HIGH RESOLUTION, MILLENNIAL-SCALE PATTERNS OF BED COMPENSATION ON A SAND-RICH INTRASLOPE SUBMARINE FAN, WESTERN NIGER DELTA SLOPE

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ABSTRACT

Near-seafloor core and seismic-reflection data from the western Niger Delta continental slope document the facies, architecture, and evolution of submarine channel and intraslope submarine fan deposits. The submarine channel enters an 8 km long x 8 km wide intraslope basin, where more than 100 m of deposits form an intraslope submarine fan. Lobe deposits in the intraslope submarine fan show no significant downslope trend in sand presence or grain size, indicating that flows were bypassing sediment through the basin. This unique dataset indicates that intraslope lobe deposits may have more sand-rich facies near lobe edges than predicted by traditional lobe facies models, and that thickness patterns in intraslope submarine fans do not necessarily correlate with sand presence and/or quality.

Core and radiocarbon age data indicate that sand beds progressively stack southward during the late Pleistocene, resulting in the compensation of at least two lobe elements. The youngest lobe element is well characterized by core data and is sand-rich, ~ 2 km wide x 6 km long, > 1 m thick, and was deposited rapidly over ca. 4,000 yr, from 18-14 ka. Sand beds
forming an earlier lobe element were deposited on the northern part of the fan from ca. 25 to 18 ka. Seafloor geomorphology and amplitudes from seismic reflection data confirm the location and age of these two compensating lobe elements. A third compensation event would have shifted sand deposition back to the northern part of the fan, but sediment supply was interrupted by rapid sea level rise during Meltwater Pulse 1-A at ca. 14 ka, resulting in abandonment of the depositional system.

INTRODUCTION

Sand-rich bodies accumulating in unconfined submarine depositional environments are referred to generically as ‘lobes’ (e.g., Deptuck et al., 2008). The progressive stacking of lobes and channels builds submarine fans (Normark, 1970), which are volumetrically the largest sediment accumulations on Earth (Covault, 2011) and host vast hydrocarbon reserves (Piper and Normark, 2001). The traditional facies model for submarine lobe deposits is based on observations from the modern seafloor (Normark, 1970), outcrops of lobe deposits (Bouma, 1962; Mutti and Ricci-Lucchi, 1972; Walker, 1978; Mutti and Normark, 1987; Smith, 1987), and flume tank experiments (Luthi, 1981; Parsons et al., 2002; Cantelli et al., 2011; Fernandez et al., 2014). These observations indicate that lobes display a downstream and axis to off-axis decrease in thickness, grain size, sand content, and sand bed amalgamation. This model has been validated with the acquisition of high-resolution seismic reflection and core data (e.g., Deptuck et al., 2008; Jegou et al., 2008).

This facies model, however, was derived from terminal lobes on basin floors with smooth bathymetric profiles. Variations to this facies model have been considered in areas where complex slope and seafloor morphology were present (Mutti and Normark, 1987; Piper and Normark, 2001; Smith, 2004). Complex slope morphology due to tectonics or mobile substrates can result in lobe deposition in areas of intraslope accommodation (Prather et al., 1998; Adeogba et al., 2005; Sylvester et al., 2015). Lobe deposition in intraslope settings has been well documented with seismic reflection data (Pirmez et al., 2000; Adeogba et al., 2005; Prelat et al., 2010; Pirmez et al., 2012; Prather et al., 2012a, 2012b; Sylvester et al., 2012), but few examples have lithologic (i.e., core) and/or age calibration. Using three-dimensional (3D) seismic data and
35 piston cores with radiocarbon ages, this study documents the facies, architecture, and millennial-scale bed compensation patterns of intraslope lobe deposits on the western Niger Delta continental slope (Fig. 1).

Terminology and hierarchy of depositional elements

Lobe deposits are hierarchical due to compensational stacking, and this study follows the hierarchy developed by Prelat et al (2010). In order of increasing dimensions and complexity, the hierarchy consists of beds/bedsets, lobe elements, lobes, and lobe complexes (Prelat et al., 2010). Beds are deposited by turbidity currents and have internal sedimentary structures (e.g., Bouma or Lowe divisions; Bouma, 1962; Lowe, 1982). Beds and bedsets stack to form lobe elements, which are generally a few meters thick and kilometers in length and width (Prelat et al., 2010). One or more lobe elements stack to form a lobe, which is fed by a single channel. Avulsion or significant migration of the channel creates a new lobe, and thus a lobe complex (Prelat et al., 2010). This terminology has typically been used to describe base-of-slope lobe deposits. Various other terms have arisen to describe intraslope lobe deposits: ‘transient fan’ (Adeogba et al., 2005), ‘intraslope lobe’ (Flint et al., 2011) and ‘perched slope apron’ (Prather et al., 2012a). We will use the term ‘intraslope submarine fan’ to avoid confusion between lobe dimensions and stacking patterns and the more general term ‘fan’ (Normark, 1970), with the understanding that lobe deposits that compose an intraslope submarine fan may have different morphology and facies architecture due to their intraslope setting.

