ABSTRACT

Great excitement has recently flowed from the East African and international press at the news of major gas discoveries in Tanzania and Mozambique. Discoveries of approximately 100 TCFG in Mozambique and close to 30 TCFG in Tanzania have been announced in this emerging world-class petroleum province, verifying the existence of a prolific petroleum system. USGS 2012 estimates of undiscovered oil and gas for this province total approximately 12.5 BBO and 250 TCF of gas (Brownfield et al, 2012). Play-opening reservoir systems have been verified in Paleocene, Eocene and at least two Oligocene deepwater submarine fan complexes (Law, 2011), with evidence mounting that the Late Cretaceous section contains deposits from similar depositional settings (TPDC, 2003). Mapping sedimentary systems through time is the key to understanding the distribution of these potentially extensive reservoirs. Here we describe the initial phase of our work to delineate the stratigraphy at multiple scales. Within the constraints of regionally interpreted mega-sequences, we apply finely spaced horizon interpretation to a single long-offset 2D BasinSPAN™ line and then extract Wheeler-transformed chronostratigraphy. Results reveal a highly detailed regional and temporal distribution of down-slope submarine deposits within mega-sequence scale regressive-transgressive successions. Further, application of this method suggests that mapping the internal seismic character of fan complexes can reveal spatial variance in prospectivity.

INTRODUCTION

ION GeoVentures recently completed a long-offset, long-record East AfricaSPAN Phase III survey that encompasses the entire offshore continental margin of Tanzania and Mozambique south to 14°S latitude. This survey follows two prior phases of BasinSPAN™ data collection, Tanzania Phase I and Phase II. Together these data comprise a comprehensive set of 400+ km transects from continental shelf to deep offshore overlying oceanic crust in 4 km water depths (Fig 1). The Jurassic-Tertiary sedimentary section exceeds 4 km in thickness in the area offshore Tanzania and Mozambique (Somali Basin), with much of the sediment derived from the Ruvuma and Rufiji delta systems.
Figure 1. Ion GeoVentures East AfricaSPAN surveys. The subject of this paper, line TZ3-2700, is highlighted in yellow.

Large volumes of sediment were shed off the African craton from Late Jurassic through at least Miocene, punctuated by several major transgressions, leaving the reservoir/seal components of a viable petroleum system present throughout the Late Cretaceous and Tertiary. Four periods of tectonically controlled sedimentation are represented in the seismic records, with large-scale mega-sequence architecture reflecting the fluctuating tectonic regimes through the Mesozoic and Cenozoic (Fig 2).
Figure 2. Tanzanian regional lithostratigraphy, corresponding tectonic events, seismic horizons correlated, and Mega-sequences delineated in East AfricaSPAN Phase III seismic interpretation.

Sources: Lithostratigraphy modified from Fairway/Lynx GIS Advisor on Tanzania, a non-exclusive report available from Lynx http://www.lynx-info.com/gis-tanzania.html. Figure partly produced with TSCreator (http://www.tscreator.org/) visualization of enhanced Geologic Time Scale 2004 database (Version 5.3); 2012 James Ogg (database coordinator) and Adam Lugowski (software developer).
A stratigraphic framework was developed based on recognizing regionally pervasive sequences and unconformities evident in the East AfricaSPAN regional seismic data, and correlated with the regional tectonostratigraphy. Stratigraphic control on unconformity ages is derived primarily from limited well information along the East Africa Coast and from DSDP site 241 (DSDP, 1974).

The four tectonostratigraphic sequences seen in offshore Tanzania and Mozambique are summarized on seismic line TZ3-2700 (Fig 3), with major stratigraphic events highlighted.

Figure 3. Line TZ3-2700 with regionally interpreted Mega-sequences, horizons and faults. Red box shows the area of detailed horizon analysis and Wheeler-transformed chronostratigraphy. This work resulted in a more detailed chronostratigraphic and systems tract analysis within the Eocene through Miocene part of the succession (Mega-sequences 3 and 4).

