Submarine Fan Chronostratigraphy From Wheeler-Transformed ION BasinSPAN Seismic Data, Late Cretaceous – Tertiary, Offshore Tanzania

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Fig. 1. ION GeoVentures East AfricaSPANTM surveys. The subject of this paper, line TZ3-2700, is highlighted in yellow.

Abstract

Great excitement has recently flowed from the East African and international press at the news of major gas discoveries in Tanzania and Mozambique. Gas discoveries of approximately 100 Tcf in Mozambique and close to 30 Tcf 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 Bbb and 250 Tcf of gas (Brownfield *et al*., 2012). Play-opening reservoir systems have been verified in Paleocene, Eocene and at least two Oligocene deep-water 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.

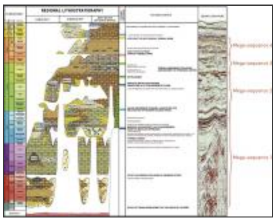


Fig. 2. Tanzanian regional lithostratigraphy, corresponding tectonic events, seismic horizons correlated, and mega-sequences delineated in East AfricaSPAN Phase III seismic interpretation.
Sources: Lithostratigraphy modified from Fairway/Lynx GIS Advisor on Tanzania, a non-exclusive report available from Lynx http://www.lynx-info.com/gis-tanzania.html.
Figure partly produced with TSCreator (http://www.tscreator.org/) visualisation of enhanced Geologic Time Scale 2004 database (Version 5.3); 2012 James Ogg (database coordinator) and Adam Lugowski (software developer).

Introduction

ION's GeoVentures group 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, processed by ION's GX Technology (GXT) experts, follows on two prior phases of BasinSPANTM 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.

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).

A stratigraphic framework was developed based on recognizing regionally pervasive sequences and unconformities evident in the ION 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).

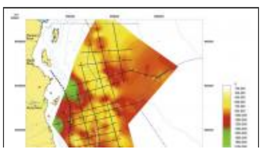
Fig. 3. Line TZ3-2700 with regionally interpreted mega-sequences, horizons and faults. Red box shows the area of detailed horizon analysis and Wheeler-transformed chronostrati-graphy. This work resulted in a more detailed chronostratigraphic and systems tract analysis within the Eocene through Miocene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

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

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 deep-water 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.



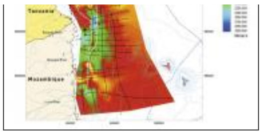
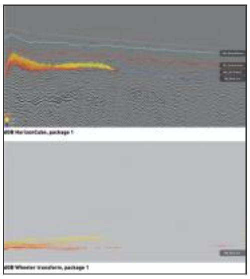


Fig. 4. Early Eocene to early Miocene isopach (051 early Eocene unconformity to 022 early Miocene transgression) showing delta-fed depositional loci offshore. Seagap Fault – black dashed line; continental to oceanic crust transition (COT) – olive green dashed line; Kerimbas Graben margin – white dashed line; offshore international boundaries – dark blue dashed lines; well penetrations – black circles; bathymetric contours – light blue dotted lines.

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 characterised by repetitive pulses of regressive lowstand deep-water 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.

Detailed chronostratigraphy using dGB Earth Sciences' HorizonCube software



High-resolution chronostratigraphy and fan system distribution on East AfricaSPAN Phase III Line TZ3-2700 (analysis area shown by red box, Figure 3). Figures 5a – 5e show five successively younger time steps, each with corresponding HorizonCube detailed horizon tracking and Wheeler (chronostratigraphic) transformation. Sediment packages 1-5 correspond to Figs 5a through 5e. 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). Seismic horizons from BasinSPAN regional interpretation shown for reference. Colors depicted in Horizon Cube detailed tracking correspond to those in Wheeler diagrams. Analyses courtesy of dGB Earth Sciences.

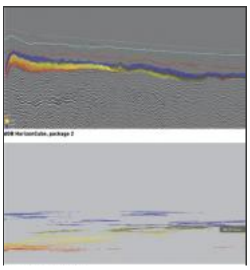
Within the constraints of the four regional mega-sequences, higher-order intervals were delineated based loosely upon conventional sequence stratigraphic methods in deep-water systems (Posamentier and Kolla, 2003). These higher-resolution units interpreted within the younger two mega-sequences 3 and 4 were further refined on Line TZ3-2700 utilising 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 20 m 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).