Dataset and Methods

Approximately 100 km² of 3D seismic reflection data were interpreted for this study (Figs. 1, 2). The 3D survey is pre-stack time-migrated, 90 degree phase rotated (quadrature), with a bin spacing (i.e., horizontal resolution) of 12.5 m (x) x 18.75 m (y). The dominant frequency is 60 Hertz, resulting in a vertical resolution, or tuning thickness, of ~ 8.3 m. All reported thicknesses were converted from time to depth using a compressional velocity of 2,000 m/s, characteristic of shallowly buried deep-marine sediments (e.g., Flood et al., 1997). Thirty-
five piston cores were collected in the study area (Fig. 2) with an average length and recovery of 4.4 m and 72%, respectively. Figures DR1 and DR2 show detailed core descriptions, photos, x-rays, radiocarbon ages, and more than 100 grain-size samples analyzed using a Malvern Mastersizer 2000 particle size analyzer. In order to attain radiocarbon ages, samples were taken from 6 cm thick muddy intervals in the cores and trimmed to avoid contamination from core edges. These samples were wet-sieved and the residue was picked to obtain ~10 mg of the near-surface dwelling planktonic foraminifera Globigerinoides ruber. Picked foram samples were pulse-sonicated in methanol to remove clays trapped inside the shell and then analyzed at the Center for Accelerated Mass Spectrometry at the Lawrence Livermore National Laboratory. The ages were calibrated and reservoir corrected using Calib 7.0 (Stuiver et al., 2005) and the MARINE13 calibration dataset (Reimer et al., 2009). A standard 400 yr marine reservoir age was applied to all ages, as no local refinements are available. All quoted ages are given in years before present (see Table DR1 [ see footnote 1]).

**NIGER DELTA**

**Modern Niger Delta**

The Niger delta is one of the largest sediment accumulations in the world (~140,000 km² and 12 km thick) and is a prolific hydrocarbon province (Allen, 1964, 1965; Evamy et al., 1978; Doust and Omatsola, 1989). The Niger River has a large but semi-arid drainage area of 1.2 x 10⁶ km², providing the delta with an annually averaged discharge of 6,140 m³/s and sediment load of 1,270 kg/s (Muld µ and Syvitski, 1995). Rapid Neogene sedimentation and associated progradation created gravity-induced tectonism that has resulted in significant intraslope accommodation (Damuth, 1994). The study area is located in ~1200 m water depth on the continental slope of the western Niger delta, where shale diapirs and ridges are common features that create intraslope accommodation (Fig. 1).

**X channel and intraslope submarine fan**
Pirmez et al. (2000) first studied the modern turbidite depositional systems in the study area, identifying the X, Y and Y’ channels (Fig. 2). The X and Y’ channels are tributaries to the Y channel (Fig. 2). Seafloor bathymetry and core data were used as inputs for a 3D numerical model that simulated turbidity currents for the Y channel (Abd El-Gawad et al., 2012a) and X channel (Abd El-Gawad et al., 2012b). The Y channel shows distinct temporal changes in stratigraphic architecture related to variations in sediment supply and tributary activity (Jobe et al., 2015). This study focuses on the X channel, which flows southwest for ~ 80 km from the shelf edge and crosses a complex slope profile (Fig. 2; Fig. 4 of Prather et al., 2012a). The X channel terminates at ~1,200 m water depth at an abrupt decrease in slope caused by shale diapirism that creates an intraslope basin (Fig. 2; Pirmez et al., 2000; Prather et al., 2012a). The intraslope submarine fan occupying this intraslope basin (hereafter the X fan) has high seafloor amplitudes and a roughly circular shape with a diameter of ~ 8 km and an area of 76 km² (Fig. 2C). The deposits of the X fan are more than 100 m thick, and Prather et al. (2012a) subdivide the fill of the X fan into two units (Fig. 3). A core on the muddy edge of the X fan has been the focus of a West African paleoclimate study by Parker et al. (2016). Moving downslope from the X channel terminus and onto the X fan, seismic reflection character becomes increasingly continuous (Fig. 3C). Increasing slope gradient at the distal edge of the X fan causes the formation of multiple knickpoints that coalesce into a steep, short channel segment that then joins the Y channel (Fig. 2C). The presence of this ‘exit’ channel and a sharp decrease in seismic amplitude indicate that flows are bypassing the X fan and eroding its distal edge (Figs. 2C, 3C).

