A snapshot of the geotectonics and petroleum geology of the Durban and Zululand Basins, offshore South Africa

Madhurima Bhattacharya[1*] and Gregor Duval[1] share the results of a broadband 2D survey that shed new light on the interpretation of the geology in the area.

The offshore Durban and Zululand Basins have recently become of interest to the oil and gas industry as a result of large discoveries made along the eastern margin of Africa, most notably in Tanzania and Mozambique. In South Africa, exploration over the last three decades has focused on near-shore trends of rotated fault blocks and a combination of structural-stratigraphic traps. This has resulted in the drilling of four wells north-east of the city of Durban. Although no wells have been drilled in the deepwater acreage yet, the area is considered to have petroleum potential.

As a result of the growing industry interest and with collaboration from Spectrum and the Petroleum Agency of South Africa (PASA), CGG acquired a new multi-client broadband 2D seismic survey (CDZ13-14) in the Durban and Zululand Basins (Figure 1). The data were processed with Kirchhoff pre-stack time migration (PreSTM). The survey was shot and processed in two phases (2013-2014) using BroadSeis, a proprietary broadband solution using variable-depth streamers and advanced imaging technologies, and consisted of 6920 km of 2D lines over held acreage. The survey is made up of 42 lines widely spaced over the Durban and Zululand Basins and includes 17 strike lines and 25 dip lines. Water depths within the area of interest range from 400 m to 3200 m. The results of this broadband 2D survey have shed new light on the interpretation of the geology in the area.

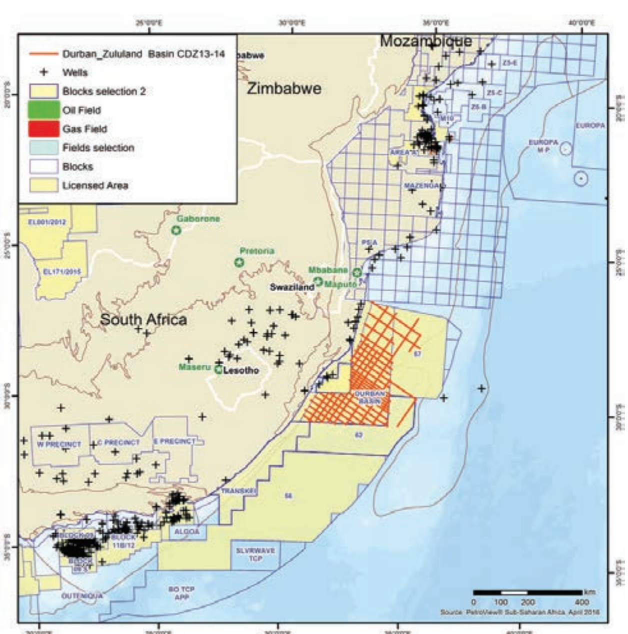

Figure 1 Map showing CGG's broadband 2D CDZ13-14 survey in the Durban-Zululand Basins along with well and field locations in the eastern and south-western margins of Africa.

South Africa exploration history

The first organised effort to explore for hydrocarbons in South Africa was undertaken by the Geological Survey of

