Wheeler-transformed 2D seismic data yield fan chronostratigraphy of offshore Tanzania

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Recent discoveries offshore Tanzania and Mozambique highlight East Africa as an emerging world-class petroleum province. Oil and gas estimates for this province total 12.5 BBO and 250 TCFG (Brownfield et al., 2012) as yet undiscovered. Play-opening reservoir systems have been verified in Paleocene, Eocene, and at least two Oligocene deep-water submarine fan and intraslope channel complexes (Law, 2011). In deep-water Tanzania, there have been seven gas discoveries (of eight attempts) since 2010, with recent announcements putting total gas reserves in Tanzania at 24–26 TCFG. In neighboring Mozambique, 19 wells were completed by Anadarko and ENI in the Ruvuma Basin from 2009 to June 2012, only two of which were not announced as commercial discoveries. With the additional drilling, the increase of reported reserves now approaches or exceeds 100 TCFG. Evidence continues to mount that suggests the Late Cretaceous section contains deposits from similar depositional settings (Tanzania Petroleum Development Corporation, 2003). There are also indications that the petroleum system may contain oil as well as the established gas.

Mapping evolving sedimentary architecture through time is the key to understanding the distribution of these potentially extensive deep-water reservoirs. In the initial phase of our work, we delineate the stratigraphy at multiple scales, using a modified version of conventional deep-water sequence stratigraphic interpretation concepts. Within stratigraphic constraints provided by regionally interpreted mega-sequence boundaries, we apply finely vertical-spaced horizon interpretation to a portion of Line TZ3-2700 of ION GeoVentures' long-offset 2D BasinSPAN survey and from it extract Wheeler-transformed chronostratigraphy (Wheeler, 1958). The resulting outputs (HorizonCube and Wheeler transform) together show the updip-downdip extent of deep-water systems, as well as the temporal variability in their architecture.

Results reveal a detailed regional and temporal distribution of deep-water submarine fan deposits within mega-sequence scale regressive-transgressive successions. Further, application of this method suggests that mapping the internal seismic character of fan complexes reveals temporal and

