Basin margin sediment wedge build out of the Eastern Niger Delta: application of shelf-edge trajectory pattern studies

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Abstract
The understanding of how basin margin sediment wedge builds out causes shelf-edge migration with time is approached based on shelf-edge trajectory pattern analysis using a high-resolution mega-merge seismic data from the eastern Niger Delta, Nigeria. The study focuses on a seismic dip transect traversing the Greater Ughelli, Central Swamp, Coastal Swamp and the Shallow Offshore Depobelts of the Niger Delta. On the regional dip transects, shelf-edge sediments occur as clinoform-bearing wedges at and immediately updip of the shelf-slope break. The shelf edge is deeply buried (> 2–4 s, twt), around the Greater Ughelli and Central Swamps. But with changing structural style, sudden change of ascending shelf edge around the Central Swamp was observed. The huge listric growth fault in the Coastal Swamp; around Bonny area, once again cut the shelf edge into half, rotated it along the listric fault and buried it distally. Several depositional packages show low to moderate ascending shelf-edge trajectory with progradational to aggradational clinoform growth that is characterized by thin sand sheets across most of the shelf and upper slope, though few are also characterized by progradational clinoform growth with thick sand on the shelf, upper-tolower slope and basin floor. The deposition is usually on the Outer Shelf Terrace (OST) which is regressive in a flat and rising trajectory style. This study has demonstrated that accommodation and sediment flux are the dominant controls on how the study basin’s sediment wedge built out, whereby limited accommodation promotes sediments with significant shelf-edge advance and descending trajectories, while increasing accommodation promotes ascending trajectories and increased deposition on the outer shelf. The greater sediments on the Outer Shelf Terrace and the shelf margin than on the slope gives more hydrocarbon prospectivity search around the outer shelf and shelf margin.

Keywords Shelf margin · Sediment supply · Shelf edge trajectory

Introduction
Apart from the deepwater oil wells of the offshore Niger Delta, most oil and gas wells are concentrated within the shallow depths of the shelf. The sediment package is relatively small in the Northern Delta depobelt, but gradually increased basinward as prograding sediments build on the hanging wall of the listric faults. These hanging wall sediments build out get deeply buried as younger faults continue to cut into previous walls until the sediments get to the edge of the shelf. The shelf-margin deep packages form potential hydrocarbon plays in the Niger Delta Basin, especially around the Central and Coastal Swamp depobelts. Recently, much discussion has centered on the deeply buried ‘shelf margin’ plays in the delta. In these settings, calibration by well penetrations is rare and much of our understanding of prospectivity relies on seismic imaging below 3 s (twt). The shelf-margin sediments are formed when there is relative sea level fall of the lowstand with corresponding high sediment supply (Mellere et al. 2002). The sediments are mainly terrigenous clastics derived from the eroded exposed shelf/coastal plain and delivered to the regressive shelf (Burgess et al. 2008). Depending on the sediment flux and gradient of the shelf, these coastal plain facies can move beyond the shelf or near the shelf break (Coleman et al. 1983; Sutter and Berryhill 1985; Coleman and Roberts 1988), from where they can be deposited on the shelf slope and deep marine. It is important to understand the evolution of shelf-edge sediments so as to predict the delivery of sediments beyond the...
The study was done on high-resolution traverse dip section of the eastern Niger Delta mega-merged seismic data analyzed using Shell GeoSigns nDi software. The mega merge was loaded as a 3D seismic volume with infill 2D seismic lines to compensate for areas without 3D data coverage. It was then loaded as a Regional Trace Volume to merge the individual seismic volumes. Amplitude balancing was done between the various seismic vintages by applying additional gain to individual volumes via 3D multi-volume manager. Also, amplitude balancing filters was applied to the entire Regional Trace Volume for better viewing. The interpretation was carried out on the 2D traverse seismic section, but features on an area of interest (AOI) of the data were observed on a three-dimensional (3D) volume view. The dip section which covers the different depobelts of the Niger Delta is oriented roughly perpendicular to the advancing shoreline and shelf edge and was used for the detailed clinoform analysis. A calibration well list of about 9 well logs through the seismic traverse was made to establish an isochronous framework for the dip section. Relatively conformable packages were delineated on the seismic data by picking major unconformities identified from reflector terminations, change in seismic facies character, or choosing
significant boundaries from the well-log data. The faults were then picked and structural restoration across main faults was performed to establish a tectonostratigraphic framework of the dip section. A seismic facies analysis was also done to define thinning, unconformity, layer cake and strata terminations to define seismic sequence stratigraphic geometries. The position of the shelf edge through time was marked by the point of maximum curvature between the topset and foreset (Pirmez et al. 1998; Helland-Hansen and Hampson 2009; Anell and Midtkandal 2017). The position was identified as a point perpendicular to the intersection of straight lines extrapolated from the inflection point of the topset and foreset of the clinoform, with few uncertainties. Then, the trap geometries along the line of section were also identified and described to provide evidence of play testing.