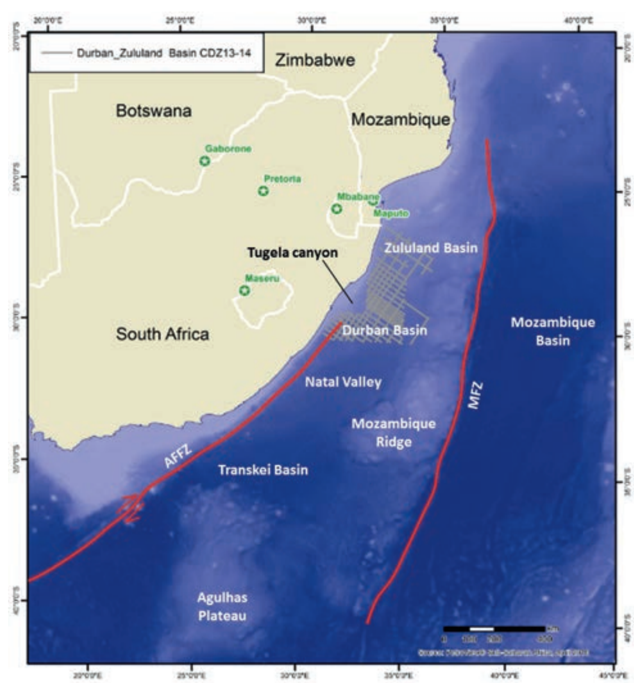

Figure 2 showing the CDZ13-14 survey and adjacent southwest Indian Ocean bathymetry. Note the location of the Durban and Zululand Basins, Natal Valley, Mozambique Ridge, Mozambique Basin, Transkei Basin and Agulhas Plateau. Two oceanic transforms are the Agulhas Falkland Fracture Zone (AFFZ) and Mozambique Fracture Zone (MFZ).

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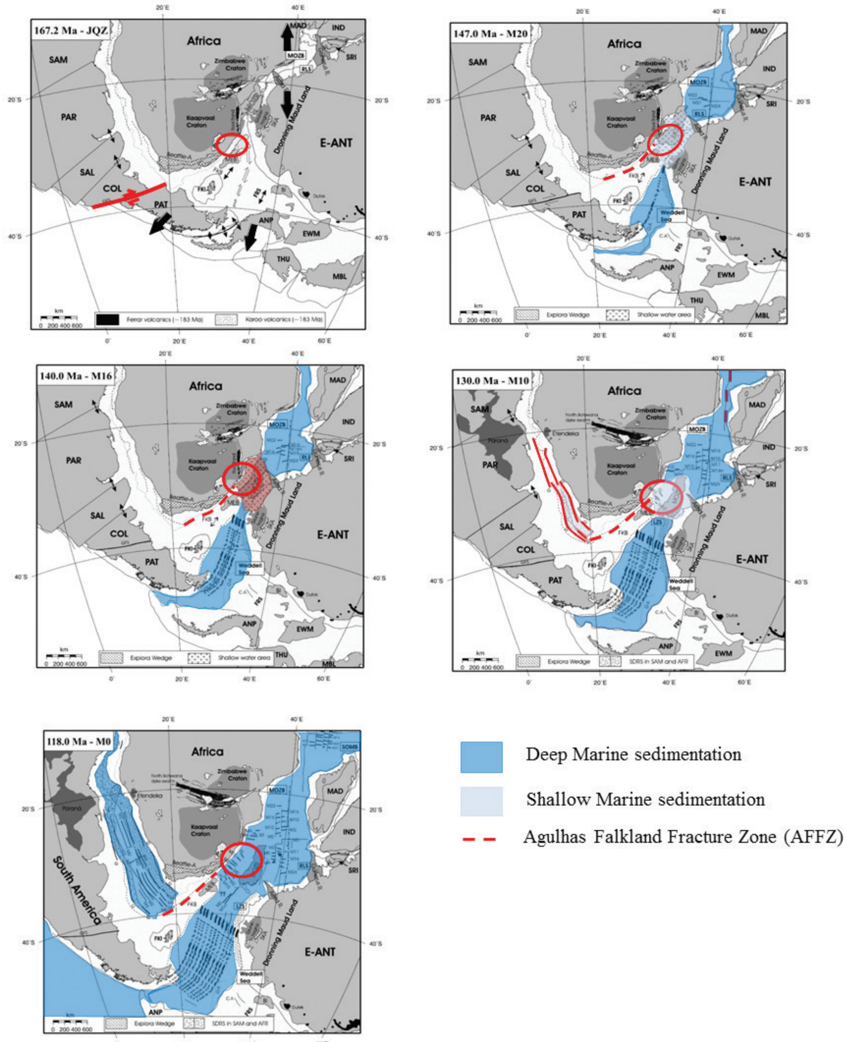

***Figure 3** Series of plate-reconstructions showing the evolution of Durban and Zululand Basins from break-up to the development of passive margin stage. Images modified from König and Jokat, 2006. Note: MOZR – Mozambique Ridge, MOZB – Mozambique Basin, RLS – Riiser Larsen Sea, MEB – Maurice Ewing Bank, FKB – Falkland Basin, FKI – Falkland Island, FRS – Filchner-Ronne shelf, MAD – Madagascar, IND – India, SAM – South America, PAR – Parana, SAL – Salado, COL – Colorado, PAT – Patagonia.*