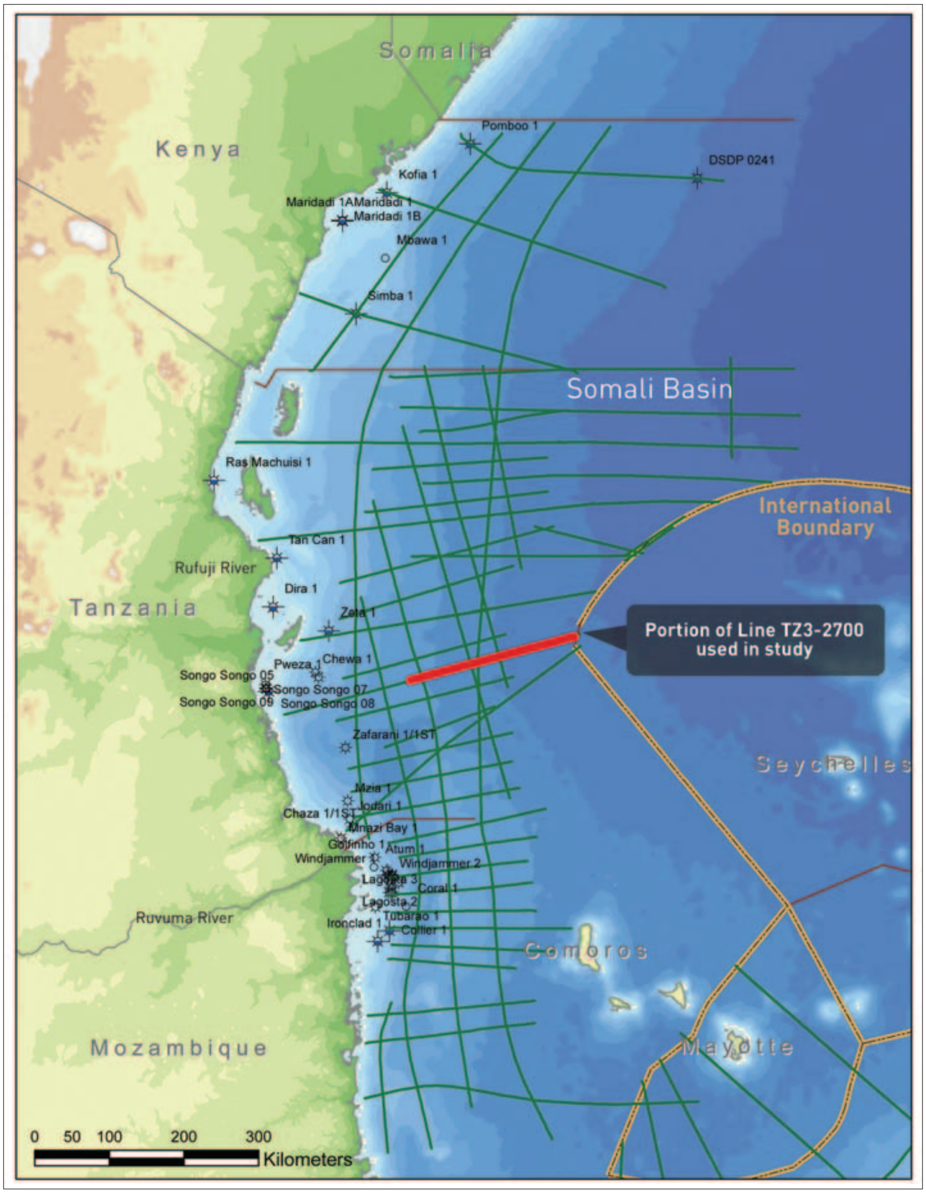

Figure 1. *ION GeoVentures East AfricaSPAN surveys. The portion of line TZ3-2700 shown in red is the subject of this article. Orange lines are proposed UNCLOS maritime boundaries in deep water.*

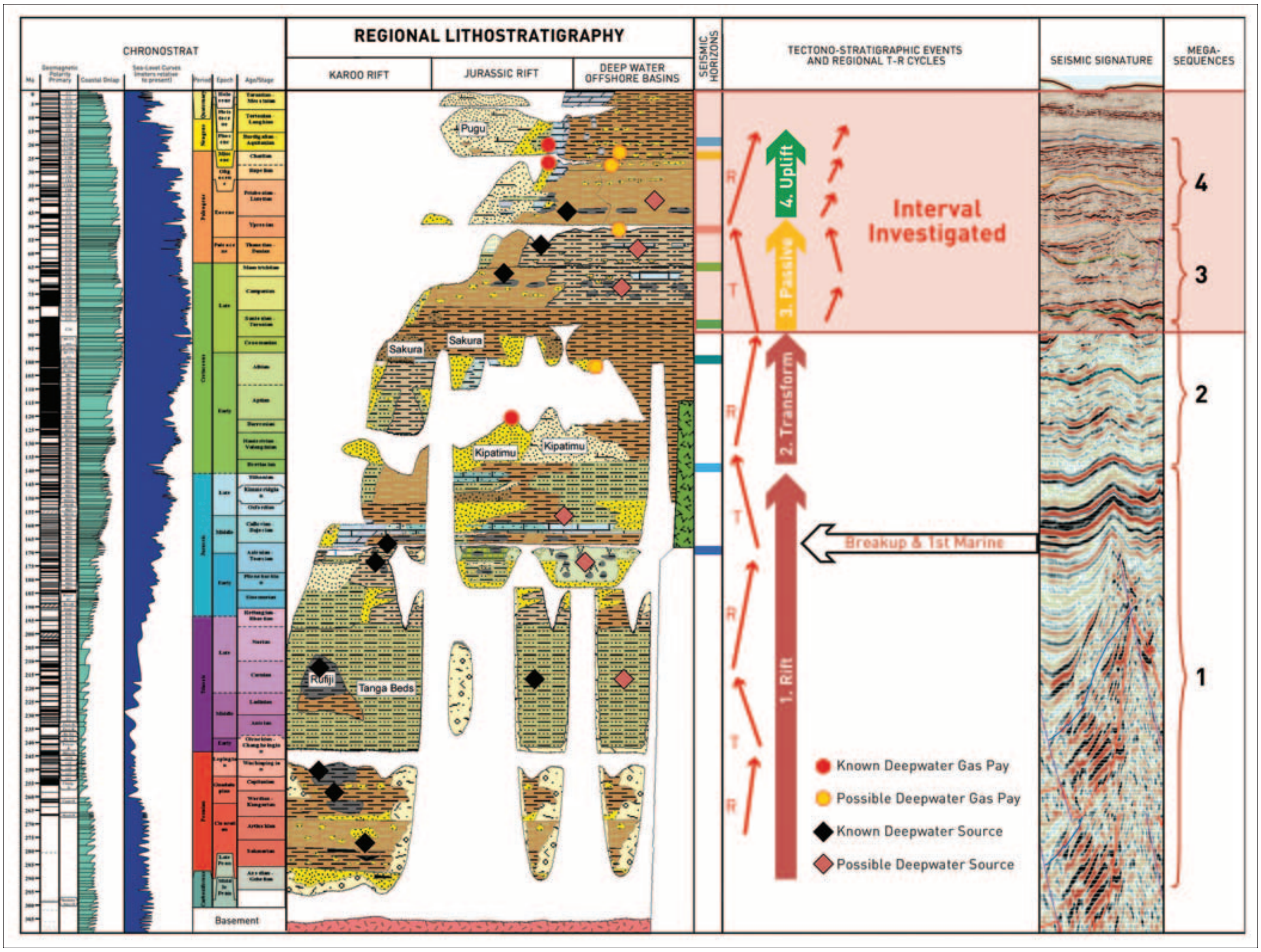

Figure 2. *Tanzanian regional lithostratigraphy showing correspondence with seismic horizons and the four tectono-stratigraphic mega-sequences correlated in the East AfricaSPAN Phase III seismic interpretation. This work details seismic geometries and chronostratigraphy within the youngest two mega-sequences (3 and 4). 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).*

spatial variance in fan character. We conclude that the mega-regional SPAN seismic surveys are sufficiently high quality to effectively reconstruct detailed chronostratigraphy, map depositional systems tracts, and refine play definition and prospectivity.