X CHANNEL FACIES AND ARCHITECTURE

The X channel has an average width of ~ 360 m (calculated from cross sections taken every 500 m along the channel reach), low sinuosity (1.25), and dominant meander half wavelengths of 1-2 km, although a few tight bends are evident (Fig. 2). Piston cores were taken in the X channel about 20 km upstream of its terminus (Figs. 2B and 4; Fig. DR1 [see footnote 1]). High seafloor seismic amplitudes suggest sand deposition in the thalweg and near-channel overbank areas (Fig. 2B). Piston cores recovered sand, gravel (up to 5 mm in diameter), and chaotic muddy units in the thalweg of the X channel and interbedded sand and mud deposits in the overbank areas (Fig. 5). Sand deposition occurred from at least 19 ka until ca. 14 ka, and an
overlying Holocene muddy drape characterizes the upper 3-4 m of every core (Figs. 4, 5). The X channel was probably active before 19 ka, but shallow core penetration does not allow characterization and dating of older channel-related deposits (Fig. 5B). Sand beds are thicker (average 5.4 cm) in the X channel thalweg than in overbank areas (average 3.1 cm; Fig. 4). Visual core descriptions indicate that the thicker thalweg sand beds are also coarser grained, with one bed having granules 5 mm in diameter (inset photo in Fig. 4B). Grain size analyses from a laser particle size analyzer (histograms in Fig. 4) confirm this trend, with average D_{10}/D_{50}/D_{90} values in the thalweg cores of 62/175/315 μm vs. 77/129/216 μm in the overbank cores. Thick T_{abc} sand beds show normal grading and an improvement in sorting from base to top (Fig. 4), suggesting deposition from turbidity currents (Bouma, 1962; Lowe, 1982). A muddy, ~1 m thick muddy unit with sheared fabric and discontinuous silty laminae (Fig. 4B, core Bend 4) suggests deposition by mass failure. A radiocarbon age in this mass transport deposit (MTD; Fig. 4B) is older than 50 ka, suggesting this unit was derived from older sediments, perhaps a nearby bank collapse or updip slope failure.

The overbank areas on the outer and inner bends of the X channel have very different architecture (Fig. 5). The levee on the outer bank thins and dims away from the X channel on seismic data (Fig. 5B), and cores show sand-bed thinning (e.g., cores Bend 2 to Bend 7, Fig. 5A), consistent with observations of other external levees (Hansen et al., 2015). The deposition rate for the distal part of the outer levee is 67 cm/k.y. (core Bend 5, Fig. 4A); proximal levee deposition rates are likely much higher (e.g., core Bend 2), but poor core recovery prevented sampling. The overbank area on the inner bend of the X channel (Fig. 5B) does not display levee morphology, but rather is a low elevation terrace, likely caused by lateral migration of the X channel (Fig. 5A, B; cf. Babonneau et al., 2010; Maier et al., 2012; Hansen et al., 2015). Low seismic resolution prevents detailed imaging of the internal architecture of the terrace, but core data (core Bend 6 in Fig. 5A) indicate a sand-rich environment. The lower elevation of the inner-bend terrace as compared to the outer-bend levee allowed for more than 2 m of amalgamated sand beds to be deposited (core Bend 6 in Figs. 4C, 5A). Radiocarbon age correlations indicate that sand deposition on the inner levee terrace was concurrent with outer levee sand deposition and emplacement of intra-thalweg sand, gravel, and MTDs (Fig. 5A).
INTRASLOPE SUBMARINE FAN ARCHITECTURE

Seafloor morphology

The X channel terminates into an intraslope basin that contains a 8 km x 8 km x 120 m thick sediment body termed the X intraslope submarine fan (X fan; Fig. 2C). Bathymetric cross sections spaced every 500 m (Fig. 6) and three seismic cross sections (Fig. 3D) show mounding of the proximal area of the X fan (near the channel mouth), while the distal area is relatively flat. The proximal mounding is roughly symmetrical and emanates from the X channel terminus (Figs. 6, 7A). Slope gradients on the X fan are low (Fig. 7A; average gradient 1.4°, 82% of values are < 2°). The mouth of the X channel has sediment waves (Fig. 17 of Prather et al., 2012a) and the northern levee continues onto the X fan as a ridge that curves and tapers to the south (Fig. 7A). Slope gradient (i.e., dip magnitude) and aspect (i.e., dip azimuth) maps (Fig. 7) clearly delineate this ridge and show the continuity from the X channel to the southern part of the X fan. Immediately downstream of the termination of the ridge there are two large (up to 1000 m long) scours, the larger of which is cored (core Fan 11, Figs. 7A and 8). This seafloor morphology suggests that the most recent flows exiting the X channel were directed onto the southern portion of the X fan, and the aspect map (Fig. 7B) reveals a 2 km x 6 km lobate feature emanating from the X channel. In contrast, the northern part of the X fan is underfilled (left side of Fig. 6) and consequently has lower seafloor amplitudes (Fig. 2C). The presence of sediment waves suggests deposition from alternating segments of supercritical and subcritical flow, with hydraulic jumps in between (cf. Covault et al., 2014.). The sediment waves are developed close to the channel mouth where the supercritical channelized flow becomes subcritical due to the sudden decrease in slope gradient and loss of confinement. At the distal edge of the X fan, multiple knickpoints coalesce into an exit channel (Fig. 7A) that eventually joins the Y channel (Fig. 2C). The presence of this exit channel indicates that flows entering the X fan from the X channel were bypassing at least some volume of sediment. The presence of large seafloor scours (Fig. 7A) supports the interpretation of bypassing flows (Kane et al., 2009).