South Africa in the 1940s. In 1965 SOEKOR (Pty.) Ltd. was formed by the South African government and the focus of exploration was directed at the onshore areas of Karoo, Algoa and Zululand Basins. In 1967 a new Mining Rights Act was passed and offshore concessions were granted to a number of international operators including Total, Gulf Oil, Esso, Shell, Arco, Superior Oil and CFP. This led to the drilling of the first offshore well in 1969 by Superior Oil which resulted in the discovery of gas and condensate in the Ga-A1 well situated in the Pletmos Basin. In 1970 all the major international companies withdrew from South Africa as a result of political sanctions against South Africa. From the mid-1970s to the late-1980s SOEKOR was the sole explorer and operator. The offshore area was reopened to international operators after a licensing round held in 1994.

In 1999, PASA was established along with a new state oil company, PetroSA, in 2001. In the entire offshore area of South Africa there are now 300 exploration wells, including appraisal and production wells. In addition, 233,000 km of 2D seismic data and 10,200 km^2 of 3D seismic data have been acquired since exploration began offshore, with the main focus being the Bredasdorp Basin since the 1980s.

The Durban and Zululand Basins off the east coast of South Africa are largely unexplored and cover an area in excess of 100,000 km^2. With sparse seismic coverage and four wells (Jc-A1, Jc-B1, Jc-C1 and Jc-D1) on the shelf, numerous leads have been identified in this underexplored frontier area. These four wells are located on the continental shelf, within a sediment bypass zone since Oligocene times (Wiles et al., 2013). At present, there are no deepwater exploration wells in the deep offshore parts of the basin which are the focus of this paper. However, DSDP well 249 located to the north-east of the new seismic survey on the Mozambique Ridge was used in our geological interpretation of the area.

Geological setting

The Durban and Zululand Basins are located off the south-eastern margin of Southern Africa. The sedimentary basin can be subdivided at ~29° south into the southern Durban Basin and the northern Zululand Basin. The Zululand Basin forms the southern continuation of the Mozambique Basin which hosts the onshore giant Pande and Temane gas fields. Physiographically, the basins sit within the Natal Valley (Figure 2), a major depression on the present-day ocean floor. To the east, the basin is bounded by the Mozambique Ridge – a large submarine plateau – and, to the west, by the South-East African continental margin. The Northern Mozambique Ridge block is considered to be of volcanic oceanic origin and the central and southern Mozambique Ridge as continental crust (Tikku et al., 2002). To the south, the Natal Valley deepens southwards where it merges with the deep Transkei Basin. The Durban and Zululand Basins are subdivided by the NE-SW trending Naudé Ridge, which is a local volcanic basement high, well identified on the new seismic data. The southern Durban Basin has been affected by the right-lateral movement (dextral) of the 1200-km long Agulhas-Falkland Fracture Zone (henceforth, AFFZ) during the Early Cretaceous and is considered to be a conjugate for the Maurice Ewing Bank located on the eastern side of the Falkland Plateau.

Tectonic and depositional history

The pre-cursor to the break-up of Gondwana was the emplacement of Early to Middle Jurassic, Toarcian-age (183-178Ma) Karoo-Ferrar volcanics (König and Jokat, 2010; Reeves et al., 2016). During this period, basalts, rhyolites and dyke swarms were emplaced in South-East Africa and Antarctica. This marked the early phase of the rupture between East Africa and Antarctica at 188Ma, followed by the break-up at 170Ma (Reeves et al., 2016). By Tithonian times (153 Ma), an extensional regime in a NW-SE direction turned into a N-S dextral strike slip on the eastern margin of Africa. This is thought to be a passive event (i.e. not plume-driven) which set the scene for Antarctica to move west with respect to Africa, thus beginning the westward movement of Antarctica past the SE margin of Africa.

By Valanginian times (136Ma), the Falkland Plateau starts to move westwards as one continent with South America marking the beginning of South Atlantic Rifting (Figure 3). During Valanginian and continuing later into Barremian–Aptian times (127-124Ma) new input from the Karoo/Bouvet plume added magmatic material on to the Mozambique Ridge and Explora Wedge off Antarctica. This movement was accommodated along the AFFZ with a right lateral (dextral) movement and cleared the southern tip of Africa, thus opening the Natal Valley and the Transkei Basin to the south of the area of interest discussed in this paper. Thereafter, the development of a deepwater gateway formed between the Indian and the South Atlantic Ocean from 122Ma (König and Jokat, 2006).

