petrophysical facies for 4th order fan retreat sequences.
GENERAL CONCLUSION

The two manuscripts presented in this dissertation demonstrate the importance of syn-sedimentary structural growth on controlling transient submarine fan development in the southeastern Niger Delta. The sedimentary response to growth is shown over a range of temporal and spatial scales, from very small-scale changes in pore space and connectivity to large-scale changes in stratigraphic architecture over the 100 km² study area. Results from the two studies presented herein are summarized below.

- Coarse-grained clastic rocks in the Isongo Fan record deepwater deposition from 10.5 – 8.2 Ma. Sedimentological descriptions of more than 1,200 ft. of conventional core define fifteen process-based facies, which may be organized from interpreted highest-to-lowest energy hydrodynamic conditions. The coarsest deposits, pebble conglomerates, are comprised of siderite pebbles in a coarse sandstone matrix, likely derived from the CO₂-rich Cameroon Volcanic Line. Clay-rich mudstone deposits, the lowest energy facies, are interpreted to record dominately pelagic fallout during periods of quiescence.

- Pore space and pore connectivity in process-based facies of the Isongo Formation are correlated to primary depositional process. Secondary effects on reservoir properties are shown to be negligible. In general, porosity correlates to mean grain size; permeability, grain size sorting. Thus, the highest mean porosity values are
observed in deposits of turbulent low-density subaqueous flows, likely due to hydraulic fractionation of finer particles resulting in better sorting (less clay content) and looser grain packing. Deposits of cohesive debris flows, while undersampled in this dataset, show wider ranges of porosity and permeability, a reflection of variable clay content and sorting.

- Sedimentation units and facies assemblages record the longitudinal structure of a flow as it passes over a single point. Within the Isongo Formation, unusually thick sedimentation units (> 10.0 ft, > 3.0 m) suggest very large events, likely linked to eruptive activity of Mount Cameroon located 75 km updip. Patterns of flow steadiness and uniformity are used to characterize ten facies assemblages across the Isongo Fan, from confined (accumulative) flow updip to unconfined (depletive) flow downdip.

- Likewise, sedimentary bodies and facies associations record time-averaged processes that operate to construct three-dimensional geometries such as channeliforms, lobeforms, wedgeforms (levees), drapes and mass transport deposits. In the Isongo Formation, porosity and permeability distributions correlate to nine facies associations. For example, the highest porosities and permeabilities are recorded in distributary channelform and lobeform deposits, whereas the lowest values are observed in clay-rich mudstone drape deposits. Porosity and permeability distributions for each body type are a reflection of
dominant deepwater processes, i.e., turbulent vs. non-turbulent, and flow steadiness and uniformity.

- Correlation of sedimentation units between two cores from the same stratigraphic interval in the Upper Isongo Formation demonstrate that events are correlative over at least 5.2 km. The most common pattern of flow steadiness and uniformity in this interval is depletive waning flow and sedimentation units show a general increase in thickness downdip.

- To identify process-based facies and sedimentation units in uncored intervals, six petrophysical facies were defined based on a suite of four wireline log signatures, including gamma ray (GR), resistivity (RES), density (RHOB) and sonic compression (DTS). Compared to similar methods of petrophysical facies analysis, this approach has a slightly lower confidence (65% compared to 75-92%) but is able to distinguish between six petrophysical facies (compared to four) (Sullivan et al., 2003).

- Petrophysical calibration and wireline log analysis demonstrate distinctly different architectural styles from the confined, northwestern Isongo Fan to the unconfined, southeastern fan. Updip, erosionally-confined slope channelforms and levee bodies are characterized by high proportions of coarse-grained petrophysical facies and thin-bedded sandstones and mudstones, respectively. Downdip,
distributary channelform and lobeform deposits demonstrate blocky sandstone packages correlative across 5-10 km distances.

- To characterize changing fan geomorphology within a 2.3 million year period during the Late Miocene, fourth and fifth order stratigraphic sequences are correlated throughout the study area. Fourth order sequences best record phases of slope adjustment, followed by fan initiation, growth and retreat. Integration of three-dimensional seismic imaging (maximum 40-60 Hz), chemostratigraphy, biostratigraphy, petrophysical calibration and sedimentological analysis establish five 4th order sequences and fourteen 5th order sequences.

- Syn-sedimentary growth in the Isongo Fan is suggested by onlap of older sandstone packages onto the growing anticline. Erosional slope channelforms incised on the crest of the structure suggest an increased gradient and knickpoint migration updip, similar to that shown by Heiniö and Davies (2007). Distributary channelforms and lobeforms on the southwestern flank of the structure record the change from confined to unconfined architecture, ultimately due to local structural growth. Renewed uplift following the Isongo Fan deposition resulted in avulsion of the system away from the study area, likely to the northwest.

This approach emphasizes the integration of subsurface data at a variety of scales to construct a sedimentary hierarchy and answer fundamental questions about the nature
of coeval sedimentation and structural growth on the continental slope. Whereas previous studies have focused on growth due to shale diapirism and normal faulting in the Niger Delta (e.g., Adeogba et al., 2005; Heiniö and Davies, 2007), this study examines growth in the outer fold and thrust belt against the backstop of the Cameroon Volcanic Line. As such, it provides a critical step in linking sand-rich sedimentation to regional tectonism in equatorial West Africa during the Late Miocene.
REFERENCES CITED