Sand distribution and characterization from core and seismic data
Core data indicate that areas with high seafloor amplitudes are sandy (e.g., X channel and
fan) while areas with low amplitudes are predominantly muddy. To compare core data from the
study area, we use the net-to-gross ratio (hereafter N:G), calculated from each core as the
summed thickness of sand beds divided by the total ‘gross’ thickness of the core (Fig. DR2 [see
footnote 1]). We exclude the hemipelagic mud-drape in each core from the N:G calculation in
order to more accurately delineate lithology when the system was active. There is no significant
proximal to distal trend in N:G (see bubble plot in Fig. 7A). However, a lateral increase in N:G is
evident from north to south (Fig. 7A). Nine cores, mostly from the southern X fan, have N:G
values larger than 0.9, while in the northern X fan, core N:G values are less than 0.5 (Fig. 7A).
The southern cores also have greater mean sand bed thicknesses than the northern cores (16 vs 7
cm, bubble plot in Fig. 7B). Sand beds are normally graded and exhibit structureless bases (T_i/S_i
divisions) with parallel laminated and current ripple cross-laminated tops (T_bc), interpreted as the
deposits of turbidity currents (Fig. 8; Bouma, 1962; Lowe, 1982). Bed amalgamation and mud
clasts are common (Fig. 8A-B). Grain size analyses show a clear progression of increasing
sorting and decreasing grain size from the base to the top of thick-bedded turbidites (Fig. 8D)
and confirm the presence of amalgamation surfaces described in the core (Fig. 8B). Generally,
sand beds deposited on the X fan are coarser-grained than in the X channel; grain size analyses
demonstrate that the average D_{10}/D_{50}/D_{90} on the X fan is 76/160/444 µm (n=118) while the X
channel is 75/130/221 µm (n=88). The difference in the coarse fraction (e.g., D_{90}) is especially
apparent when comparing grain size histograms between channel and fan (compare Figs. 4 and
8). This indicates that most of the coarser-grained fraction is likely bypassing the X channel,
with only a coarse-grained bypass lag deposited in the channel thalweg (e.g., Fig. 4B).
Interestingly, there is no significant trend in sand grain size across the X fan, indicating that
unconfined/non-channelized flows carried even the coarsest grains in the flow for 8 km to the
distal edge of the intraslope basin (Fig. 7). Supporting this inference are high amplitudes in the
exit channel downdip of the X fan (Fig. 2C) and thick-bedded, coarse-grained sand beds in the
most distal X fan core (core Fan 7, Fig. 7).

STACKING PATTERNS

_Turbidite bed stacking at the millennial scale_
The 28 piston cores provide excellent lithologic calibration for lobe deposits in the X fan (Fig. DR2 [see footnote 1]). Because cores average 4.3 m in length, the 3D seismic data could not be used for correlation due to its ~ 8 m vertical resolution (Fig. 3). Consequently, extensive radiocarbon dating of the piston cores provides the basis for inter-core correlation and calculation of sedimentation rates across the X fan. Given that most cores have > 1 km spacing, correlation of individual sand beds is sometimes uncertain, but bedsets (i.e., time-equivalent packages of sand beds) are easily correlated (Fig. 9). Time lines for 14, 18, and 25 ka (shown as dashed lines in Figs. 9, 10) were calculated by assuming a linear sedimentation rate between ages in each core and that the top of each core has an age of 0 ka. Strike-oriented core cross-sections in Figure 9 show a prominent younging of sand beds and bedsets from north to south. No sand was deposited on the northern X fan younger than 17 ka, while sand beds as young as 13.9 ka are present on the southern X fan (Fig. 9). In the most proximal strike section, sand beds are thicker and younger on the southern X fan (Fig. 9A). The youngest sands on the northern and southern X fan are 17.0 ka (core Fan 15) and 15.2 ka (core Fan 1), respectively, while X channel mouth sands have ages similar to the southern X fan (e.g., 13.9 ka in core Fan 16 3 inch; Fig. DR2 [see footnote 1]). Core Fan 17 consists of mud throughout this time interval (Fig. 9A), demonstrating the pinchout of sand against the southern basin margin (see also Fig. 2C, 3D). Core Fan 17 was also used to constrain longer-term deposition rates using oxygen isotope methodologies (see Parker et al., 2016). Radiocarbon ages from the medial strike section (Figs. 9B) indicate that sand deposition shifted southward at least 4 km in ca. 4 k.y., from 18.0 ka to 14.1 ka. The distal strike-oriented core cross-sections display the same southward younging trend (Figs. 9C-D), although poor core recovery (likely due to the presence of amalgamated, thick-bedded sands) prevents full characterization. The southward younging trend is also observed in dip-oriented core cross sections, where the youngest sand on the northern X fan is ~ 16.9 ka (Fig. 10A) while sand beds on the southern X fan are as young as 13.9 ka (Figs. 10C-D).

Back-stepping is also observed in deposits on the X fan, best shown in dip-oriented core cross sections (Fig. 10). The central dip-oriented core cross section most clearly shows the back-stepping, with progressively younger sand beds deposited towards the mouth of the X channel (19.6 ka to 13.9 ka; Fig. 10C). The southern dip section shows a similar back-stepping trend, with distal ages of ~16 ka and proximal ages of 13.9 ka (Fig. 10D). The shorter duration of back-
stepping on the southern X fan is further evidence that it was most recently active (Figs. 7B, 9, 10). Back-stepping has been observed in other lobe deposits on the modern seafloor (Deptuck et al., 2008; Prather et al., 2012b) and in flume tank experiments (Cantelli et al., 2011; Fernandez et al., 2014).