This period of intense tectonism was followed by passive margin development in the Durban and Zululand Basins. By the Mid-Early Cretaceous, a proto-Tugela River drainage system became active, thus depositing sediments into the deep basinal areas of the Natal Valley via the Tugela Canyon. The Tertiary saw three periods of uplift: an Oligocene-age uplift of the African craton accompanied by marine regression, followed by a second phase of uplift in the Miocene, which is observed in the shelf area accompanied by the deposition of modern Tugela River sediments, which was then followed by a Pliocene uplift (Wiles et al., 2013).

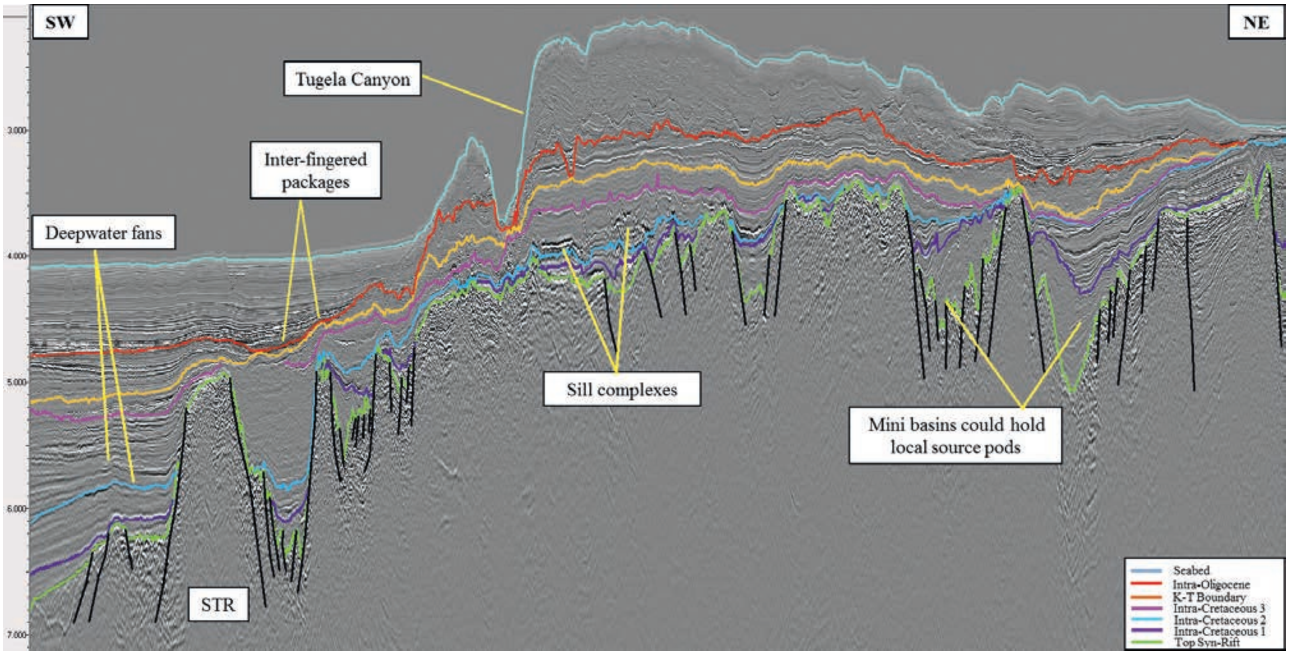

***Figure 4** Seismic cross-section illustrating the different basin elements observed within the survey area around the South Tugela Ridge (STR).*

Seismic interpretation

Keeping the complex tectonic context in mind, seismic interpretation was carried out in order to assess the basin development and to subsequently highlight the presence of a potential petroleum system within the CDZ13-14 survey. A total of eight regional reflectors were picked to improve the overall understanding of the development of the Durban and Zululand Basins, namely: Basement and Pre-Rift, Syn-Rift, Intra-Cretaceous reflectors (three in total), K-T Boundary, Intra-Oligocene and Seabed. The nearest wells are all located on the shallow water shelf (Jc-A1, Jc-B1, Jc-C1 and Jc-D1) in the Tugela North and South exploration blocks and, despite making use of these data to calibrate the ages of seismic horizons as possible, the absence of wells within the survey area renders datation and stratigraphic characterization of the various seismic horizons highly speculative. However, the majority of the horizons are easily correlated regional stratigraphic events. For this discussion, the stratigraphic units have been divided into basement, pre-rift sediments, syn-rift sediments and sag unit followed by drift deposits.