Introduction

ION's GeoVentures group recently completed a long-offset (10 km), long-record (40 km) East AfricaSPAN Phase III survey that traverses the offshore continental margin of Tanzania and Mozambique. Processed by ION's GX Technology (GXT) group, this survey follows on two prior phases of BasinSPAN data collection, Tanzania Phase I and Phase II. Together these data comprise a comprehensive set of 400+ km long transects from continental shelf to deep-offshore overlying oceanic crust in 4 km water depths (Figure 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.

Following a regional interpretation of the Phase III data that delineated only the major tectono-stratigraphic sequences, we needed to extract more detailed information, possibly at the sequence scale, than was possible at the mega-regional scale. Therefore we chose a single, prestack depth-migrated (PSDM) dip line upon which to attempt a more detailed sequence stratigraphic interpretation. This single-line demonstration served as a test of dGB HorizonCube software's ability to extract meaningful, detailed chronostratigraphy from high-quality seismic data. The dramatic results described here paved the way for additional sequence-scale work, currently underway, on other seismic lines from the Tanzania and Mozambique surveys.

Regional tectono-stratigraphic framework

Large volumes of sediment were shed off the African craton from the Late Jurassic through at least the Miocene, punctuated by several major transgressions, that left the reservoir/seal components of a viable petroleum system present throughout much of the Cretaceous and Tertiary section.

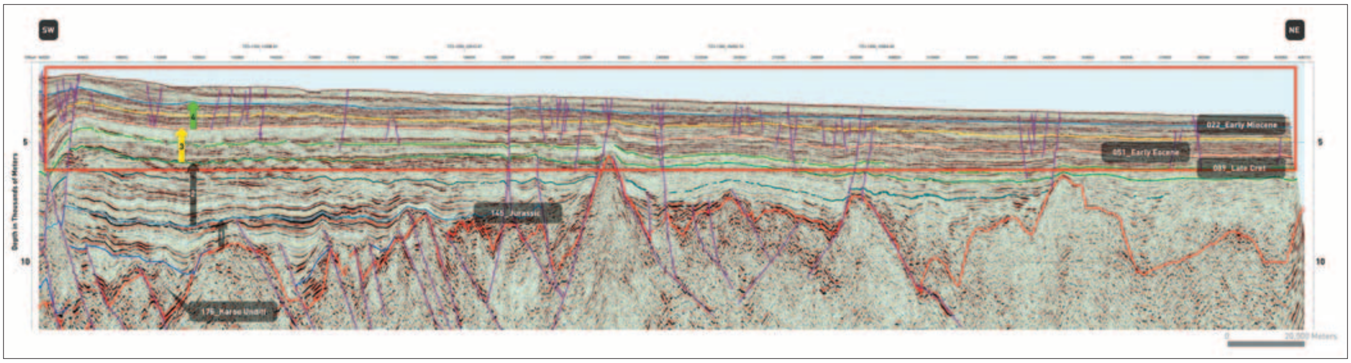

Figure 3. *Line TZ3-2700 with regionally interpreted mega-sequences, seismic horizons, and faults. Red box shows the area of detailed HorizonCube analysis and Wheeler-transformed chronostratigraphy. These results show the highly detailed chronostratigraphic and systems tract analysis extracted from the Eocene through Miocene part of the succession (mega-sequences 3 and 4).*

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 (Figure 2).

A stratigraphic framework was developed based on recognizing regionally pervasive sequences and unconformities evident in the regional seismic data that were “jump” correlated with major tectonostratigraphic events recognized in compiled onshore well and outcrop data. All of the 2D seismic data lie far offshore and do not directly tie any wells. The unobserved strandlines, presumably coeval with the deep-water sediments of this study, lie to the west. In the absence of a coeval shoreline with which to relate shoreline and shelf migration, as in conventional seismic stratigraphy (we were operating in an “onlap-free” world), we developed revised interpretation techniques for determining the regional tectono-stratigraphic packages. An example is the distinct seismic facies contrast representing the boundary between mega-sequences 3 and 4, shown in the center of line TZ3-2700 (Figure 3) and present over a wide area. Boundaries such as these were taken to represent the deep-water correlative conformities of mega-sequence boundaries within our study area downdip from the only well control, which occurs in shallow water west of the study area. Stratigraphic control on unconformity ages was derived primarily from limited well information along the East Africa Coast and from DSDP site 241 (DSDP, 1974) in Kenya, 800 km to the north (Figure 2).