Large-scale stacking patterns

While this study focuses on millennial-scale event bed/bedset stacking patterns, we briefly describe here the larger-scale stacking patterns on the X fan. Prather et al. (2012a) interpreted two main phases of deposition, and mapped lower and upper units (Fig. 3). Both units were deposited in the X intraslope basin (Fig. 3) and are relatively thick for their areal extent (e.g., ‘confined lobes’ of Prelat et al., 2010). The lower unit covers an area of 6 x 8 km and has a maximum thickness of 75 m (Fig. 3). The lower unit is thickest in the center of the X fan (Fig. 3A). The upper unit is areally larger (8 x 8 km) but thinner, with only ~ 40 m maximum thickness (Fig. 3B). Covault and Romans (2009) observed a similar trend of successively larger and thinner lobate deposits in the California Borderland. Assuming roughly constant sediment supply, this trend is the consequence of filling a bowl-shaped intraslope minibasin (Sylvester et al., 2015). The upper unit is thickest where the lower unit is thin (Fig. 3A-B), indicating large-scale compensational stacking of the lower and upper units of the X fan. Linear extrapolation from oxygen isotope age data (core Fan 17; see Parker et al., 2016) suggest that the age of the base of the upper unit is ca. 130 ka, roughly coincident with low sea level during Marine Isotope Stage (MIS; Lisiecki and Raymo, 2005) 6, and the base of the lower unit is ca. 630 ka, coincident with low sea level during MIS 16. These ages assume constant sedimentation rate through time and are thus speculative.

DISCUSSION

Compensation of Beds and Architectural Elements
This study interprets the character and timing of bed and bed-set compensation on a
modern intraslope submarine fan. While other studies have described bed and bed-set
compensation in modern submarine lobe deposits (e.g., Vittori et al., 2000; Deptuck et al., 2008;
Jegou et al., 2008; Romans et al., 2009), this study is the first to document higher-resolution,
bed-scale compensation in an intraslope basin setting. Our interpretations rely on shallow core
penetrations, and while the patterns of compensation are convincing, they are not unequivocal.
Additional data from deeper stratigraphy are needed to support our interpretations of bed-scale
compensation during the late Quaternary. Our correlations indicate a 4 km southward shift in
sand deposition that occurred over a ca. 4 k.y. period. This scale of compensation most likely
represents the emplacement of two ‘lobe elements’ (terminology of Prelat et al., 2010) on the
northern and southern parts of the X fan. The older lobe element was deposited on the northern
part of the X fan from ~ 25-18 ka (Fig. 9). The most recent lobe element on the southern part of
the X fan is approximately 2 km wide and 6 km long and can be seen on core cross sections (Fig.
9) and the seafloor aspect map (Fig. 7B). The thickness of the most recent lobe element is at least
1 m but is limited by core penetration; scaling from Prelat et al. (2010) suggests a thickness of 3-10 m. The seafloor geomorphology (Fig. 6) and backstepping of beds in the most recent lobe
element (Fig. 10) suggests that if sand deposition had not been interrupted at 14 ka, a third lobe
element would have been deposited on the northern X fan (cf. Cantelli et al., 2011). These lobe
elements stack in a compensational manner to form a larger depositional element termed a lobe
(cf. Prelat et al., 2010).

The larger-scale stacking patterns in the X intraslope basin seem to be compensational as
well (Fig. 3; Prather et al., 2012a). The upper unit is 35 m thick and has a clearly depositional
lobate shape (Fig. 3B; Fig. 15B of Prather et al., 2012a), suggesting it can be considered a ‘lobe’
in the scaling and hierarchy of Prelat et al. (2010). In contrast, the lower unit can be considered a
lobe complex, as it is thicker (~ 75 m) and its thickness pattern is not lobate, but rather mimics
the shape and subsidence pattern of the basin (Fig. 3A). This, along with the convergent nature
of the seismic reflections (cf. Sylvester et al., 2015), suggests that the morphology of the lower
unit is recording subsidence history rather than depositional morphology. The striking difference
between the thickness patterns of the lower (lobe complex) and upper (lobe) units (Fig. 3)
demonstrates the concept of the ‘stratigraphic integral scale’ (Sheets et al., 2002; Lyons, 2004;
Straub et al., 2009), where individual depositional elements have a process-based thickness pattern (e.g., lobe element in Fig 7B, lobe in Fig. 3B), but over longer time scales, the thickness pattern reflects the basin subsidence history (e.g. lobe complex in Fig. 3A). The duration of the lower (ca. 500 k.y.) and upper (ca. 130 k.y.) units reinforces the interpretation of the thickness patterns and hierarchical assignments.