Results and discussion

Description of sequence

The results show the presence of six distinct sequence geometries (Figs. 3, 4). They are characterized by sheet geometry landward (Greater Ughelli and Central Swamp) and are wedge shaped basinward (Coastal and Shallow Offshore). Internally, the reflectors are wavy to parallel and are predominantly semi-continuous to continuous with low to moderate amplitude in sequences #1 to #3. The top of Seq.#4 in Greater Ughelli and Central Swamp shows parallel to wavy while the base, which is erosional shows wavy to chaotic internal configuration, typical of mass transport deposits. In well data, such chaotic reflectors are described as mudstones with intercalations of sands.
which are strongly affected by syn-sedimentary deforma-
tions (Berton and Vesely 2016). Sequences #5 and #6 also
show sheet external forms proximally, which grades to
clinoform-bearing wedges distally, especially around the
Shallow Offshore (Figs. 3, 4). The reflectors are sub-paral-
lel to parallel landward and parallel to divergent to oblique
basinward towards the shelf edge (Figs. 3, 4).

The gamma ray log signature through Sequences #1 to
#3 show alternation of sand and shale with moderate net-
to-gross; typical of inner to mid-shelf environment in the
Greater Ughelli and Central Swamps. Seq. #3 thins land-
ward due to the erosional truncation, but thickens bas-
inward (Coastal and Shallow Offshore) because of the
accommodation created on the hanging wall of the huge
down-to-basin growth faults; resulting in the formation of
extensional rollover topset structures (Figs. 3, 4). The deeper
burial of the sediments on the hanging wall of the down-to-
basin fault in the Coastal Swamp gradually reduces the net-
to-gross towards the offlap break (shelf edge) in the Shallow
Offshore.

Also, sequences #4 and #5 show high net-to-gross (N/G)
of the alluvial plain from the Greater Ughelli to Coastal
Swamp and grades through mid to outer shelf with moder-
ate net-to-gross (outer terrace) in the Shallow Offshore. The
deposits beyond the shelf edge show very low net-to-gross
with isolated sands in the mud dominated slope. Seq. #6
started from the Central Swamp proximally and thickens distally at the Shallow Offshore (Figs. 3, 4). This is due to the accommodation created by the crestal collapse synthetic and antithetic faults that were initiated by the compaction of the prodelta muds.

**Shelf-margin development**

The shelf-edge trajectory analysis shows that around the Greater Ughelli and Central Swamp, the shelf edge is buried deep (> 2–4 s, twt) below the poor seismic resolution.
But with changing structural style, there is sudden change from deeply flat to ascending shelf edge around the Central Swamp. The huge listric growth fault in the Coastal Swamp (Figs. 3, 4); around Bonny Island, once again buried the shelf edge (Sequences #1 and #2); cutting it into half, rotated along the fault and buried deeper (Fig. 3). Seq. #2 shows an ascending shelf-edge trajectory (early sea level rise), followed by backstepping signature which indicates transgression due to sea level rise. Relative sea level fall initiated an active down-to-basin fault that gave rise to the basinward build out of the shelf edge in sequence #3 (Mid-Inner Shelf) (Fig. 5). This is followed by sea-level rise, creating sets of backstepping clinoforms; which indicates retrogradation-dominated margin that has landward shelf-edge imprint; with mud dominated slope.