The four tectonostratigraphic sequences seen in offshore Tanzania and Mozambique are summarized on seismic line TZ3-2700, with major stratigraphic events highlighted. Within the four mega-sequences and some of the prominent transgressive surfaces delineated, multiple regressive events contributed to the development of deep-sea fan/channel/mass transport lowstand systems at several stratigraphic 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, Paleozoic-early Mesozoic (Karoo-age) 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). The end of this succession is marked by the initial marine incursion into the area, including deposition of potential source rocks.

Mega-sequence 2. The second phase of tectonostratigraphic evolution 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 the evolving sub-basins with restricted circulation as well as Early Cretaceous regressive progradational fan systems that downlap them.

Mega-sequence 3. Late Cretaceous drift followed by Early Tertiary passive margin subsidence produced an initial succession of coarse siliciclastics distributed basinwide into fan systems, blanketed by an impressive thickness of transgressive, potentially organic-rich shale. This depositional phase constitutes one Sloss-scale (Sloss, 1963) regressive-transgressive cycle.

Mega-sequence 4. Initiated by Eocene thermal (?) uplift of the African craton, a flood of sediment into the Somali Basin distributed reservoir-quality clastic sediments into slope and basin fan systems over much of the Tanzania and Mozambique deepwater offshore. The Tertiary succession is characterized by repetitive pulses of regressive lowstand deep-water fan systems responding to this tectonism. The Early Eocene to Early Miocene isopach (Figure 4) shows thick depocenter loci splaying eastward offshore, reflecting increased sediment input by the Ruvuma, Rufiji and other rivers along the coast. Multiple stratigraphic traps in offshore Tanzania and Mozambique have been created by large volumes of sediment dispersal into submarine fan complexes. These are delta-fed and comprise a system of slope and intraslope feeder channels, levees and outflow fans that were later transgressed and sealed by thick marine shales.

Methodology: Extracting detailed chronostratigraphy within mega-sequences 3 and 4

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). To evaluate seismic geometries and their distribution in the Late Cretaceous and Tertiary sedimentary section (mega-sequences 3 and 4), dGB Earth Sciences' HorizonCube analysis (within the OpendTect SSIS module) was applied to a portion of PSDM Line TZ3-2700 (Fig 3). The goals were twofold: (1) to test whether the software could effectively delineate finer-scale stratigraphic geometries and sediment distribution in 2D on an individual 400+ km 2D seismic line, and (2) to convert any detailed seismic stratigraphic output that might result into a chronostratigraphic (Wheeler) diagram. Meeting these two objectives together would allow multiple petroleum system components to be mapped both spatially and temporally. Additionally, tying sequence boundaries mapped in the 2D seismic data offshore to the bounding surfaces of higher-order stratigraphic packages identified in onshore positions would facilitate comparison and prediction of reservoir/source/seal occurrences in the offshore.

The workflow used to generate the high-resolution stratigraphy within the HorizonCube was constrained by the primary seismic horizons of mega-sequences 3 and 4 and by key faults selected by the interpretation team: the 108 Ma Early Cretaceous unconformity, the 51 Ma Early Eocene unconformity, and the 22 Ma Early Miocene transgression (Figure 3). The 65 Ma K/T horizon was also carried and is shown for reference in the figures, but was not used to constrain the algorithm in the initial phase. The first step began with calculating a dGB Steering Cube of apparent