Basement and pre-rift

The basement was picked on a regional bright reflector indicative of a sharp increase in acoustic impedance. The basement appears to be eroded and rugous over most of the survey area but especially on the margins of rotated half grabens in the central part of the survey. The depth to basement is highly variable. The basement reaches shallow depth to the very north of the survey (especially to the north-east near the North Mozambique Ridge) but it plunges much deeper in the southern part of the survey area. The volcanic nature of the basement is very evident in the north and central parts of the survey since it appears as a very bright, hard and rugose reflector. We have noted the presence of at least two phases of volcanism on this margin.

There is evidence of steeply dipping Seaward Dipping Reflectors (SDRs) along with the presence of local volcanoes (especially in the north of the area of interest). Intrusions (sills and dykes) are quite common in the pre-rift section, especially over the Tugela High. The south-west part of the survey seems to have been affected by both the dextral AFFZ with a short rift margin, where the basement appears to be very steep with low-angle crustal listric faults observed at depth. To the east of this zone, a bright moho reflector is observed at relatively shallow depth (about 9 sec TWT or approximately 8 km) and has been interpreted as oceanic crust. As we move north (approx. 40 km) in the same strike direction, the crustal nature dramatically changes around the North-South trending South Tugela Ridge. As shown in Figure 5, the South Tugela Ridge has an estimated crustal thickness of about 6 sec. The boundary of a strike-slip fault in the South-East side can be observed which demarcates this thick section of crust from the oceanic crust in the Natal Valley to the east. Figure 4 indicates that the basement has a different texture around this area. We postulate that the South Tugela Ridge was possibly a continental sliver which was left behind as the MEB moved away during the break-up of Gondwana at about ~136Ma. Pre-Rift sediments might be found interlayered with volcanics in the north of the survey where a succession of continuous reflectors are visible at depth. However, we cannot confirm the presence of these sediments until a well is drilled.

Syn-Rift

The Syn-Rift unit displays varied seismic characters. In the north of the survey, sediments appear to be stratified with high-amplitude continuous reflectors and, in places, these