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 channelised 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).

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.

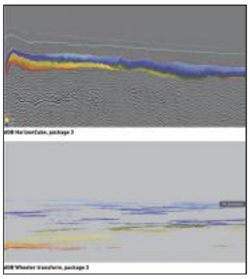


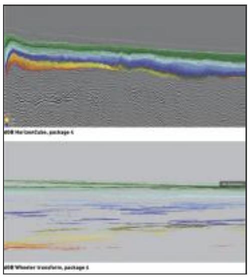
Finally, the dark green horizon package shows that another widespread regressive package crosses the entire area, followed shortly thereafter by the start of the long-term Miocene transgression, which shows a low-amplitude continuous seismic character throughout the survey area. The Miocene-aged (?) 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.

Conclusions

A high-resolution chronostratigraphic and systems tract analysis in the Late

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.





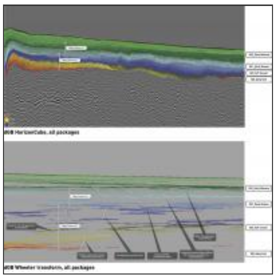


Fig. 5e. Time step 5. High-resolution chronostratigraphy and potential fan system distribution, Early Cretaceous through Miocene.

Acknowledgements

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References

Brouwer, F., de Bruin, G., de Groot, P., and Connolly, D., 2008, Interpretation of seismic data in the Wheeler domain: integration with well logs, regional geology and analogs, 2008 SEG Technical Program Expanded Abstracts, Las Vegas, Nevada.

Brownfield, M.E., Schenk, C.J., Charpentier, R.R., Klett, T.R., Cook, T.A., Pollastro, R.M., and Tennyson, M.E., 2012, Assessment of undiscovered oil and gas resources of four East Africa Geologic Provinces: U.S. Geological Survey Fact Sheet 2012–3039, 4 p. http://pubs.usgs.gov/fs/2012/3039/contents/FS12-3039.pdf

Catuneanu, O., 2006, Principles of Sequence Stratigraphy, Elsevier, Amsterdam, The Netherlands, 375 pp.

deBruin, G., Hemstra, N., and Pouwel, A., 2007, Stratigraphic surfaces in the depositional and chronostratigraphic (Wheeler-transformed) domain, The Leading Edge, July, p. 883–886.

DSDP (1974) Vol. XXV: DSDP Program in the Indian Ocean.

http://www.deepseadrilling.org/25/volume/dsdp25_01.pdf ; http://www.deepseadrilling.org/; or http://www-odp.tamu.edu/

Hunt, D., and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, no. 1–2, p. 1 –9.

International Commission on Stratigraphy (2006). http://www.stratigraphy.org/upload/GSSP_table2011.pdf

Law, C., 2011, Northern Mozambique: True 'Wildcat' Exploration in East Africa* Carol Law1, Search and Discovery Article #110157 (2011), http://www.searchanddiscovery.com/documents/2011/110157law/ndx_law.pdf Posted June 20, 2011

Posamentier, H.W., and Kolla, V., 2003, Seismic geomorphology and Stratigraphy of depositional elements in deep-water settings: Journal of Sedimentary Research, v.73, p. 367–388.

Qayyum, F., de Groot, P., Yasin, J. and Akhter, G. , 2012, Building a Sequence Stratigraphic Framework from HorizonCube and Well Data, 74th EAGE Conference & Exhibition, Copenhagen, Denmark, 4–7 June 2012.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America. Geol. Soc. Am. Bull., 74: 93–113.

Tanzania Petroleum Development Corporation, 2003, Tanzania Petroleum Opportunities, Brochure inviting investment in exploration for oil and Gas.

Wheeler Harry E., 1958, Time Stratigraphy, Bulletin of American Association of Petroleum Geologists: v 42, n. 5, p. 1047–1063.