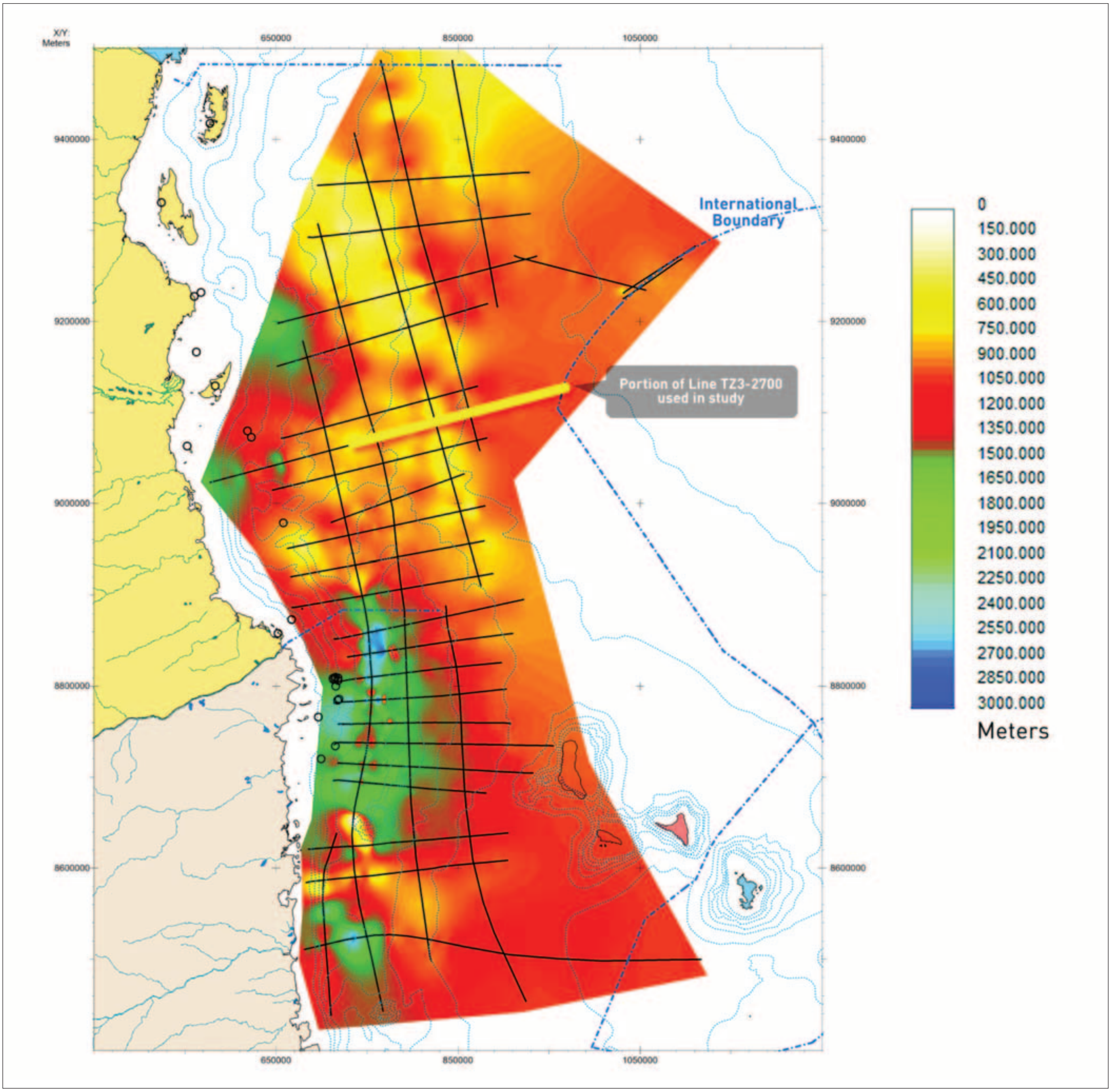

Figure 4. *Mega-sequence 4 (Early Eocene to Early Miocene) isopach showing Ruvuma and Rufiji delta-fed depositional loci offshore (green colors where isopach thickness > 1500 m).*

dips along the 2D line, preserving both global and local dip trends. These apparent dips were then used to filter the data using a dip-steered median filter (DSMF) for noise reduction and improved horizon tracking. The DSMF is a dip-oriented filter aimed at amplifying trace-to-trace coherence. After calculating a Steering Cube of apparent dips along line TZ3-2700, finely spaced horizons (20 m vertical spacing) were seeded and then tracked. Seeding occurred at a single trace location. At this starting position, a fixed number of events were initiated with user-defined vertical spacing between seeding events. Events then propagate outward from the start position. These detailed horizons were preserved as a calculated HorizonCube. Horizons generated were then flattened and displayed in vertical position relative to their geological age to create a Wheeler diagram. Finally, a density attribute was also calculated, which defines the density of HorizonCube events in a defined depth window.

HorizonCube generation

The HorizonCube analysis applied in this work utilized software developed by dGB Earth Sciences. A HorizonCube is a data element created by combining many closely spaced, vertically stacked horizons, typically spaced on the order of the seismic sampling interval. A HorizonCube is created using strata-slicing methodology, which can be either model-driven (Zeng et al., 1998a and b) or data-driven (using dip or azimuth steering, for example). The HorizonCube generates events using either model-driven or data-driven computation. In this case, we chose data-driven calculation, using the precomputed dip-based steering cube. This method of event generation is powerful in combination with an advanced multi-horizon auto-tracking algorithm. The tracking algorithm is based on following the dip and azimuth of the seismic data. Dip fields are preferred over amplitude fields because they are more continuous and less prone to noise. The interval in which the HorizonCube is calculated is bounded by at least two framework or constraining horizons. Framework horizons are either mapped with a conventional amplitude and similarity tracker or with the same dip-steered autotracker. The advantages of the dip-steered auto-tracker are the speed and the tracker's greater awareness of faults. By automatically stopping against mapped fault planes, for example, precise horizon intersections at faults can be generated (Qayyum et al., 2012).