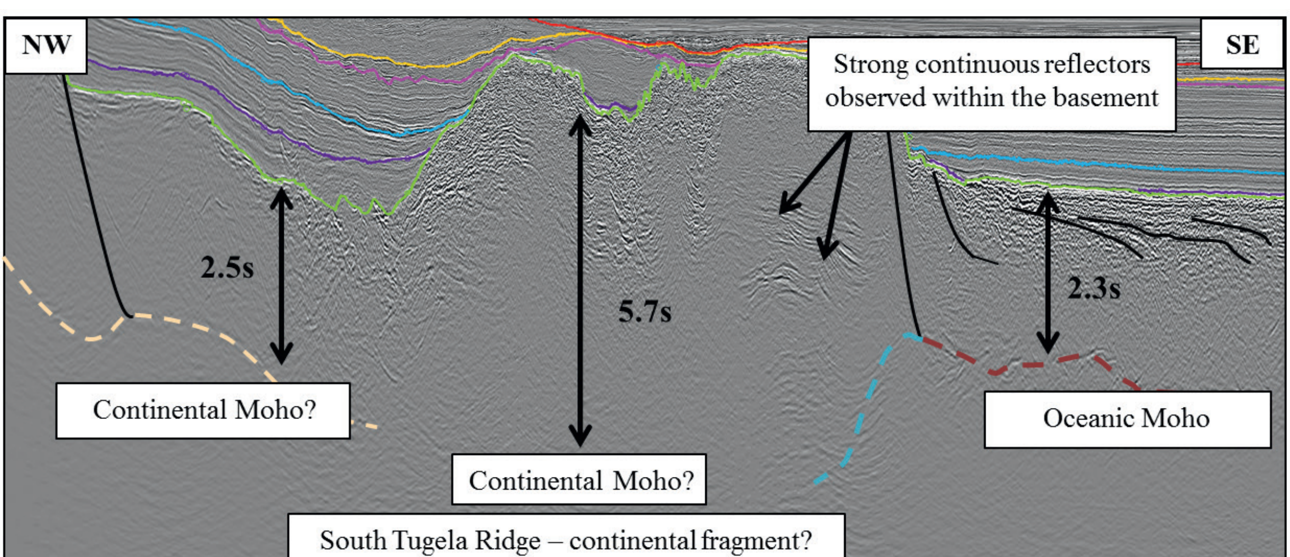

Figure 5 *Complex crustal nature of the basement near the South Tugela Ridge.*

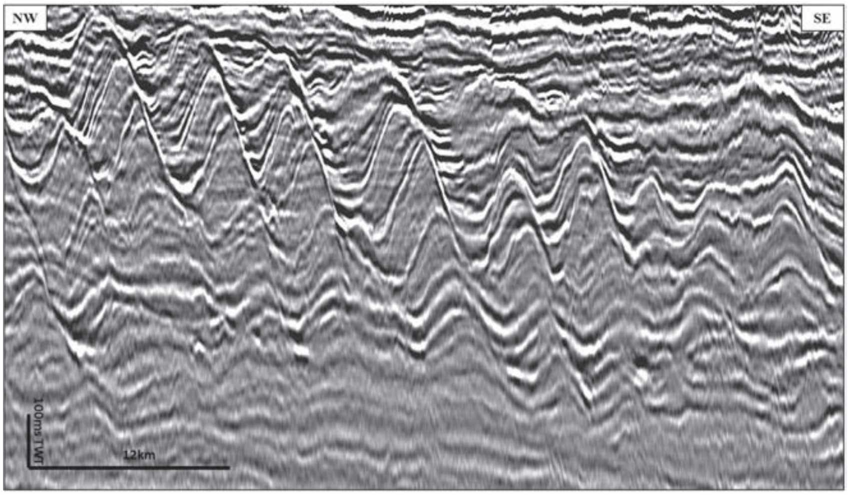

Figure 6 *An example of a contourite section within the eastern part of the survey. Note the high-amplitude wavy reflectors indicating a high-energy drift deposit.*

onlap on to the volcanic basement. Based on the aggradational nature of these reflectors it is assumed that these sediments were deposited in a deeper water setting.

In the central parts of the survey, deposition took place within trans-tensional grabens. These mini-basins could hold local source pods. Wedge-shaped geometry coupled with rotation of these grabens have been observed, which clearly indicate that the deposition of those sediments was synchronous to tectonic deformation. To the south, two depocentres are present and they are separated by the South Tugela Ridge. The western depocentre, being proximal to the slope, received sediments directly from the Proto-Tugela river/delta system and led to the deposition of early basin floor fans and turbidites visible on the seismic data. The depocentre to the east of the Tugela Ridge is characterized by aggradational isopach stratigraphy and continuous reflectors, which confirms these sediments were deposited in a low-energy, deep marine setting.

Sag unit

The sag unit drapes the whole Durban and Zululand Basins and its thickness unit is variable across the basins. This is associated with a phase of regional thermal subsidence. In the western part of the survey sediments were deposited by the Proto-Tugela River which had fully developed at the time and sediments were transported via the developing Tugela Canyon which became established by mid-Tertiary times, as observed by the cross-cutting nature of the canyon through early Tertiary sequences (Figure 4). The bulk of these sediments were deposited in the western Tugela depocentre. The eastern Tugela depocentre developed as a deep marine pelagic basin, probably mud-prone.