The basin margin build out in this sequence is characterized by lower prograding (flat and ascending) and upper aggrading (ascending) clinoform growth (Fig. 5). The low-angle upward prograding shelf-margin part of this package occurred during sea-level fall (or slight rise); with prograding high shelf-edge sand-mud submarine canyon system that has moderate sand–shale ratios. Also, the steeply upward aggrading clinoforms were formed during sea-level rise; with aggradation-dominated margins associated with sand-rich submarine fans with moderate sand-shale ratios and mud dominated Mass Transport Complex (MTC). These depositions are usually on the Outer Shelf Terrace (OST) due to high sediment flux enough to withstand the rising sea level. In Seq. #4, the shelf edge is cut into half by one of the longest collapse crestal faults, rotating it along the fault plane and buried it deeper (Fig. 6). Both sequences #4 and #5 show low to moderate ascending (rising) shelf-edge trajectories with progradational to aggradational clinoform growth that is characterized by thin sand sheets across most of shelf and upper slope. The aggradational clinotherm sets occur with thick shale between sands that are usually storm-wave generated. Such gently ascending trajectories (Fig. 4) also contribute to a significant basin-floor fan development (Johannessen and Steel 2005). The number of shelf delta successions and their thicknesses are also greater for more steeply rising (ascending) shelf-edge trajectories than they are for falling (descending) or gently rising (flat and ascending) trajectories.

Overall, the clinoforms of the packages preserve a semi-sigmoidal shape with thick topset successions. They have mildly chaotic internal reflectors on the topsets and foresets with shelf-edge trajectories that show generally positive (ascending) trends. The trajectory indicates a system with generally continuous rising relative sea level with good accommodation, probably related to the tectonic subsidence (Anell and Midtkandal 2017) in the Niger Delta.

All the sequences with flat and ascending (rising) shelf-edge trajectories are indications that the eastern Niger Delta is a sediment supply-dominated margin. This kind of margin is linked to sea-level fall and rise or still stand with progradation-aggradation dominant shelf-edge and mud-prone deposition (Carvajal and Steel 2006). This supply-dominated margin is continuous across the entire clinoform from top to bottom, despite times of stronger accommodation influence on some clinoforms (Fig. 5). The shelf-edge deltas of
this margin are consistently connected with the basin floor through slope channels at sea-level stand (Koo et al. 2016). This implies that there is a consistent link between shelf-edge deposits and basin floor despite the reworking of the shelf-edge progradation by waves and tides. The channels are more on the slopes of the flat and ascending (low-angle prograding) shelf-edge trajectory (Fig. 5), through which much sediments are routed to the basin floor than in ascending trajectory. The play segments identified are mainly fault dependent (Figs. 3, 4), which includes extensional rollover plays, high pressure outer shelf-edge plays, hanging wall shelf-edge plays and slope channel/basin floor turbidites. It is also observed that these shelf-edge plays are typically buried beneath a thick shelf and alluvial plain overburden where well penetrations are rare. Because of this, prediction of reservoir presence relies mainly on seismic reflector characters. For example, in Figs. 3 and 4, the presence of sand was predicted in the D-deep well using the adjacent calibrated D-001 well because of similarity in seismic facies and likely aggradation of sand-rich sediments on the outer shelf terrace (ascending trajectory) of the D-deep well.

**Conclusions**

An interpretation of the dip section of the mega-merge seismic from eastern Niger Delta was carried out in this study. Six distinct sequence geometries were delineated; characterized by sheet geometry landward (Ughelli and Central Swamp) and wedge shaped basinward (Coastal Swamp and Shallow Offshore). The shelf-edge trajectories show flat and ascending, ascending and backstepping clinoforms corresponding to low-angle prograding, aggrading and retrograding, respectively. The variation in trajectory inclination is because of varying sediment supply and relative sea level. The dip section also indicates a sediment-supply dominated margin. Sediments are routed to the basin floor through the slope channels during progradation while more sands and shales are stacked on the Outer Shelf Terrace (OST) during aggradation. The play segments are mainly extensional rollover plays, high pressure outer shelf-edge plays, hanging wall shelf-edge plays and slope channel/basin floor turbidites. This study has demonstrated that accommodation and sediment flux are the dominant controls on how the sediment wedge built out in the Niger Delta Basin. It confirms that limited accommodation promotes sediments with significant shelf-edge advance and descending trajectories, while increasing accommodation promotes ascending trajectories and increased deposition on the outer. It also helps to predict the reservoir presence and hydrocarbon plays vertically and laterally, especially in such settings where calibrations by well penetrations are rare.

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