The multihorizon tracking then typically starts at the position of maximum isopach value and horizons are initiated at a user-determined seismic sampling density. On 3D sections (or 2D lines), the algorithm extends the horizons outward from the start position. Two modes are supported and have been used in this study: continuous horizon tracking and truncated horizon tracking. In the continuous mode, horizons tend to merge along unconformities and condensed sections. Such geologic features are highlighted with the HorizonCube density attribute. When horizons diverge extra horizons are tracked in a second or later iteration. In the truncated multi-horizon tracking mode, horizons stop when they converge below a user-defined vertical spacing threshold. Three iterations were utilized to complete the HorizonCube across the survey.

Wheeler (chronostratigraphic) transform generation

Both types of HorizonCube output can be used as input to a Wheeler transformation, which flattens each seismic tracked horizon (deBruin et al., 2007). The truncated mode of HorizonCube generation is preferred in sequence stratigraphic interpretations as it clearly shows hiatuses and depositional trends in the Wheeler domain. The software produces a Wheeler transform directly from the seismic data by converting closely spaced, vertically stacked seismic horizons (time lines) into "Wheeler-space" high-resolution chronostratigraphy. Each time line is flattened and its spatial extent displayed while retaining relative geologic age relationships between horizons.

The relative ages of the detailed horizons calculated in the HorizonCube step were converted to a Wheeler diagram, thereby illustrating seismic "time" horizons converted to geologic time (y-axis) relative to distance across the survey (x-axis) (Qayyum et al., 2012). Conventionally in a chronostratigraphic display, the y-axis is linear geologic time and is calibrated with data from nearby wells (e.g., biostratigraphy). However, because the only age calibration available was the ION interpretation team's age assignments to mega-sequence boundaries, the time scale calibration in this case is an approximation at best. A constant sedimentation rate was assumed for similar reasons.

Density attribute

Reflection events often converge and diverge in space; this feature is particularly pronounced in the closely vertically spaced horizons generated in HorizonCube, and therefore can be calculated as an attribute. HorizonCube density is a trace-based attribute which calculates the vertical density of HorizonCube events within a user-defined time or depth window. It outputs two sub-attributes: event count, i.e., the number of horizons tracked by the HorizonCube within the defined gate (±10 m in this case), and density, which is the ratio between the event count and the interval thickness (meters in this case). These attributes are then used to map or visualize zones of changing event density and convergence patterns such as pinch outs, unconformities or condensed intervals. These features appear as high-density values, reflecting zones of slow sedimentation or nondeposition.

Results

This work yielded a detailed chronostratigraphic and systems tract analysis of the Late Cretaceous through Miocene part of the succession (Figure 5, mega-sequences 3 and 4). HorizonCube-tracked detailed horizons and their corresponding Wheeler transform were output for the entire stratigraphic interval.

Several seaward-stepping regressive pulses are observed immediately above the 108 Ma Early Cretaceous unconformity (red through yellow in Figure 5). The early packages appear to have been limited in their basinward extent, which is reasonable considering that they were deposited soon after the onset of a tectonic episode (Figure 2), where the paleoslope was likely relatively steep and where paleo water depth increased dramatically. 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. The steep profile of these deposits suggests that they were heaped across a narrow distance into a deepwater basin. Several transgressive pulses are observed within the red-to-yellow package, enhancing the prospects for Late Cretaceous fan complex reservoirs to be interbedded with and sealed in shales.

The yellow-to-olive green zone in Figure 5 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).

The dark blue interval on the chronostratigraphic diagram (Figures 5a and 5b) corresponds to a regionally extensive, transparent seismic zone and represents the Early Tertiary major transgression, which blankets the depositional