Drift unit

By the beginning of the drift phase, the two depocentres (eastern and western) in the Durban Basin coalesced into one single depocentre as the South Tugela Ridge, which acted as a barrier for sediment transport between the two sub-basins and became deeply buried below the sediment overburden of the Tugela Delta system shedding off the African hinterland. At this time, no significant tributaries of the Tugela Canyon were observed, leading to the conclusion that it developed as a straight slope system – generally associated with fluvial-like erosion dominated by bypassing of sedimentary flows during the lowstand intervals. The Tertiary also saw three phases of uplift – mid-Oligocene uplift (represented by a period of canyon incision and non-deposition across the basin), Miocene uplift and Pliocene uplift. These uplift phases, combined with regressive marine conditions, resulted in considerable sediment shedding from the hinterland and sediment transport across the shelf. These sediments were transported to the slope by the Tugela Canyon which was formed as a result of downslope erosion and a mass-wasting process associated with sediment loading and a steep slope gradient. All these conditions probably helped coarser-grained sediment to move farther into the eastern parts of the Durban Basins. The Tugela downslope fan represents a mixed turbidite-contourite (bottom-smoothed) pelagic system with characteristic wave-like geometries on seismic data (Figure 6). Within this stratigraphic unit, the distribution of sediments is a result of the sweeping action of the Agulhas current and subsequent contourite deposits. Where parts of the basin have been fed with coarse-grained sediments, these are reworked and potentially cleaned of the clay content by these deepwater ocean bottom currents. They have been proved to enhance reservoir properties in the Rovuma Basins, for example, offshore Mozambique (MacGregor, 2016; Cazzola, 2016; Rebesco et al., 2014). Contourite deposits are primarily observed in the eastern depocentre of the Durban Basin.

In the eastern Natal Valley, we see three distinct phases of contourite evolution which can be classified using Rebesco et al.'s method (2014). The older contourite units show moderate- to high-amplitude waves with concordant reflectors which are possibly indicative of a higher-energy deposit with the formation of large sediment waves. The next phase was dominated by a moderate-to-low-amplitude, semi-continuous contourite sequence with more chaotic reflectors and has been affected by polygonal faulting, indicating the presence of low-permeability, muddy facies. The geometry of these contourites is very similar to those observed in the North Sea Miocene sequences. The most recent phase of contourite deposits have been deposited as sheet drifts consisting of pelagic and hemipelagic sedimentation.

Hydrocarbon potential

All five components of a petroleum system were evaluated. Two possible source intervals were identified: Barremian-Aptian (based on global Aptian oceanic anoxic event (OAE)) and Cenomanian-Turonian age (based on interpretation and Cenomanian-Turonian oceanic anoxic event II (OAE II)). Well Jc-D1 on the shelf also indicates the possibility of Eocene-aged source rocks with TOCs as high as 0.25-1.25%. The presence of lightly biodegraded oil in the Oligocene and the presence of minor gas in the Eocene have been described in this well. Bitumen staining was observed in the Cenomanian-Maastrichtian section.

To understand the present-day maturity in this area we calculated kitchen maps and maturity isotherms with a simple geothermal model. The results for one line are shown in Figure 7a. The reservoirs are represented by Late Cretaceous and Tertiary, deepwater, basin floor fans and turbidites. Potential traps include pinch-outs and sediments onlap on to the Tugela cone and channel fills. Structural traps are