**Timing of Sand Delivery to the X Channel and Fan**

Core data indicate that sand was delivered from the X channel to the X fan from at least 25 ka until 14 ka (Fig. 9). The lack of deeper cores limits knowledge of earlier deposits of the X fan, but we infer that sand was being delivered to the X fan since at least 50 ka, when the nearby Y channel was active (Jobe et al., 2015). Average deposition rates for sandy deposits on the X fan are more than two times higher than muddy deposits (35.8 vs. 13.5 cm/k.y., respectively). The youngest sand beds present in the X channel and fan were deposited at 13.5 ka and 13.9 ka, respectively (Figs. 5C, 9A). The 400 yr difference suggests that the backstepping trend observed in the youngest lobe element on the X fan (Fig. 10) may have continued up the X channel for ca. 400 yr after the end of sand deposition on the fan. This style of progressive updip abandonment has also been demonstrated in nearby submarine channel systems (Jobe et al., 2015).

The mechanism forcing the cessation of sand deposition in the study area is interpreted to be allogenic in nature, as no autogenic forcing mechanisms (e.g., submarine channel avulsions) are observed. While we cannot exclude tectonic forcing (e.g., growth fault or shale diapir movement), we have no evidence of tectonic activity at ~14 ka. Other allogenic signals, such as relative sea level and climate change, tend to be propagated very quickly from source to sink (Romans et al., 2009; Covault et al., 2010; see discussion in Romans et al., 2016). The abrupt cessation of sand delivery to the study area occurred at 14 ka, the same time period that sea level rose dramatically during Meltwater Pulse 1-A (~ 20 m in 300 yr; Deschamps et al., 2012). From 14.6 to 14.3 ka, global sea level rose from -105 m to -85 m, approximately the current water depth of the Niger shelf edge (Allen, 1964, 1965). This rapid sea level rise likely caused abrupt flooding of the continental shelf, preventing sand delivery off the shelf edge.
Facies models for lobes in intraslope settings

Traditional lobe facies models indicate a progressive decrease in sand thickness and N:G away from the lobe axis (e.g., Pyrcz et al., 2005; Deptuck et al., 2008; Prelat et al., 2009). Thickness maps similar to those in Figure 3 are often interpreted as evidence of such trends in internal properties (e.g., Pirmez et al., 2000). This study indicates, however, that the traditional facies model does not apply for lobes deposited in intraslope settings where flows are often able to bypass large volumes of mud (Fig. 11). Many turbidites on the X fan lack mudcaps and well-developed laminated $T_b$ and $T_c$ divisions, probably due to significant bypass of fine-grained sediment. This results in intraslope lobe deposits that are very sand-rich (Fig. 11), and thick-bedded, coarse-grained sands are present even in the most distal core location (core Fan 7 in Fig. 9D).

While this study documents the sand-rich nature of intraslope lobe deposits (Fig. 11), fine-scale heterogeneity is still present. For example, a scour imaged on Figure 7A affects bed continuity of sand beds inside (core Fan 11) and outside (core Fan 10) of the scour. These two cores are only 450 m apart, and Figure 8A-B shows the rapid facies change caused by the scour (cf. Kane et al., 2009). Although we believe that Figure 11 characterizes the differences between intraslope and base-of-slope lobes, exceptions to the sand-rich intraslope fan facies architecture are possible, and may include cases where mud-rich flows are dominant or where the intraslope basin is large compared to the flow size (e.g., Prather et al., 2012b). For natural resource prediction and production, the X channel-fan system provides a well-constrained example of sub-seismic heterogeneity that is vital in understanding inter-well connectivity in reservoirs contained in intraslope submarine fan deposits.

CONCLUSIONS

Core and seismic data on the western Niger Delta continental slope illustrate the facies architecture and temporal evolution of a linked channel-lobe depositional system in an intraslope environment. The X channel has low-sinuosity and is ~ 360 m wide, with thalweg deposits consisting of thick-bedded sand and gravel interbedded with chaotic muddy units, and overbank
deposits consisting of thin-bedded, fine-grained sands and muds. The intraslope submarine fan (X fan) at the terminus of the X channel is 8 km long x 8 km wide, and contains > 100 m of intraslope lobe deposits sourced by the X channel. There are two distinct large-scale units imaged by 3D seismic data. The lower unit is 6 x 8 km x 50 m thick and is thickest in the basin center, while the upper unit is 8 x 8 km x 25 m thick and has a pronounced southward shift in its maximum thickness. This compensation is at a large (i.e., lobe or lobe-complex) scale, and may be linked to sea level variation during the last glacial cycle (130-0 ka).

Core data indicate that deposits on the X fan are more sand-rich, thicker-bedded and coarser-grained than in the X channel, implying bypass on steeper, channelized slope gradients and deposition on lower, unconfined slope gradients. There is no significant downslope trend in grain size or net-to-gross ratio on the X fan, indicating that flows were likely bypassing some sand and most mud through the intraslope basin. This results in more sand-rich deposits and partial sediment bypass than predicted by traditional facies models for lobes, particularly near lobe/fan edges. The most recent flows exiting the X channel were directed onto the southern fan, building a lobe element ~ 2 km wide x 6 km long, and at least 1 m thick. Deposition rates average 36 cm/ky, but are locally greater than 80 cm/ky. This most recent lobe element was emplaced in only 4000 yr, from 18-14 ka. Prior to the deposition of the most recent lobe element, flows from the X channel were directed onto the northern part of the X fan, from ~ 25-18 ka. This bed-scale compensation shifted the locus of sand deposition 4 km over millennial time scales (4 ka). Radiocarbon dating, seafloor geomorphology, and 3D seismic amplitudes confirm the location and age of these two compensating lobe elements. Sand deposition in the X channel/fan was interrupted by rapid sea level rise during Meltwater Pulse 1-A at ~ 14 ka, causing abandonment of the system.