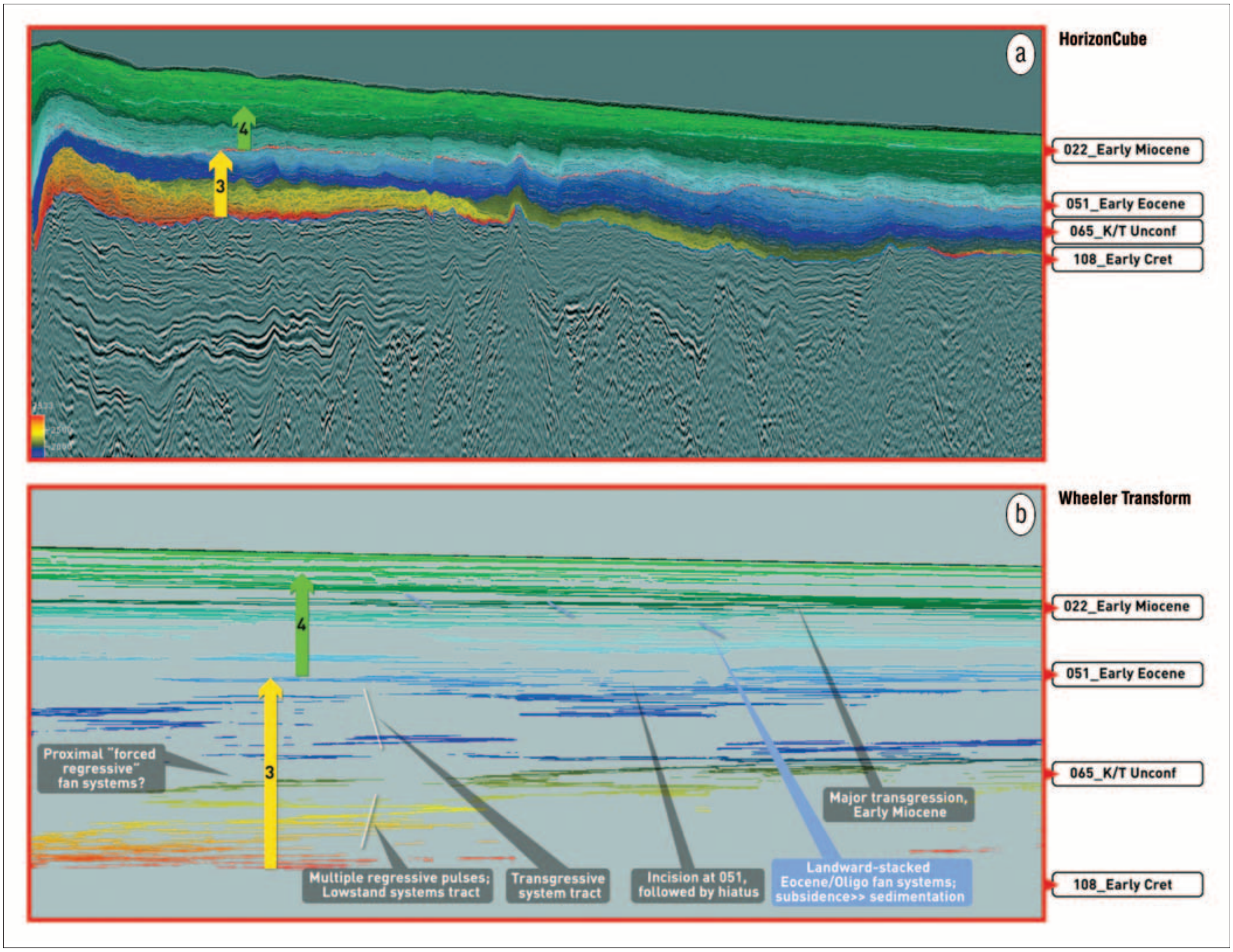

Figure 5. *High-resolution chronostratigraphy and fan system distribution, Early Cretaceous through Miocene, East AfricaSPAN Line TZ3-2700 (analysis area shown by red box in Figure 3): (a) calculated HorizonCube, or the distribution of the multiple, closely spaced horizons generated and tracked at 20-m vertical spacing across the seismic profile and (b) the corresponding Wheeler transform of the HorizonCube, or the relative ages and lateral distribution of each interpolated horizon (time line). Seismic horizons from regional interpretation used to constrain HorizonCube calculations shown for reference. Reflection package colors in HorizonCube displays correspond to those in Wheeler diagrams. Sequence stratigraphic significance of internal elements of mega-sequences 3 and 4, delineated by dGB Wheeler-transformed seismic data.*

margin. The Wheeler-transformed seismic data clearly shows landward-stepping deposition within transgressive systems tract.

A great degree of incision occurred at the 51 Ma 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 51 Ma Eocene SB) and the light blue series. Interestingly, several overlying Eocene and Oligocene fan packages (the reservoirs of recent exploratory success) successively step landward above the 51 Ma 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.

The horizon density attribute reveals the higher-order, landward-seaward shifts of depositional elements within the mega-sequences (Figure 6, bottom). Zones of maximum reflection convergences represent slowest sedimentation rates or condensation (darker red colors). This attribute highlights several internal components within each mega-sequence, which were not easily observed in the amplitude or horizon data. It also highlights potential architectural differences between the deepwater systems of mega-sequence 3 and mega-sequence 4. For example, a steepened (slope?) margin occurs at the base of mega-sequence 3 (small arrow 3a), followed by an onlapping depositional lobe (lowstand fan system?) represented by 3b, followed by another basinal downstep shown as 3c (younger lowstand fan?). The depositional locus shifts landward at 3d and oversteps the underlying fan systems. The system shown by 3e suggests either a landward expansion of the transgressive

