Multiage Plays in Offshore Nigeria: Hidden Plays of Neogene Shale Structures, and Robust Lower Miocene to Paleogene Deposition

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Abstract

As Offshore Nigeria enters a third decade of deep-water exploration, unsuccessful wells in the structures of the deep-water Outer Fold and Thrust Belt have spurred a reevaluation of plays in the regional basin. Key lines from a newly-acquired seismic data set having 10 km long-offset, deep-tow acquisition parameters, and modern PSDM processing are examined here and show significant improvements in deep imaging. The interpretation of these lines advances the understanding the Paleogene Akata Shale and structural styles of mobile shale features and focuses new attention towards exploration leads of older sediments in intermediate water depths of the Inner Fold and Thrust Belt. The data show a clearer imaging of crustal structure, and the interpretation of the Tertiary supports the view of the offshore Nigeria as a linked extension to a contraction system driven primarily by gravity spreading. The Inner Fold and Thrust Belt of deep to intermediate water depths has been difficult to image in past data sets showing only thick sections of seismically opaque facies commonly interpreted as shale 'diapirs' and only thin sediments. Deep tow data here reveals several deep areas of stacked thrust sheets, within the Paleogene strata, as well as associated floor and roof detachments interpreted throughout the delta. The formation of these 'duplexes' uplifted existing Neogene thrusted sediments and folded these sediments often to very shallow depths where they are eroded near the present-day water bottom. Improved resolution of the lower Miocene and Oligocene sediments shows a robust deposition of these sequences that are involved in the inner belt structuring. The Inner Fold and Thrust Belt shows features that form a variety of hidden, deeper reservoir targets, structures of different timings, and areas where the deeper imbricates of the Akata could provide thickened source rock intervals.

Introduction

Offshore deep-water Nigeria is entering its third decade of exploration. After a period of large discoveries in the mid-1990s and 2000s, prospective thrust features in the Outer Thrust Belt have been drilled in the past years and have yielded few commercial successes. Danforth *et al.,* 2010 has reviewed the failures in the thrust belt and suggested a number of reasons for these failures, including small closures as faults do not seal and shallowing detachments that may close off migrating hydrocarbons form the Akata shale source rocks below the detachment. This suggests that an examination of new data capable of imaging deep structure and a basin reevaluation of plays and sediments is timely and can set the stage for advancing the structural and stratigraphic framework for the delta.

The interpretation presented here is based on a new 2012 offshore infill, 'deep tow' acquisition and PSDM imaging that was performed by ION Geophysical Inc. The interpretations are integrated with and update previous work on the first long-offset data acquired in 2006 in the deep water offshore Nigeria area (Connors *et al.,* 2006; Connors *et al.,* 2007; Connors *et al.,* 2009; Radovich *et al*., 2006; Radovich *et al*., 2007). These data consist of a basin-wide, mega-regional, long offset PSDM survey and show improved imaging of the deep crustal structure and the Tertiary sediments and complex mobile shale features.

The Tertiary has presented significant problems with data imaging, and the focus of this paper is to show advances in the imaging and interpretation of the Tertiary section. The new 'deep-tow' seismic data acquisition has improved signal and imaging into the core of complex shale structures and delineates new play opportunities. The interpretation presented here builds on the previous work showing offshore Nigeria as a linked extension to contraction system driven by gravity spreading. The previous data and interpretations show this system having significant sediment loading and expansion onshore and near shore, translation of sediments basinward along several detachment surfaces, and the formation of major contractional fold and thrust belts related to regional detachments.

The location of a key line utilized in this study is shown in Figure 1, a base map of the offshore deepwater margin. The map shows the position of the Inner and the Outer Fold and Thrust Belts, the Extensional Belt, and the trends of major thrusts and folds that develop in the basin.

Deep Image Seismic Data Clarifies Tertiary 'Mobile Shale Structures,' Detachments, and Timing

It is well established that most of the deformation in the offshore Niger Delta is due to a linked extension-to-contraction system driven by gravity spreading. Significant sediment expansion onshore and near shore drives prominent deep-water fold and thrust belts that are related to multiple regional detachment surfaces within the Paleogene Akata mobile shale (Lehner and De Ruiter, 1977; Evamy *et al*., 1978; Doust and Omatsola, 1990; Damuth, 1993; Rowan *et al*., 2004; Corredor *et al*., 2005; Connors *et al*., 2009). The response to gravity-driven loading occurs as two significant basin-wide fold and thrust belts that form: one proximal inner belt and one distal outer belt shown in Figure 1, Also shown is the location of a key seismic line presented in Figure 2 to illustrate refinements in the interpretation of the structures. Figure 2A shows the key seismic line interpretation, and Figure 2B illustrates a detail of the same line at a vertical exaggeration of 1:1.