This unique dataset constrains the facies and stratigraphic architecture of bed- and lobe-scale compensation in an intraslope basin setting. Core data indicate that intraslope lobe deposits can have very different facies architecture than predicted by traditional lobe facies models, and that thickness patterns do not necessarily correlate with sand presence and net-to-gross. Further work aims to incorporate simple analytical modeling to quantify the effects of sediment flux on lobe compensation in intraslope submarine fans.
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Figure 1. Slope map of the seafloor on the western Niger Delta continental slope, with depth contours in black. Note the complex bathymetry produced by mobile shale, including diapirs and ridges. The white box denotes the location of Figure 2.
Slope (i.e., dip angle) map

Fig. 2

Shale ridge

depth contour interval 100m

Minna UTM projection Zone 31N

Dip angle (deg)

10

0

20

N

5 km

X fan

Y channel (Jobe et al., 2015)

Y' channel

Bonga' channel

500m

1000m

1500m

1000m

1500m

2000m

1000m

1500m

2000m

Shale ridge

study area

Benin

Nigeria

Cameroon
Figure 2. Bathymetric map (10 m contour interval) and seismic amplitude (color) of the seafloor. (A) shows the entire study area, while (B) and (C) focus on the X channel and fan, respectively. Piston core locations are shown with white circles.
**A**

X channel

Y channel

Y prime channel

**B**

Cross section in Fig. 5C

Cross section in Fig. 5A-B

Terrace

Flow direction

**C**

Exit channel

Knickpoints

Fan 1

Fan 2

Fan 3

Fan 4

Fan 5

Fan 6

Fan 7

Fan 8

Fan 9

Fan 10

Fan 11

Fan 12 3 inch

Fan 13 3 inch

Fan 14 3 inch

Fan 15

Fan 16 3 inch

Fan 17

Fan 18

Fan 19 3 inch

Fan 20 3 inch

Fan 21 3 inch

Fan 22

Fan 23 3 inch

Fan 24 3 inch

Flow direction

10 m depth, contour interval

1000 m

2 km

2000 m
Figure 3. Characterization of the X intraslope submarine fan. (A) Thickness map of the lower unit (likely a lobe complex), with a fairly symmetric fill around the X feeder channel. (B) Thickness map of the upper unit (likely a lobe). The southward shift in thickness is caused by compensation of large-scale depositional elements (lobe to lobe-complex scale). Note the increase in areal extent in (B) as compared to (A), reflecting basin filling. (C) Dip seismic profile (red line in inset) showing the character of the intraslope basin fill and the underlying mobile shale uplifts. (D) Strike seismic profiles from the proximal, medial and distal X fan (refer to (C) for locations). Seismic character becomes more homogenous downdip and the mounded topography diminishes. Thickness maps modified after Prather et al. (2012a). VE – vertical exaggeration.
Figure 4. Cores from the overbank (A, C) and thalweg (B) areas of the X channel (see Fig. 2B for core locations). Core Bend 4 was taken in the thalweg of the X channel, where coarse amalgamated sands with gravel up to 5 mm are interbedded with chaotic muddy units (interpreted as MTDs). Cores Bend 5 and Bend 6 sample overbank deposits, and have thinner bedded, finer (< 0.5 mm) ripple-laminated sands with preserved mudstone interbeds. Despite being thinly-bedded, the net-to-gross (N:G) ratio can be quite high in these overbank areas (e.g., excluding the mud drape, core Bend 5=0.44; core Bend 6=0.93).
Figure 5. Core cross-sections for the X channel (see Fig. 2B for location). (A) Strike-oriented section demonstrating contemporaneous sand deposition in the X channel and in both overbank areas. Note the heterogenous channel infill and the thinning of sand beds from proximal to distal overbank areas. (B) Seismic profile of (A), demonstrating the shallow core penetration (white lines) and the overbank morphology. While the outer bank has levee morphology, the inner bank has a terrace/bench morphology and thus more sand accumulation. (C) Dip-oriented core cross-section, illustrating the overbank facies architecture. Sand beds generally thin upslope and away from the X channel. MTD – mass transport deposit.
Figure 6. Bathymetric cross-sections reveal the seafloor morphology of the X fan. Note the most recent flow path is onto the southern fan due to the presence of the right-hand levee/ridge of the X feeder channel. The northern X fan is underfilled and will likely be the next area of sand deposition. Cross sections spaced every 500 m and colored from red to blue in a proximal-to-distal sense. Inset map shows cross-section locations.
The diagram illustrates a cross-section of a submarine channel with various features labeled. The X channel is indicated, and the most recent flow path is shown. The next compensation event is predicted to bring flows here. The diagram also shows the current flow path and the exit channel. The water depth is marked along the vertical axis, while the horizontal axis represents meters. The vertical exaggeration is noted as 30x and 1x.
Figure 7. Seafloor morphology of the X fan. (A) Slope (i.e., dip-angle) map with core net-to-gross (N:G) bubble plot (white circles) and individual core N:G values next to each bubble. Slope gradients on the X fan do not exceed 5 degrees, and average slope is 1.4 degrees. The right-hand levee of the X channel extends onto the fan as a ridge between cores Fan 13 and Fan 14, and two large scours are present just downslope of the ridge (Fan 11 core location). Note that the southern X fan cores have high N:G (> 0.9) while the northern X fan cores have N:G < 0.5. (B) Aspect (i.e., dip-azimuth) map with average sand thickness bubble plot (black circles). The X channel clearly feeds sediment to the southern part of the X fan, where sand beds, on average, are thicker. Dashed line shows the extent of the youngest lobe element.
Figure 8. Details of cores on the X fan (see Fig. 7 for core locations). Muddy upper portions of cores not shown. (A) and (B) Cores Fan 10 and 11 are 450 m apart on the central X fan. Core Fan 11 was taken inside a scour (see Fig. 7A), and core Fan 10 just outside the scour. These cores demonstrate significant lateral heterogeneity in the youngest lobe element. (C) Core Fan 15 on the NW part of the X fan has lower N:G, with medium-bedded sands and thick mud interbeds. (D) Single sedimentation unit from core Fan 4 on the SE part of the X fan. Grain size histograms show a well-defined fining and sorting upwards grain size profile. The medial/distal location of core Fan 4 demonstrates that non-channelized flows were competent enough to carry very-coarse sand and gravel > 5 km from the X channel mouth across a very low gradient fan surface.
1. Increasing sorting and decreasing grain size.