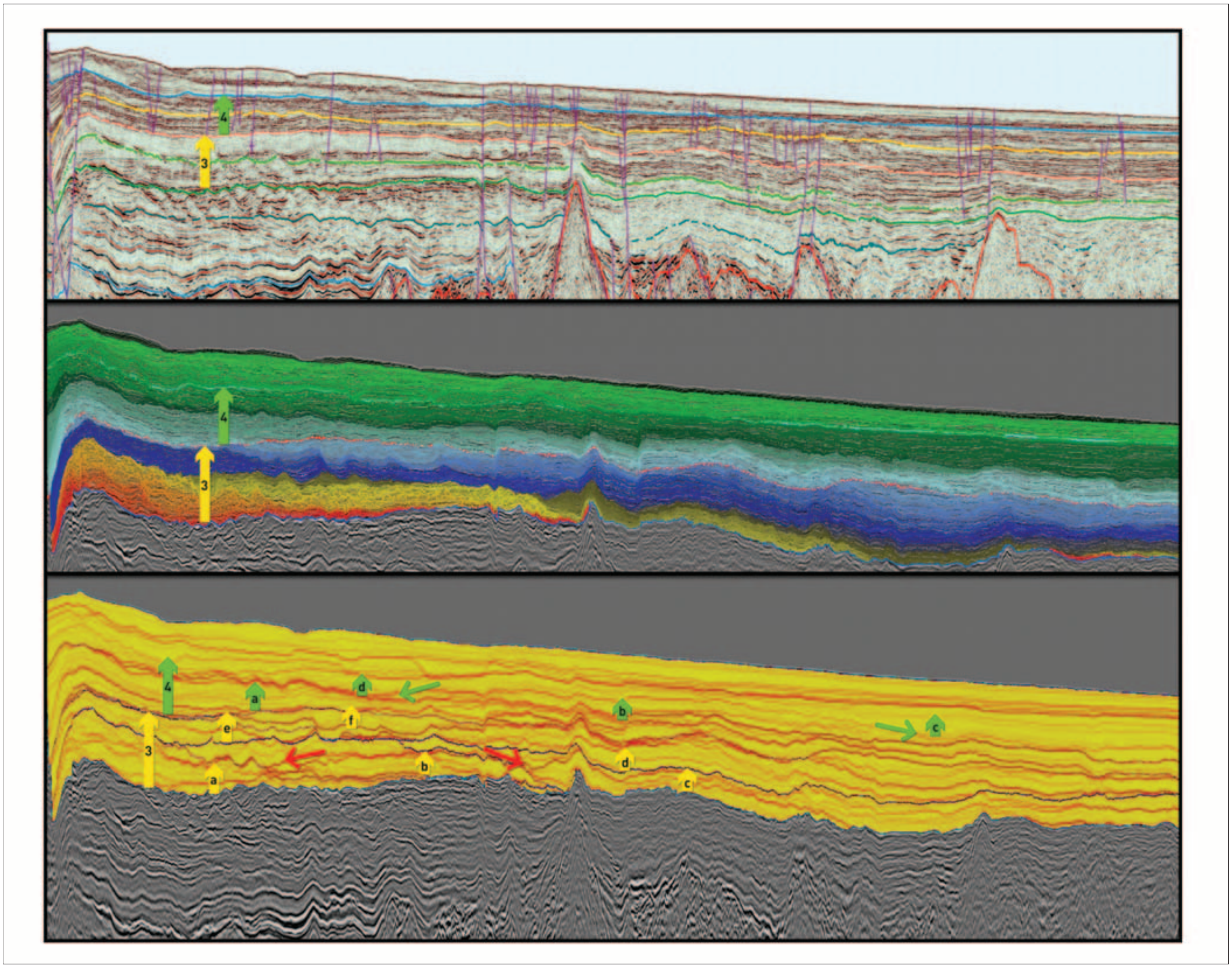

Figure 6. *Density attribute display (bottom) compared to original seismic data and HorizonCube details.*

portion of 3d or a younger higher-order system. In either case, the reservoir/source/seal configuration is ideal for hydrocarbon entrapment. In contrast, the base of mega-sequence 4 (small arrow 4a) suggests the existence of a possible slope margin, followed by a basinward shift in deposition (arrows 4b, 4c) with bidirectional downlap of the enormous depositional lobe represented by 4b. A transgressive systems tract (4d) oversteps this system and is easily distinguished on the density attribute as well as on the Wheeler transform diagram.

Conclusions

A high-resolution chronostratigraphic and systems tract analysis in the Late Cretaceous through Miocene part of the succession of offshore Tanzania has clarified potential reservoir system spatial distribution. It has also resulted in a more detailed chronostratigraphic and systems tract analysis in the Late Cretaceous through Miocene part of the succession (mega-sequences 3 and 4). The likely reservoir intervals identified are comparable to producing horizons encountered in recent exploration wells in Tanzania and Mozambique, and are observed commonly in the 2D seismic survey data. These intervals show seismic geometries, facies, and attributes analogous to productive intraslope and basinal fan complexes in other deepwater hydrocarbon provinces worldwide (Chakhmakhchev and Rushworth, 2012). Chronostratigraphic relationships that could not be deciphered at the regional scale using conventional 2D data analyses were clarified at a higher order of resolution (Figure 5). Detailed horizon tracking, Wheeler time/space displays and density attributes offered powerful enhancements to our interpretation. Results from the single-line demo were encouraging enough that the analysis is currently being extended to create a regional framework. The analysis improved our understanding of the existing target reservoirs and offers enhanced predictability for the distribution of those reservoirs and the petroleum system that encloses them across the offshore East Africa region.

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