The Inner Fold and Thrust Belt includes features that have been called mobile shale structures (Morley, 2003; Corredor *et al*., 2005), and have been interpreted as diapirs in early literature (*e.g.*, Morley and Guerin, 1996). Imaging of these structures has typically been poor, particularly on time-migrated data, but the new deep-tow PSDM seismic data shows criteria to advance the understanding of these structures. Interpreters often have recognized mud volcanoes and other fluid expulsion features in the data above the structures. Fluid expulsion features are present on some of the ION PSDM data but over an extremely limited extent. The crests of these structures are often characterized by incoherent seismic reflections, but given the quality of the overall imaging of these data, it is very possible that these are truly chaotically deformed section and possibly even unconsolidated muds. What is significant is that in most places, the mobile shale structures imaged with these modern PSDM actually show coherent reflectors on their crests (Fig. 2A).

Connors *et al.* (2009) interpreted these mobile shale structures in the Inner Fold and Thrust Belt as large, thrusted detachment folds with incoherent thickening in their cores. In many places this may still be the case, such as on the left side of Figure 2A. A key insight gained from these new data is that below the areas that lack coherent seismic reflections are data that are clearly reflective and show thrust imbrication such as on the right side of the contractional high of Figure 2A. The cores of many detachment folds have been proposed to be composed of imbricate sheets (*e.g.*, Epard and Groshong, 1993).

Imbrication has also been proposed in the cores of simpler detachment folds of the Niger Delta in the Outer Fold and Thrust Belt (Rowan *et al*., 2004; Maloney *et al*., 2010) but not previously within these complex Inner Fold and Thrust Belt mobile shale structures. The line shown in Figure 2A lies south of the Bonga field but is part of the same structural high. On the right side of the line is a clear, thrusted section that has a well-imaged floor or basal detachment (labeled Regional Detachment surface in Fig. 2A) and a roof or upper shallow detachment (labeled Upper Detachment surface in Fig. 2A); thus it is a duplex. These two detachments are regional in extent and have been mapped across the entire gravity-driven system. Above the duplex lies what would generally be called a mobile-shale structure, which is itself imbricated and has an associated detachment.

The key point is that the section below the orange 39.5 Ma horizon shows dramatic thickening.

Below the Upper Detachment surface, the section is thickened also although as discrete thrust sheets of more competent Akata section. This is best shown in the detail seismic line in Figure 2B at a 1:1 vertical exaggeration. These structures have accommodated significant shortening in two ways, and this explains why these mobile-shale complexes are so structurally high. The uppermost imbricate structures that do not show clear seismic reflectors in their cores would come from a more proximal position, ultimately thrust over the deeper duplex, as they are themselves carried on the thrusts of the shallower imbricate system (Fig. 2B).

Growth strata on the flanks of these structures show that some probably started growing in the lower to middle Miocene. Thus onlap and ponding of sands onto the flanks of these structures is possible, and deeper thickening of probable source rocks could lead to potential prospectivity.

Robust Sedimentation in Lower Miocene-Oligocene Sequences

The improved resolution and resulting refinement in structural interpretations allow, in turn, an improvement for the interpretation of the deeper sediments; *i.e.*, the lower Miocene, Oligocene and top Akata mobile shale, and focus new attention on the Inner Fold and Thrust, and Extensional Belts of deep to intermediate water depths. Bonga Field drilling has documented lower Miocene and Oligocene sands and pay zones (Chapin *et al*., 2002), but the regional mapping of these units has been difficult due to poor imaging into the core of the structures.

The key line in Figure 2 is located adjacent to and south of Bonga Field and shows a 2-4 km thick section of seismic reflections from the 10.5 Ma horizon (light blue) to the interpreted top Akata shale, 39.5 Ma (orange). These sediments are now more clearly revealed in folds and thrusts that sole out onto an upper detachment surface. They demonstrate robust deposition for this unit throughout the Niger Delta, and the unit is a high potential, deeper reservoir target. Figure 3 is a regional isopach map for the 17.5 Ma to 39.5 Ma (Top Akata) interval from 0 to 2500 meters in thickness. The map shows the thick areas in excess of 1000 meters to 2500 meters in the green to blue color-fill contours and illustrates a broad wedge of sediments deposited throughout the paleoslope position along the margin. These sediments are interpreted to be in an unconfined sand system of the middle slope to basin floor facies and derived from a multiple fairways along the margin, in addition to the Opuama Channel to the northeast that has long been documented with Oligocene canyon fill sediments (Peters, 1984). These sediments have been deposited on a largely undeformed Akata Shale and thus spread out into a characteristic slope front-fill wedge shape. Within the broad wedge of sediments, though, are paleo-high thins and paleo-synclinal thicks, documenting structures that existed at the time of deposition. These features show an early phase of contraction occurring by the Early Miocene age.