Within the four Mega-sequences delineated, multiple regressive events contributed to the development of deep sea fan/channel/mass transport lowstand systems at several levels. The tectonostratigraphic evolution of the margin in offshore Mozambique and Tanzania reveals the major steps in basin evolution as follows:
Mega-Sequence 1. Initially, Karoo-age (Paleozoic-early Mesozoic) continent-wide rifting affected mostly the Tanzanian and Kenyan offshore. Karoo-aged rift-fill successions include terrestrial and lacustrine sediments (onshore) transitioning to marine slope and deepwater systems (offshore).

Mega-Sequence 2. The second phase relates to the separation and early drift of the India-Madagascar-Antarctica landmass from the African landmass (Late Jurassic-Early Cretaceous). This breakup and early drift phase includes potential source rocks deposited within sub-basins with restricted circulation as well as Early Cretaceous progradational fan systems which downlap them.

Mega-Sequence 3. The third depositional phase constitutes one Sloss-scale (Sloss, 1963) regressive-transgressive cycle. It ‘blanketed’ the Late Cretaceous-Early Tertiary margin with an initial succession of coarse siliciclastic influx distributed basinwide into fan systems, followed by an impressive thickness of potentially organic-rich shale.

Mega-Sequence 4. Initiated by Eocene uplift of the African craton, a flood of sediment into the Somali Basin distributed reservoir-quality sediment into correlative slope and basin floor fan systems over much of the Tanzania and Mozambique deepwater offshore. The Tertiary succession is characterized by repetitive pulses of regressive lowstand deepwater fan systems responding to this tectonism. The Early Eocene to Early Miocene isopach (Fig 4) shows thick depocenter loci splaying eastward offshore, reflecting increased sediment input by the Ruvuma, Rufiji and other rivers along the coast. Thus many stratigraphic traps in offshore Tanzania and Mozambique are created by large areas of sediment dispersal into basinal fan complexes. These are delta-fed and comprise a system of slope and intraslope feeder channels, levees and outflow fans.
Figure 4. Early Eocene to early Miocene isopach (051 early Eocene unconformity to 022 early Miocene transgression) showing delta-fed depositional loci offshore. Seagap Fault – black dashed line; continental to oceanic crust transition (COT) – olive green dashed line; Kerimbas Graben margin – white dashed line; offshore international boundaries – dark blue dashed lines; well penetrations – black circles; bathymetric contours – light blue dotted lines.
DETAILED CHRONOSTRATIGRAPHY USING dGB Earth Sciences’ HORIZONCUBE SOFTWARE

Within the constraints of the four regional mega-sequences, higher-order intervals were delineated based loosely upon conventional sequence stratigraphic methods in deepwater systems (Posamentier and Kolla, 2003). These higher-resolution units interpreted within the younger two mega-sequences 3 and 4 were further refined on Line TZ3-2700 utilizing dGB Earth Sciences’ HorizonCube analysis (within dGB’s OpendTect SSIS module). After calculating a dGB Steering Cube of apparent dips along the line, finely spaced horizons (seeded at 20m vertical spacing) were then tracked. The relative ages of the detailed horizons were converted to a Wheeler (chronostratigraphic) diagram (Brouwer et al., 2008), which converts seismic horizons to geologic time relative to distance across the survey (deBruin et al., 2007; Qayyum et al., 2012). This work yielded a more detailed chronostratigraphic and systems tract analysis in the Eocene through Miocene part of the succession, which is shown in Figure 5. The corresponding Wheeler transform for each of five time steps is shown below the HorizonCube tracked detailed horizons (Figures 5a thru 5e).
Figure 5. Time step 1. High-resolution chronostratigraphy and fan system distribution on East AfricaSPAN Phase III Line TZ3-2700 (analysis area shown by red box, Figure 3). HorizonCube detailed horizon tracking and Wheeler (chronostratigraphic) transformations shown for 5 ‘time steps’ (packages 1-5 correspond to Figs 5a through 5e). Analyses courtesy of dGB Earth Sciences.

- Each time step shows the distribution of synchronous reflections tracked at 20 m vertical spacing across the seismic profile (HorizonCube) and the relative ages and spatial distribution of each synchronous reflection or “time line” (Wheeler transform).
- Five successively younger time steps. Seismic horizons from BasinSPAN interpretation shown for reference. Colors depicted in Horizon Cube detailed tracking correspond to those in Wheeler diagrams.