Fan 4:
- 14,055 ± 135 yrs
- 14,186 ± 629 yrs
- 17,567 ± 195 yrs

Fan 11:
- 14,186 ± 629 yrs
- 17,075 ± 216 yrs
- 18,097 ± 179 yrs
- 19,698 ± 209 yrs
- 24,972 ± 383 yrs

Fan 10:
- 14,055 ± 135 yrs

A correlation line indicates cores 450 m apart.
Figure 9. Strike-oriented core cross-sections on the X intraslope submarine fan. (A) Proximal strike-section, where sand beds become progressively younger from north to south, indicating 4 km of bed-scale compensation during ca. 4 k.y. (B) Medial strike-section, where progressively younger sand beds offstack to the south. (C) Medial strike-section, showing that sand beds thin and pinch out towards the NW, indicating most recent deposition on the southern X fan. (D) Distal strike-section, again showing the most recent sand deposition on the southern X fan. Note that thick-bedded sands occur at the most distal edge of the X fan, indicating that flows were able to transport sand > 5 km from the channel mouth. (E) Seafloor amplitude map with lines indicating parts A-D. The southward compensation is expressed here as hotter colors (red) indicating sand of the most recent lobe element on the southern X fan and cooler colors (blue) indicating coeval mud deposition on the northern X fan.
Figure 10. Dip-oriented core cross-sections on the X intraslope submarine fan. (A) Seafloor amplitude map showing locations of parts B-D. (B) Northern dip-section, showing no systematic upslope or downslope bed-thickness trends. (C) Central dip-section, suggesting an apparent backstepping trend, with younger sand beds deposited closer to the X channel mouth. Note that the youngest sand deposition correlates with the dashed line in Fig. 7B. (D) Southern dip-section, showing downdip pinchout of sand beds from the X channel mouth. Poor core recovery suggests the presence of thick, amalgamated sand beds.
The image contains a geological diagram showing various fan deposits with associated radiocarbon ages. The diagram includes labeled sections with fan numbers and corresponding radiocarbon ages. The map also highlights different geological layers with color coding for high and low amplitudes. The diagram outlines the age progression and geographical orientation of the fan deposits, indicating key features such as NE-SW orientation and specific radiocarbon dates for each section.
Figure 11. Conceptual diagram of the geomorphologic characteristics and facies distribution of an intraslope submarine fan (left) and base-of-slope submarine fan (right). Because of the bypass of muddy sediment and erosion at the distal edge of the basin, intraslope submarine lobe deposits may have more sand-rich facies architecture (left) than predicted by traditional lobe facies models (right). It is important to note, however, that intraslope fans can be more similar to the base-of-slope type if the intraslope basin is large compared to the flow size and/or flows are predominantly mud-rich.
Intraslope fan with bypass

- sand-rich facies in marginal and distal locations
- well-defined sand pinchout
- large scours
- flow convergence, acceleration, and erosion near exit point

Base-of-slope fan

- facies variability due to channelization and transitional flows
- less sand in marginal and distal settings
- poorly defined lobe edges
- lack of erosion in distal part
Supplementary Figure 1. Cores from the X channel area, with photos, x-rays, visual descriptions, grain size analyses, and radiocarbon ages.
Supplementary Figure 2. Cores from the X intraslope submarine fan, with photos, x-rays, visual descriptions, grain size analyses, and radiocarbon ages.
Supplementary Table. Radiocarbon age data.
REFERENCES