Examples of leads of different types and timings are shown in Figure 2A. The seismic line shows the 17.5 Ma horizon (green) and deeper section involved with numerous fault-related folds that demonstrate more closure deeper into the lower Miocene and Oligocene sediments, as younger growth wedges fill in the topography. Additional leads along this trend are expected to be hidden under erosional surfaces formed during the youngest fold and thrust events. These are shown in Figure 2A at the southwestern edge of the Inner Fold and Thrust Belt (left side of figure) where several features show seismic truncations at the crest as the continued translation of sediments affected the basin in the Pliocene and Pleistocene. The inner structured areas also have an advantage for exploration, as the deeper imbricates of the Akata would provide thickened source rock intervals.

Conclusions and Summary of Exploration Plays

The deep imaging of the long offset and deep-tow seismic data show a number of highlights that advance the understanding of the offshore Nigeria structural and stratigraphic framework. The Tertiary sediments show several phases of gravity sliding and contractional response along two major detachment surfaces: a floor and roof detachment, that form in the Akata Shale. Key events include lower Miocene age contractional features, a Miocene translation and duplexing within the Akata Shale including re-deformation and uplift of existing detachments, and the youngest folds and thrusts formed by continued translation basinward with these features soling-out onto both detachments often with shallow erosion on their crests. The Tertiary section of the Inner Fold and Thrust Belt offers a variety of leads and timings. This area shows lower Miocene to Oligocene sediments that would provide a thick section of deeper drilling targets, leads that are hidden under younger and shallower structures and erosional events, and structures where deeper imbricates of the Akata Shale would provide thickened source rock intervals.

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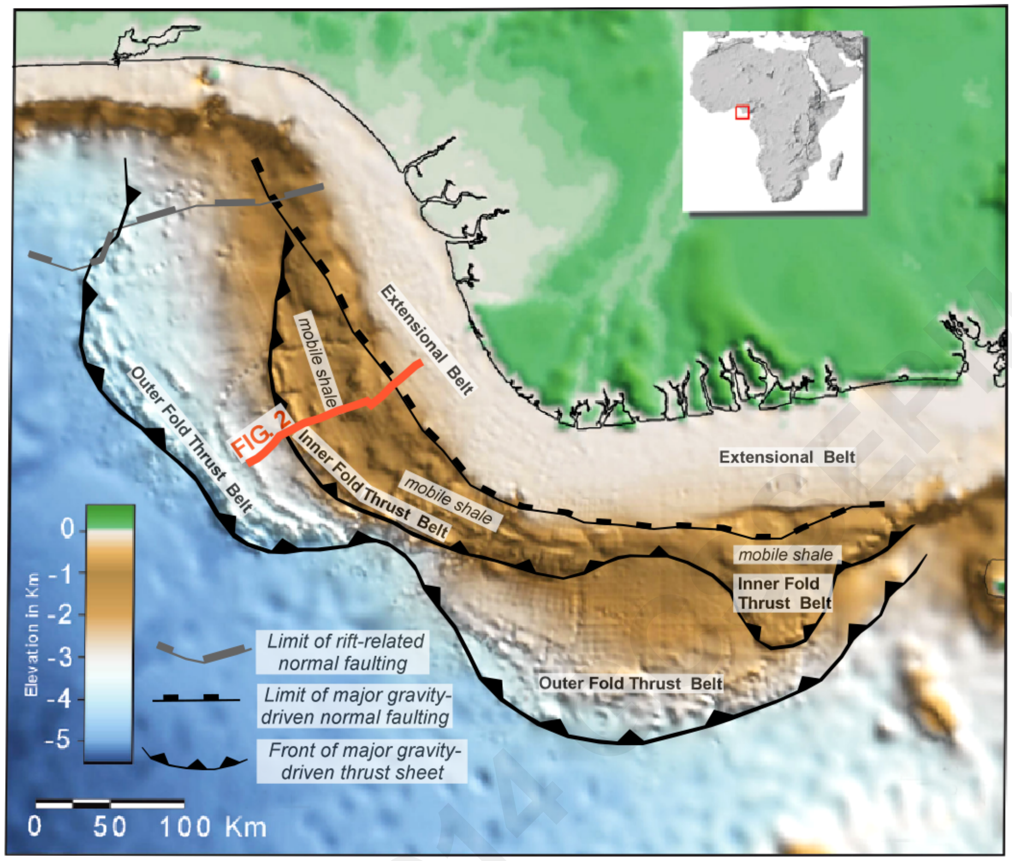