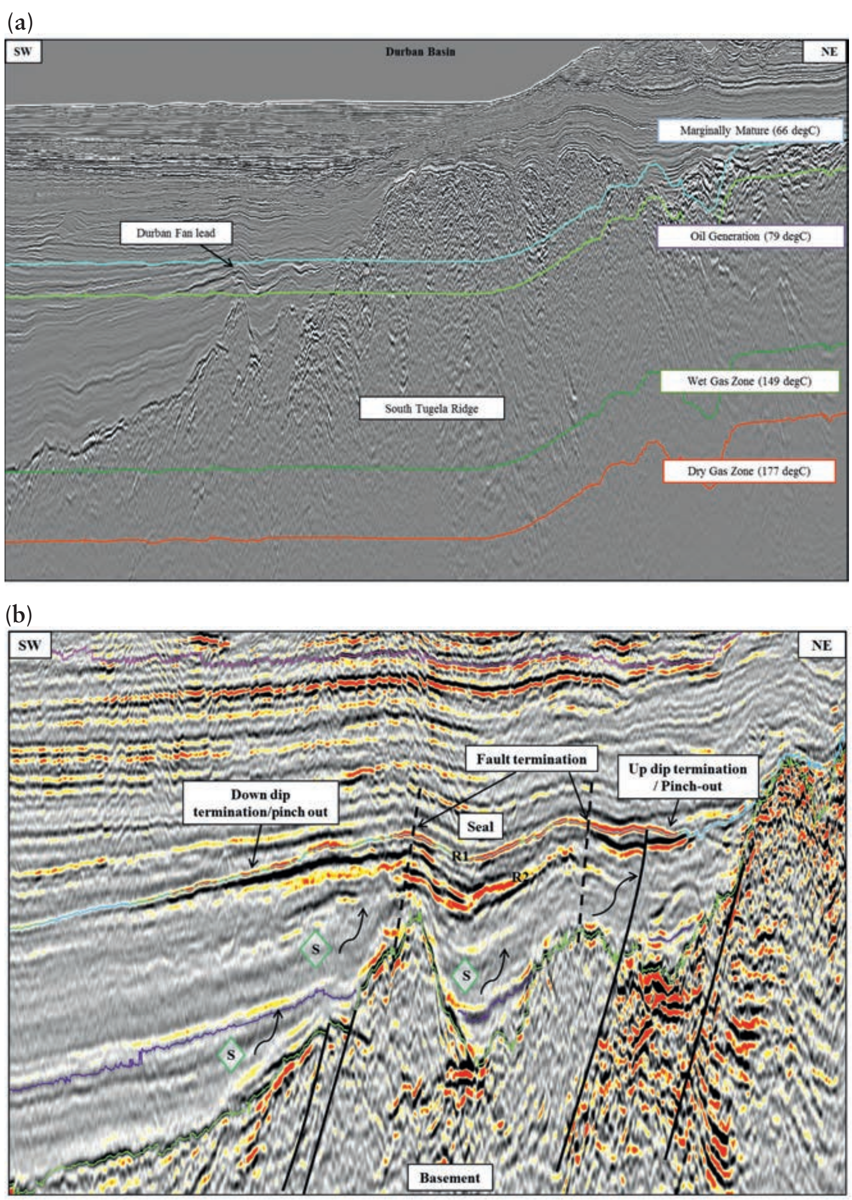

***Figure 7** a) illustrates the isotherm gradients which were calculated for the basin. The Durban fan lead sits within the oil generation window. b) illustrates the Durban fan lead which is a structural/stratigraphic trap. Reservoirs are possibly of Late Cretaceous age with Aptian-Albian aged source rocks.*

dominated by rotated fault blocks creating four-way dip closures at depth and compactional drapes with the overlying sediments of Cretaceous and Tertiary age. Intra-formational seals are represented by deepwater shales and muds throughout the stratigraphic section. Locally, porous and permeable sediments can act as lateral carrier beds for hydrocarbons to migrate to the traps, but fractures are thought to provide the main vertical migration pathways.

Figure 7b shows the example of one potential lead which lies in an area where the Lower Cretaceous source rocks are expected to be presently mature (Figure 7a). This lead takes the form of a compactional fan drape associated with high amplitudes conforming to closure. However, these amplitude anomalies need to be investigated further in terms of their AVO characteristics and relationship with a potential hydrocarbon presence. A closer look at the seismic data reveals the typical fan-like geometry and pinch-outs.

Conclusions

The Durban and Zululand Basins have a complex tectonic history mainly because of the fact that they formed on a major transform margin where multiple continental plates have split and rotated. The new seismic data have revealed details about the local development of this margin in terms of how compartmentalised the various basins are in the area of interest and how their internal structures and facies distribution have evolved in relation to the various tectonic events that affected the area. The nature of the separation between the Durban and Zululand Basins consists of a prominent trans-tensional ridge: the Naudé Ridge. In addition, the Durban Basins itself is split into two sub-basins (east and west) by the South Tugela Ridge which has created a differential in both sediment input quantity, distribution and grain properties between the eastern and western sub-basin. Some major contourite systems have been observed in the eastern part of the Durban Basin which can be related back to the Agulhas bottom currents. This study is a good example of how tectonics affect the emplacement of a petroleum system.

In addition, a number of leads have been identified within the CDZ13-14 survey and may develop into prospects which will need further investigation and analysis. One example was shown in Figure 7. However, exploration offshore the Durban and Zululand Basins is at a nascent stage and significant exploration risks remain for such a frontier basin. A closely-spaced 2D survey or 3D survey in a specific area of interest would be the next step in the exploration cycle for this area. Advanced geophysical techniques including depth imaging and amplitude versus offset (AVO) analysis will help to reduce uncertainties in interpretation. Furthermore, a detailed assessment of the key timing elements and a full basin model will improve our understanding of the petroleum system models. Drilling will ultimately provide new downhole data, enabling better calibration of the current models.

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