Several seaward-stepping regressive pulses are observed immediately above the 108 Early Cretaceous unconformity (red through yellow, Fig 5a). The early packages appear to have been limited in their distribution, which is reasonable considering that they were deposited soon after the onset of a rifting episode (see Fig 1), therefore the paleoslope is likely to have been relatively steep. If these deposits comprise high-density turbidites (of late lowstand or falling stage systems tracts sensu Catuneanu, 2006; Hunt and Tucker, 1992), as is likely after a tectonic pulse steepens basin topography, then the siliciclastics comprising the interval can be expected to be the result of high-density turbidite flows, and therefore sand prone and of good reservoir quality. Several transgressive pulses are observed within the red-to-yellow package, enhancing the prospects for Late Cretaceous fan complex reservoirs to be sealed in shales.

The yellow-to-olive green zone (Fig 5b) delivers sediment much further basinward (possible “forced regressive” systems tract sensu Posamentier and Kolla, 2003), and corresponds to a high-amplitude, growth-faulted and channelized zone within otherwise relatively transparent seismic facies, which occurs widely at this level. These sediments were likely deposited on a lower gradient in a partially filled sub-basin; therefore the clastics are likely to have been distributed distally by lower-density turbiditic flows, so that the vertically stacked, prospective parts of this potential fan package may lie in more eastern positions (olive green).
Figure 5b. Time step 2.

dGB HorizonCube, package 2

dGB Wheeler transform, package 2

Figure 5b. Time step 2.
Figure 5c. Time step 3.
The dark blue interval on the chronostratigraphic diagram (Figs 5b, 5c) corresponds to a regionally extensive, transparent seismic zone and represents the Early Tertiary major transgression, which blankets the depositional margin.

A great degree of incision occurred at the 051 Early Eocene sequence boundary in this area, as is highlighted in the Wheeler diagram by the gap between the medium blue (~ the age of the 051 SB) and the light blue series (Figs 5c, 5d). Interestingly, several overlying Eocene and Oligocene fan packages (the reservoirs of recent exploratory success) successively step landward above the 051 unconformity. This large-scale onlap suggests that the rising African craton experienced decreased uplift rates through the Oligocene, reducing sediment flux to the basin and resulting in regional transgression. This interval also hosts the majority of the known fan reservoirs in burgeoning numbers of recent gas discoveries, suggesting that fan deposition under the long-term overall transgressive regime may give rise to ideal source/reservoir/trap configurations.

Finally, the dark green horizon package shows that another widespread regressive package crosses the entire area, followed shortly thereafter by the start of the long-term Miocene transgression, which shows a low-amplitude continuous seismic character throughout the survey area. The Miocene-aged (?) regressive package is likely coeval with the Miocene fan systems discovered in southern Tanzania and Mozambique; if so, the horizon tracking and chronostratigraphy suggest that these sand-prone reservoirs may exist in a regressive/transgressive pair across much of the survey area.
Figure 5d. Time step 4.

dGB HorizonCube, package 4

dGB Wheeler transform, package 4
dGB HorizonCube, all packages

dGB Wheeler transform, all packages
CONCLUSIONS

A high-resolution chronostratigraphic and systems tract analysis in the Late Cretaceous through Miocene part of the succession of offshore Tanzania clarified potential reservoir system spatial distribution and chronostratigraphic relationships that could not be deciphered at the regional scale using conventional 2D data analyses. The analysis fueled understanding of the existing target reservoirs and offers an enhanced predictability for the distribution of those reservoirs and the petroleum system which encloses them across the region.

ACKNOWLEDGEMENTS

We acknowledge the staffs of ION GeoVentures, the Tanzania Petroleum Development Corporation (TPDC) and dGB Earth Sciences (http://www.dgbes.com). With guidance and input from ION’s East AfricaSPAN interpretation team, dGB provided OpendTect demonstration software, preprocessed the data for the demo line, and ran the Sequence Stratigraphy Interpretation Software module to generate the HorizonCubes and Wheeler diagrams. We are grateful to Brian W. Horn (Chief Geologist, Ion GeoVentures), who accepted our proposal for this work and also suggested this publication venue.

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