Figure 1. The Nigeria offshore base map with location of the key seismic line in bold red color. Major structural features of the delta are labeled shown over a bathymetric map from Corredor *et al.*, 2005.

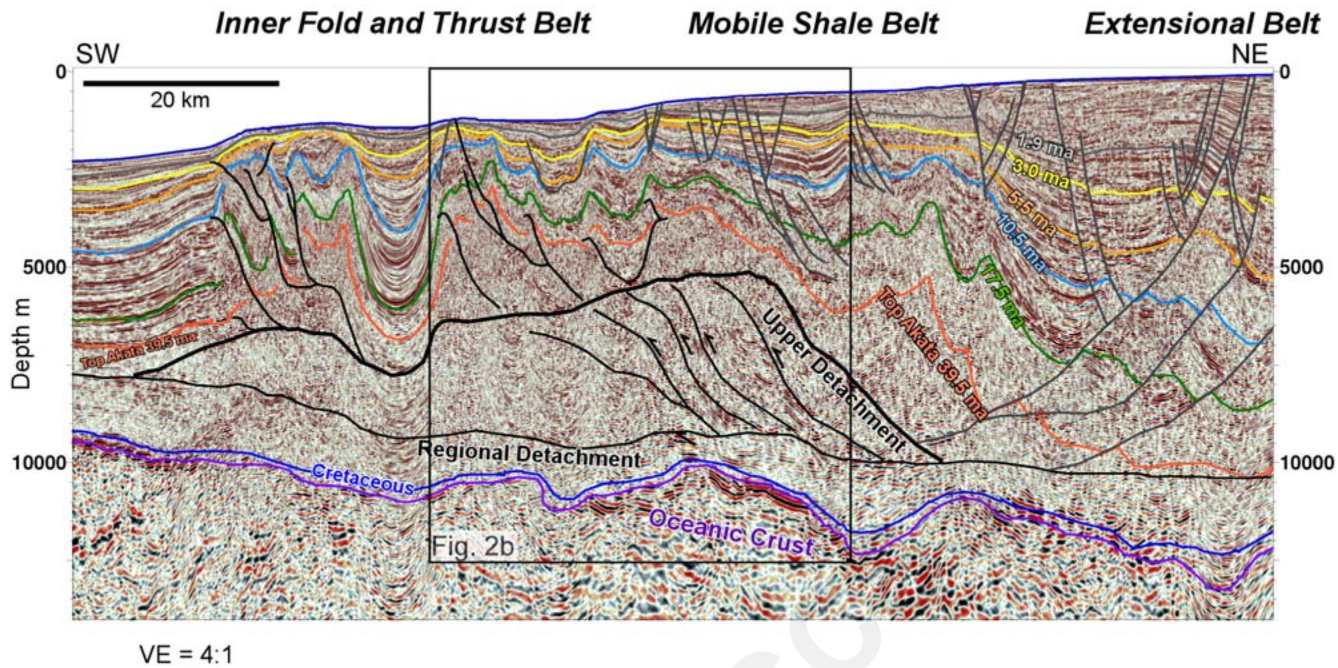

Figure 2A. The regional deep-tow, long-offset, PSDM seismic line located near the central delta, showing the shelf position into deep water and highlighting the Inner Fold and Thrust Belt (vertical exaggeration is 4:1). The seismic data is shown courtesy of ION Geophysical Inc.

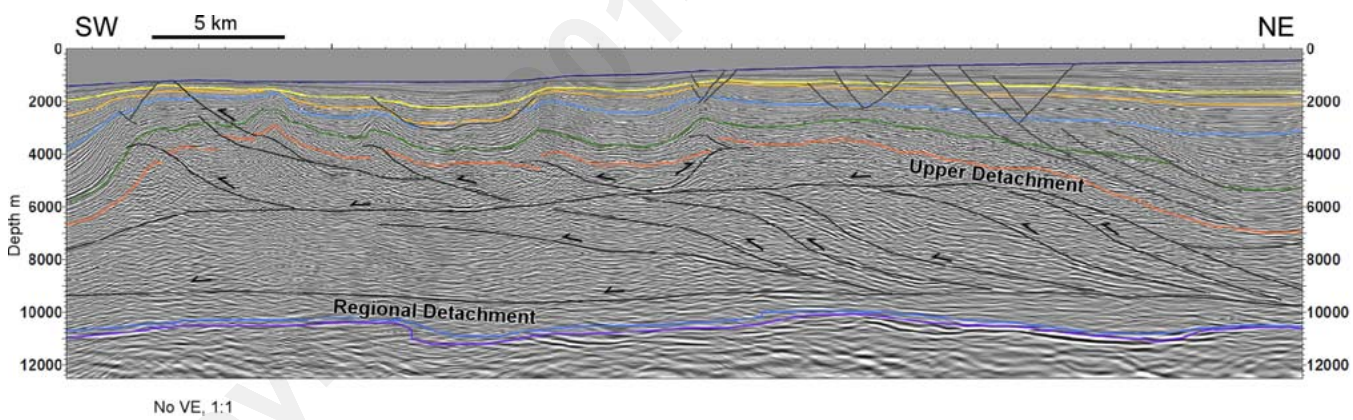

Figure 2B. Detail of Figure 2A shows the duplex feature consisting of an imbricated Akata shale section having an Upper (roof) Detachment and a (basal) Regional Detachment surface. The lower Miocene (17.5 Ma, green) to the Top Akata (39.5 Ma, orange) interval shows a variety of deep drilling targets, involved in folds and thrusts soling out onto the detachment surfaces (no vertical exaggeration). The seismic data is shown courtesy of ION Geophysical Inc.

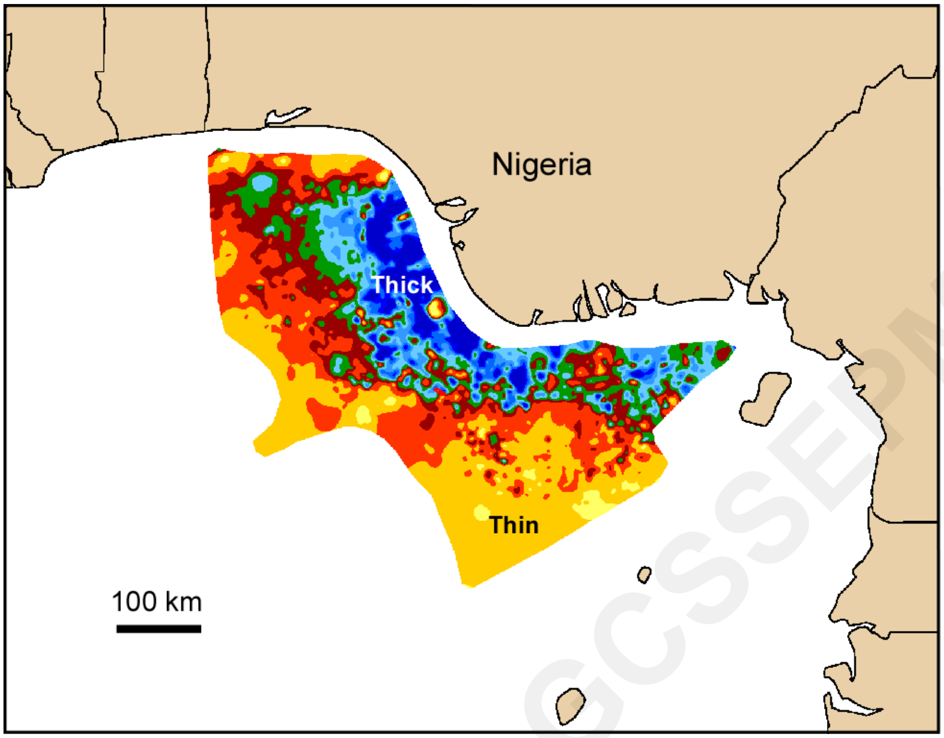

Figure 3. A regional isopach map of the lower Miocene and Oligocene sediments, illustrating thicknesses of the interval from 17.5 Ma (green horizon in Fig. 2) to Top Akata, 39.5 Ma (orange horizon in Fig. 2). The color-fill contours on the map range from thins in the yellow colors to the thicks in the blue colors. The areas that map as thicknesses of 1000 to 2500 meters are shown in the green to blue color fill contours and demonstrate a time of robust deposition, forming a regional wedge of slope-front fill and basin floor sediments derived from a number of fairways on the shelf.